Environmental Assessment of the Alaskan Continental Shelf

Annual Reports of Principal Investigators for the year ending March 1979

Volume VI. Effects

U.S. DEPARTMENT OF COMMERCE
National Oceanic and Atmospheric Administration

U.S. DEPARTMENT OF INTERIOR
Bureau of Land Management

VOLUME I	RECEPTORS -- MAMMALS BIRDS
VOLUME II	RECEPTORS -- BIRDS
VOLUME III	RECEPTORS -- FISH, LITTORAL, BENTHOS
VOLUME IV	RECEPTORS -- FISH, LITTORAL, BENTHOS
VOLUME V	RECEPTORS -- MICROBIOLOGY CONTAMINANT BASELINES
VOLUME VI	EFFECTS
VOLUME VII	TRANSPORT
VOLUME VIII	TRANSPORT
VOLUME IX	HAZARDS
VOLUME X	HAZARDS DATA MANAGEMENT

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Outer Continental Shelf Environmental Assessment Program
Boulder, Colorado

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U.S. DEPARTMENT OF COMMERCE
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DISCLAIMER

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EFFECTS

CONTENTS

RU #	PI - Agency	Title	Page
71	Kooyman, G. Costa, D. - Scripps, U. of California, San Diego, CA	Effects of Oiling on Temperature Regulation in Sea Otters	1
72	Rice, S. Korn, S. Karinen, J. - Northwest & Alaska Fisheries Center, NMFS, NOAA, Auke Bay, AK	Lethal and Sublethal Effects On Selected Alaskan Marine Species after Acute and Long-Term Exposure to Oil and Oil Components	27
73	Malins, D. et al. - Northwest & Alaska Fisheries Center, NMFS, NOAA, Seattle, WA	Sublethal Effects of Petroleum Hydrocarbons and Trace Metals, Including Biotransformations, as Reflected by Morphological, Chemical, Physiological, Pathological, and Behavioral Indices	60
454	Anderson, J. et al. - Battelle, Sequim, WA	Research to Determine the Accumulation of Organic Constituents and Heavy Metals from Petroleum-Impacted Sediments by Marine Detritivores of the Alaskan Outer Continental Shelf	172
467	Truett, J. et al. - LGL Limited, Edmonton, Alberta, Canada	Beaufort Sea Barrier Island-Lagoon Ecological Process Studies	235
	Part I	Avian Ecology in Simpson Lagoon Beaufort Sea, Alaska	238
	Part II	Ecology of Fishes in Simpson Lagoon, Beaufort Sea, Alaska	363
	Part III	Ecology of Invertebrates in Simpson Lagoon, Beaufort Sea, Alaska	471
	Part IV	Oceanographic and Geologic Processes- A Synthesis of Ecologically Important Information	601

EFFECTS OF OILING ON TEMPERATURE REGULATION IN SEA OTTERS

by

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Yearly Progress Report
Research Unit No. 71
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I. SUMMARY OF OBJECTIVES, CONCLUSIONS AND IMPLICATION WITH RESPECT TO OCS OIL AND GAS DEVELOPMENT.

A. The objective of this study was to measure effects of crude oil contamination on sea otters through studies on the changes in the animals's metabolic rate and subcutaneous temperatures before and after contact with oil. A second objective was to attempt to rehabilitate the otters after crude oil contamination.

B. Conclusions:

The study has shown that small amounts of crude oil contamination have large effects on the metabolic rate of sea otters. Light oiling of approximately 25% of the animal's pelt surface area resulted in a 1.4X increase in metabolic rate while immersed in water at 15°C. Furthermore, when the oil was removed by detergent, the animal's metabolic rate increased 2.1X while immersed in water at 15°C. Of the three animals studied two contracted pneumonia and one died.

C. Implications:

Any contact with oil at any time of year would have a profound influence on the health of individual sea otters through increases in the animal's thermal conductance and the subsequent increase in metabolic rate. It is probable that death may follow from pneumonia or hyopthermia depending upon the amount of the animal's fur fouled. Rehabilitation of oil-fouled sea otters would be very costly requiring holding facilities to keep the animals for at least two weeks. Even if adequate facilities were available the success rate of rehabilitating oil-fouled sea otters is likely to be rather low.

II. INTRODUCTION:

A. General Nature and Scope of Study.

This project represents an extension of studies that began with the investigations of diving and feeding behavior, and thermoregulatory effects of oil pollution in fur seals (Kooyman et al.,1976a). In this species, which relies on fur for insulation against cold sea water, the effects of oiling were profound. It is thought, but not measured, that sea otters are even more dependent on their fur for insulation.

It is predicted that oil will have an impact on sea otters through increasing their maintenance costs due to increased heat loss in air and in water as a result of pelage contamination. The magnitude of this increase will also vary between neonates and adults. External oil may also impair their diving and feeding abilities. Kenyon (1974) noted that malnutrition was common in contaminated fur seals. Finally, we would anticipate direct metabolic effects of ingested oil. This proposed research will continue physiological research on sea otters, and will include an analysis and evaluation of other studies on the effects of oil pollution on sea otters. The results will provide an answer to such questions as well as help in providing basic information on the general aspects of respiration in all marine mammals. Furthermore, determination of the characteristics of diving, and measurements of the energetics involved will help to provide general information on the energy requirements of the various marine mammals and their different modes of propulsion.

B. Specific Objectives:

1. Energy requirements of normal sea otters at various water temperatures.
2. Energy requirements of sea otters after oiling.
3. Appropriate procedures for rehabilitating oiled sea otters.
4. Energy requirements of washed sea otters and time required for complete recovery.
5. At sea behavior and energetics of sea otters.
6. At sea behavior after oiling.

Information of this kind will provide a data base from which the assessment of any kind of oil contamination, or other activity which may alter the nature of the otter's food sources can be derived. In addition, relative to oil contamination the difficulties and costs of protecting from oiling, and the rehabilitating of oiled otters can be estimated.

C. Relevance to problems of petroleum development:

The sea otter is a conspicuous faunal element of many nearshore communities in Alaska and California where offshore oil development and transportation is either underway or planned. As fur bearers they are among the marine mammals most likely to be affected by oil. Furthermore, the California sea otter population has been determined to be a threatened population by the Department of the Interior due primarily to the threat of an offshore oil spill. By measuring the physiological responses of individual animals to surface contamination, the present research effort provides basic information from which the impact of an oil spill within the sea otter's range can be predicted.

III. CURRENT STATE OF KNOWLEDGE

The effects of oil spills on marine mammals have been reviewed recently by Geraci and Smith (1977), and by Davis and Anderson (1976). From both these sources it appears that hair bearing marine mammals (either adult or immature) are not usually killed by simple surface contact with oil. However, fur-bearing marine mammals (either young or adult) are much more susceptible, and may be killed by such contact.

Our previous study has shown that small amounts of crude oil have a large effect on thermal conductance of fur-bearing pelts, and no effect on nonfur-bearing pelts. In living fur seals light oiling of approximately 30% of the pelt surface area resulted in a 1.5X increase in metabolic rate while immersed in water of various temperatures. Furthermore, this effect lasted at least two weeks.

Preliminary research by Siniff, Johnson and Williams (1977) indicates that crude oil contamination of live sea otters results in death under certain circumstances. However, their investigation was of a limited nature and no conclusions can be made from their study. Metabolic rates of immersed sea otters have been measured previously (Morrison, Rosenmann and Estes, 1975; Iverson and Krog, 1973) and are useful only in comparisons with control animals used in the present study.

IV. STUDY AREA

Laboratory experiments were done at the Physiological Research Laboratory, Scripps Institution of Oceanography, University of California at San Diego, California. Captive sea otters were collected from Monterey, California with the assistance of the California Department of Fish and Game. Preliminary field studies were conducted in Prince William Sound, Alaska during July 7-22, 1978.

V. SOURCES, METHODS AND RATIONALE OF DATA COLLECTION

A. Metabolic Rates During Immersion

Sea otters were held for several months at the Physiological Research Laboratory. A total of five female sea otters have been maintained over the last year. One female was transferred to Sea World, San Diego, when she indicated signs of pneumonia which resulted in chronic lung damage.

The sea otters were weighed wet on a platform beam balance just prior to the metabolic run. Soon after weighing all animals were placed in the metabolic test chamber specially designed for these studies. The chamber, which was 151 cm long, 84 cm wide, 84 cm deep and which held about 1400 liters of fresh water, was constructed of styrofoam sheets (about 05 cm thick) which were coated with wood and fiber glass for strength. The lid of the chamber was fastened tightly over a neoprene gasket and the box was filled with fresh water to 2 cm above the lip of a 30 x 60 cm lucite dome projecting above the chamber top. Opposed ports in the lower portion of the dome functioned as intake and exhaust for air drawn through this air space. The rate of air flow was measured with a Wright respirometer. Humidity was determined with a dial hygrometer, and barometric pressure was measured with an aneroid barometer.

Air temperature and water temperature of the box were measured with thermocouple probes, one of which was placed at the mouth of the air intake and the other on the upper portion of the chamber wall about 2 cm below the lid. Water was slowly, constantly and uniformly stirred in the box by means of a series of outlet and inlet manifolds. Water temperature usually varied less than 0.5^{o}C. Readout of the thermocouple probes was with a Bailey Batt 4 coupled to a digital voltmeter which made possible the reading of temperatures to 0.1^{o}C.

Deep body temperatures were obtained by inserting an encapsulated radio transmitter down the esophagus of anesthetized animals. The transmitter signal was received on a standard FM broadcast receiver modified by Konigsberg Instruments, Inc. to demodulate the pulsed interval ratio to an analog voltage which was then measured on an oscilloscope.

Subcutaneous temperatures were taken by surgically inplanted radio transmitters. The pulse rate of the transmitter varied with temperature. The signal was received on a standard AM radio and the pulses were counted and converted to temperature readings. (McKay 1970).

A sample of the exhaust from the dome was drawn through a glass "U" tube filled with drierite, two "U" tubes containing CO_2 absorber, and a final "U" tube of drierite before entering the sensing cell of an AEI O_2 analyzer. In those experiments with oiled or washed animals a "U" tube of 4-12 mesh activated charcoal preceded the first drierite "U" tube. This material absorbed all oil fumes.

The AEI O_2 analyzer signal was continuously recorded on a 25 cm chart recorder adjusted to record from 19-21% full scale. At 60-minute intervals the inlet air sample was checked, and the instrument's reference cell adjusted if it had drifted. Once a session the analyzer was calibrated by flushing the sensing cell with outside air.

The plotted curves of O_2 concentration changes were smoothed by eye and the difference in O_2 concentration from the intake and exhaust were determined every minute. The averages for 60-minute intervals were collated. Appropriate factors for correction of gas volumes to STPD were incorporated into a computer program, and oxygen consumption rates were calculated.

Sea otters were oiled by first putting them lightly to sleep with gas anesthesia (Halothane). This was accomplished by placing the sea otter's head in a plastic mask and flowing gas throught the mask at a known concentration. Gas flow rate and concentration were maintained with a Bird MK 5 respirator and fluotec vaporizer. Prudhoe Bay crude oil was then brushed over the back of the animal. About 60 ml of oil was brushed onto the fur. The rest of the animal was left oil-free. This process took no more than 15 minutes. After oiling the animals were permitted to swim in a clean pool of sea water for 30 minutes before the metabolic test.

Upon completion on three of the metabolic tests the animals were anesthetized and cleaned with Amberlux detergent. Cleaning took 30-45 minutes. On the fourth and final oiling crude oil was left on the otter 8 days before washing. Post oiling metabolic measurements were made on day 1 and 6. Eight days after oiling, the oil was washed off with a shampoo and conditioner, formulated by Redkin Laboratories, Los Angeles, California.

B. Studies on Wild Sea Otters

In order to investigate the at sea behavior and energetics of control and oiled sea otters, we conducted a preliminary study of sea otters in Prince William Sound, Alaska in July, 1978. A suitable study site was looked for to conduct our investigations during the 1979 field season.

A field site was set up on the west end of Hinchinbrook Island in Constantine Harbor. Four sea otters were captured utilizing "floating tangle nets". Two of these animals were removed from the net and immediately released. The other two were anesthesized and a floating collar with a telonics telemetry transmitter and a mock depth recorder were attached. The animals were radio tracked until the collar released by a corrosable link and the collar was then recovered by boat.

A sea otter population survey of approximately 2/3 of Prince William Sound was also conducted during this time. Observations were made from a Bell Jet Ranger 200. Two people counted and a third person recorded the other sightings on the appropriate charts.

VI. RESULTS

A. Studies on Captive Animals

A total of 67 control metabolic experiments, totalling over 402 hr metabolic measurements were made on five female sea otters immersed in water at 5,10,15,20 and 30°C. The mean resting or standard metabolic rate measured in these animals at all water temperatures was 12.0 ± 1.2 ml O_2/kg-min or 4.0 ± 0.4 Watts/kg. (Table 1).

No significant difference was measured in the resting oxygen consumption from 5° to 30°C,however, a significant increase in both average and active oxygen consumption was observed as the water temperature decreased (Figure 1).

Oiling experiments have been conducted on three sea otters, once on otter D and S, and twice on otter B. (Figure 2). The subcutaneous and core body temperatures for the four oiling experiments can be seen in Table 2. The average metabolic rate of otter B increased 22% after oiling 16% of her body surface with 38 mls of crude oil. After washing, her metabolic rate increased 102% above the control rate. Eight days after oiling her metabolic rate returned to normal. In the second experiment 13% of otter B's surface was oiled with 60 mls of crude oil. After oiling there was a 69% increase in her normal metabolic rate. After washing her metabolic rate was 125% above normal and was still 33% higher than normal after 14 days. In the third oiling experiment, 26% of the body surface of otter D was oiled with 60 mls of oil. Her average metabolic rate increased 36% after oiling and 111% after washing. In the fourth oiling experiment 23% of otter S's body surface was oiled with 35 mls of crude oil. After oiling,her average metabolic rate increased 35%. In this experiment, oil remained on the otter for 8 days. The average metabolic rate was 63% greater than the control 1 day after oiling and was 98% higher than control 6 days later. Washing the otter with a shampoo and conditioner supplied by Redkin Laboratories (Los Angeles, California) resulted in a metabolic rate that was 87% higher than control, three days later the metabolic rate was 75% higher than control and 8 days post-washing it was still 75% higher than control. After washing, the sea otters' furs appeared wet and the animals were observed shivering. The lower subcutaneous temperatures observed in oiled pelt areas suggests an increased thermal conductance of oiled fur.

After the first oiling otter B recovered in our normal holding facility. However, after the second and third oiling experiments the washed otters were incapable of completely grooming their fur into its normal condition.

Forty-eight hours after washing, otter B had groomed only her upper torso and the fur on her lower abdomen was totally wetted. During this time she was constantly shivering. The water temperature of our holding tank was 16.7°C. Due to constant shivering and the inability of otter B to groom herself properly, she was removed from the holding tank and placed in a small tub filled with 25-30°C water. The tank was left filled for three hours and then drained and left empty for 1-2 hours and then filled again. This procedure was carried out for 24 hours. After the 24 hour period the otter had managed to successfully groom her entire body and was returned to our regular holding tank where she continued to groom normally and was not observed to shiver again.

Two weeks after oiling otter B, we took a routine blood sample and measured a white blood cell count of 16,500 cells/mm^3. The normal white count is around 8,000 cells/mm^3 . Otter B was then transferred to Sea World for veterinary care, where they diagnosed pneumonia. Otter B recovered after treatment with antibiotics. When she was returned to the Physiological Research Laboratory 100 days after oiling, her fur was matted and her metabolic rate was 71% greater than normal.

After washing otter D we put her into a tank of warm water (26-30°C). However, unlike otter B, she would not groom. Over the next six day period, we put her into cold water then warm water and then left her dry. She did attempt to do some grooming but was unsuccessful in restoring the air layer into her fur. On the sixth day after oiling we transferred her to Sea World, where they diagnosed initial signs of pneumonia. Five days later she died (11 days post oiling). A necropsy was conducted and revealed gross inflammation of the lung from acute pneumonia. No problems were encountered with otter S' after washing. She appeared to be able to withstand the thermal stress without grossly noticeable ill effects.

However, otter S's fur retained a slick appearance long after the washing. This was probably due to the inability of the new shampoo to completely remove the crude oil. The otter was transferred to Sea World and when observed four months later, otter S's fur appeared normal.

The holding tank temperature on the day of the oiling experiments were: 1st experiment otter B 20.2°C, 2nd experiment otter B 16.4°C, otter D 16.1°C and otter S 20°C.

A reduction in the subcutaneous temperature was observed beneath the oiled fur (Table 2). However, washed fur had a similar high subcutaneous temperature as control areas.

B. Studies on Wild Sea Otters

Radio collars were recovered from two animals without difficulty and a total of four animals were captured. This preliminary study established the feasibility of working in this area. The mock depth recorder system worked well.

The results of the population survey can be seen in figures 3-7. Figures 3 shows the overall area surveyed. These figures are modified from Calkins, Pitcher & Schneider (1975).

VII. DISCUSSION

A. The mean standard metabolic rate of 12.0ml O_2/kg -min measured for five California sea otters immersed in water compares well with the 14.2 ml O_2/kg-min measured in water immersed Alaskan sea otters by Morrison, Rosenman & Estes (1974). The standard metabolic rate of these sea otters is 2-3 X the predicted standard metabolic rate for a terrestrial mammal of equal size. Elevated metabolic rates of immersed marine mammals have been observed by others (Irving and Hart, 1957; Kooyman et al., 1976a; Miller et al., 1976; Morrison et al., 1974). Similarly elevated metabolic rates have also been recorded for immersed penquins (Kooyman et al, 1976b).

Morrison et al (1974) observed sea otters are floating very low in warm water (Tw = 30°C) . They suggested that the otters' fur was allowed to wet at this higher water temperature allowing an increase in heat dissipation. We also observed this phenomenom in our otters at 30°C. Conversly, we also observed that the amount of the otter floating out of the water was highest at 5.0°C. This orientation in the water could explain the very wide thermal neutral zone observed in these animals. Increasing the amount of body surface in contact with the water at high water temperatures would increase heat flux to the environment. Whereas, decreasing body surface exposed to water at low water temperatures would decrease heat flux. However, at high wind velocities and very low ambient air temperatures, heat loss could be lower with total immersion in cold sea water (Miller et al, 1975). Another mechanism which could account for the large thermal neutral zone in sea otters is an increase in heat production by increasing the amount and intensity of their activity. As can be seen in Figure 1, the average metabolic increases with decreasing water temperature as does active metabolic rate. Body temperatures in our sea otters appeared to be quite variable, up to a 1.0°C range.

The labile body temperature could reflect increased heat production and storage during activity. The animal could then gradually lose heat lowering T_B at rest. In addition, grooming was usually the activity most often observed while the otters were in the chamber. Increased grooming would not only increase heat production but would also improve the insulating quality of the fur whereas total immersion and deep prolonged periods of sleep would both decrease insulation by allowing slight water infiltration of the fur and in a lower overall heat production (otters must groom in order to maintain the fur air layer).

The changes in the sea otter's metabolic rate after oiling and washing parallel those previously observed in live fur seals and in excised pelts (Kooyman et al., 1976a). In both studies the post wash condition was twice the control. The fact that the fur becomes wet to the skin after washing seems to indicate that the natural fur oils have been removed along with the crude oil. If this hypothesis is correct, a minimum of 8 days are required for the natural fur oil's to be replaced. This assumption is based on the minimum of 8 days required for the metabolic rate (therefore overall thermal conductance) to return to control levels (Figure 2).

The difficulty encountered with recovery in two of the oiling experiments correlates with the holding tank temperatures. In the 1st and 4th oiling experiments, where the animals recovered without special handling, the tank temperature was above 20°C. In the 2nd and 3rd oiling experiments where both animals required special handling, both animals contracted pneumonia and one died, the tank temperatures were around 16°C. It is interesting to note that the average metabolic rate increases below 20°C. From these observations it would appear that the greatest success in oiled otter rehabilitation would occur if the animals are maintained in holding tanks with water at 20°C or warmer.

The post oiling, washing occurence of pneumonia in two animals is not surprising. Many marine mammals become susceptible to pneumonia when in a weakened condition. This fact is further supported for sea otters by the high frequency of pneumonia found in otters which died of non-traumatic causes (Morejohn, Ames and Lewis 1975).

Rehabilitation of oil fouled sea otters would require veterinary supervision and warm water holding facilities to decrease the chance of death by hypothermia or pneumonia prior to release of the sea otters into the wild. It may not be possible to treat large numbers of fouled sea otters successfully. Especially when we consider the amount of food sea otters require (25-30% of their body weight daily), and the size of the holding facility.

The matted fur and high average metabolic rate of otter B after returning from Sea World may not be entirely due to the oiling and washing. Otter B was maintained in a tank flushed with chlorinated sea water. It is possible that the chlorine also removed some natural fur oils causing the fur to mat. This hypothesis is further supported by two facts. Otter B's metabolic rate was 17.8 ml O_2/kg/hr just before she went to Sea World and was 23.0 ml O_2/kg/hr upon her return. The matted fur extended into areas which were not oiled or washed (even the hind flippers were matted).

The lower subcutaneous temperature beneath oiled fur agrees well with the increased thermal conductance of excised oiled pelts by Kooyman et al., 1976a. The lower subcutaneous temperature under the oiled fur indicates that the fur has lost some of its insulating quality. In order to compensate for the localized loss of insulation the peripheral circulation was probably reduced resulting in a lower subcutaneous temperature, thereby lowering the heat loss to the environment.

It is possible to calculate the changes in total thermal conductance if certain assumptions are made: 1. body temperature remains constant. 2. cutaneous and respiratory heat loss are insignificant when compared to overall heat flow. If these assumptions are met in sea otters, we can then calculate total thermal conductance from the following expression:

$$C = \frac{M}{(T_B - T_A)S}$$

where T_B = Body Temperature °C
T_A = Ambient Temperature °C
M = Metabolic Rate Watts
C = Total Thermal Conductance Watts/°C
S = Surface Area m^2

Thermal conductance calculated in this way can be seen in Table 3. The highest increase in conductance was measured in the 2nd oiling experiment with otter B. Her conductance increased 2.7 times. As would be expected, the oil density was highest in this experiment.

The highest thermal conductances were measured in washed animals. This is not unexpected when we consider that a larger percentage of the animal's fur is effected by washing, as well as completely wetting the fur almost completely eliminating it's insulating qualities.

B. Studies on Wild Sea Otters

Lensink (1962) estimated the 1960 Prince William Sound-Kayak Island sea otter population at 1000 to 1500 based on fixed-wing aircraft observations of 702 animals. According to Schneider (1971), this estimate may be in error by as much as 100%. The Alaska Department of Fish and Game (1973) estimated the population at 5000, which is reasonable in light of the numbers of otters counted in the 1973-74 surveys: 2015 in June 1973 compared to 1441 in March 1974 (Calkins, Pitcher, and Schneider, 1975). Both were helicopter surveys. In July 1978, 2148 otters were counted when slightly less area was surveyed. (Figure 3).

Hinchinbrook-Hawkins Islands

The number of sea otters in this census block has increased as a result of significant growth in localized areas. Hinchinbrook Island has several embayments and harbors in which sea otters are well established. Constantine Harbor is still densely populated, but it appears that carrying capacity has been reached and population growth has stabilized. On the other hand, the Port Etches area supports a much larger population than previously, perhaps as a result of overflow from Constantine Harbor. (Figure 6).

The southeast side of Hinchinbrook was relatively bare compared to previous years, but the number of otters increased as the mouth of Orca Inlet was approached. The Inlet population as observed in March 1974 appears to be maintaining but not rapidly expanding.

The otters felt to have migrated from the Knowles Head-Port Gravina area to the Sheep Bay area in the 1974 survey are still present, although only a pod of thirty animals was observed compared to 202 otters in 1974 (Pitcher, 1975).

Knight Island Area

There does not appear to have been a significant increase in the number of sea otters in the Knight Island area (Figure 5). A small population with a few pups was spotted around Eleanor Island. Around Ingot, Sphinx, and Disk Islands, only isolated, single otters were observed. The general pattern around Knight Island is one of small groups of otters widely dispersed along the coast. Very few pups were present.

Montague Island

Like Hinchinbrook Island, there is a trend evident here toward population growth in restricted areas. The area around Graveyard Point and into Stockdale Harbor is now the home of a sizeable population with many pups. (Figure 7). Port Chalmers inlet continues to support a dense population, and numerous pups were present. Hanning Bay, Macleod Harbor, Jeanie Cove, and Patton Bay all support only small groups of otters at this time. Otter sightings were rare between Box Point and Zaikof Point, so that the east side of Montague Island remains basically unpopulated. Significant numbers of otters exist in both Zaikof and Rocky Bays.

Valdez Arm-Port Gravina Area

It is especially crucial to monitor the otter population in the Valdez Arm-Port Gravina area (Figure 4) since this is the site of heavy oil tanker traffic. By comparison between 1973-74 and recent survey results, a dramatic increase in sea otter numbers is apparent. One hundred seventy-seven animals were observed in this area in 1973, 73 in 1974, and 974 in 1978.

After his survey, Pitcher (1975) stated:

> Areas which appear to be acceptable habitat but are not presently supporting significant sea otter populations include Perry Island, Bligh Island and Galena Bay.

A major trend in population recovery in this direction is evident from the data, as otters have spread to Goose Island, up into the entrance of Port Fidalgo, especially in Snug Corner Cove and Boulder Bay, and Bligh Island, all of which were nearly unpopulated less than five years ago.

While few otters inhabit coastline bordering on Port Valdez or the upper portions of the Valdez Arm, the area included in their recent range extension would be directly affected by a massive oil spill or even constant low level pollution. If growth and range extension continue, which seems probable in view of the large number of pups observed, otters will most likely spread further north into the Galena Bay area as predicted.

It is evident from the data that the sea otter population in Prince William Sound has increased in size over the past five years, and the process appears to be continuing. Dense populations now exist in specific areas which previously did not support sea otters. Of major significance is the population growth and range extension occurring in the Valdez Arm-Port Gravina area, since these otters are moving into sites that are in direct contact with the oil traffic waterway.

VIII. CONCLUSIONS

Crude oil contamination over small areas of the sea ooter's fur causes noticeable increases in their heat loss and metabolic rate. Oiled sea otters had metabolic rates 1.4X normal. Removal of crude oil by washing with a detergent resulted in metabolic rates that were 2.3X normal. Crude oil contamination of wild sea otters would probably cause significant thermal stress and could lead to hypothermy and/or pneumonia resulting in death. Rehabilitation of large numbers of sea otters would require sophisticated pre-existing facilities and would be extremely expensive if at all possible.

IX. NEEDS FOR FURTHER STUDY

Four areas which deserve further study are: how well the sea otter survives the increased energy demands of oil contamination; do wild sea otters avoid oil slicks; what are the natural oils in sea otter fur and can we successfully replace the oils after washing.

X. SUMMARY OF JANUARY - MARCH QUARTER

1. Scientific Party

    a. Dr. Gerald Kooyman - Principal Investigator

    b. Daniel Costa - Project Coordinator

    c. John Wood - Development Technician

    d. Michael Bergey - Animal Caretaker

    e. Richard Price - Lab Assistant

    f. Mike Gregory - Southwest Fisheries Center Paid Volunteer

    g. Deborah Zmarsly - Research Assistant

2. Methods

    The laboratory analysis is described in the final report .

3. Data Collected

    a. Testing of the depth recorders were accomplished along with final debugging.

    b. Equipment has been purchased and arrangements made for summer field research in Prince William Sound.

4. Oral Presentations

Southern California Academy of Science Annual Meeting May 11-12,1979; Effects of Oiling on Temperature Regulation in Sea Otters. Daniel P. Costa and Gerald L. Kooyman.

5. Papers Published

Costa, D.P. 1978. The Sea Otter; its interactions with man. Oceanus .

XI. AUXILLIARY MATERIAL

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Table I

Mean resting oxygen consumption (mls O_2/kg-min) for each experimental period at various water temperature

	Water Temperature °C								
Otter	5	10	15	20	25	30	Oil	Post Oil	Wash
B	14.4 17.7 11.14 13.2	12.0 10.8	12.0 13.7 9.7 10.4 11.9 12.7	12.4 14.2	12.9 12.9 14.4 11.7 12.0	12.7 10.4			
EXP.1							15.9		31.2
EXP.2							16.3		27.7
M	15.4	--	--	11.9 13.0	9.2	--	--	--	--
D	14.1 12.2	10.8 11.1	11.2 12.0 9.7	9.7 11.2 11.3	10.5 10.6	10.5 10.9	14.8		26.0
J	12.6 6.0	10.7 11.5	15.3 13.8 9.5 9.6	8.5 8.3	11.1 9.1 9.6	9.1 9.4			
S	7.1 16.0	15.2	11.4 13.8 13.2 12.8	10.1 12.0	11.9 13.7	13.0 11.5 12.0	13.5	15.5	28.8

Table II

Subcutaneous (T_{SQ}) and deep core body (T_B) temperature in °C in control, oiled, washed, 1 day post wash and 1 day post oil animals. All temperatures measured from otter immersed in 15°C water unless otherwise indicated. Numbers below temperature are one standard deviation and numbers in parenthesis equals the sample size.

Animal	Control		Oiled		Post oil		Washed		Post wash
	T_{SQ}	T_B	T_{SQ}	T_B	T_{SQ}	T_B	T_{SQ}	T_B	T_{SQ}
B 1	36.4 ±0.3 (4)	36.7	26.2 ±0.7 (19)	37.3 ±0.2 (12)	-	-	34.2** ±0.3 (7)	-	35.8 0.4 (13)
B 2	32.3* ±1.1 (15)	-	26.0 ±0.6 (14)	-	-	-	-	-	-
D	-	-	28.5 ±0.3 (21)	38.1 (2)	-	-	34.5 ±2.2 (19)	-	-
S	-	-	24.6 ±0.4 (37)	37.6 ±0.2 (38)	33.7 ±0.5 (24)	-	35.0 ±1.3 (34)	36.8 ±0.5 (24)	-
J	-	37.9	-	-	-	-	-	-	-
B at 5°C	-	37.2	-	-	-	-	-	-	-
$\bar{X}$	34.4	37.2	26.3	37.3	33.7		34.6	36.8	35.8

* This temperature was recorded under an unoiled fur of partially oiled sea otter.

** This temperature was measured under a unoiled but subsequently washed portion of an otter's fur.

Table III

Total thermal conductance calculated from the 4 oiling experiments Bette 1 and Bette 2 are the 1st and 2nd oiling experiments on Bette respectively. Shannon 1 and 6 are 1 day and 6 days post oiling respectively. Fur oil density refers to the amount of oil applied over the fur surface.

Animal	Control $\frac{W}{m^2\ °C}$	Oil $\frac{W}{m^2\ °C}$	Wash $\frac{W}{m^2\ °C}$	$\frac{\text{Oil}}{\text{Control}}$	$\frac{\text{Wash}}{\text{Control}}$	Fur oil density $\frac{\text{ml oil}}{\text{cm}^2}$
B 1	6.5	8.2	15.8	1.3	2.4	0.05
B 2	5.3	8.6	14.5	1.6	2.7	0.08
D	5.8	7.9	13.6	1.4	2.3	0.04
S	7.0	7.4	16.3	1.06	2.3	0.03
S 1	-	8.2	-	1.2	-	
S 6	-	13.0	-	1.9	-	
$\bar{X}$	6.1	7.0	15.1	1.2	2.5	

Table IV. Summary of sea otter surveys, Prince William Sound

Area	Pre-1959[a]	1959[b]	1960[b]	1964[c]	1970[c]	1973[d]	1974[d]	1978[e]
Hawkins I.	1 (1951)	NS*	NS	NS	1	4	123	110
Hinch I.	150 (1951)	58	48	167	101	367	86	467
Montague I.	78 (1957)	349	100	42	259	514	206	492
Galena Bay to Fish Bay	NS	NS	NS	NS	1	6	2	145
Esther Pass. to Valdez Arm	NS	0	NS	NS	NS	24	132	14
Knight, Eleanor I.	2 (1956)	NS	1	3	145	241	77	75

NS* = not surveyed

a Lensink (1962) - summary of miscellaneous observations

b Lensink (1962)-fixed-wing aerial survey

c ADF&G-fixed-wing aerial survey

d ADF&G-helicopter survey

e Kooyman & Costa-helicopter survey

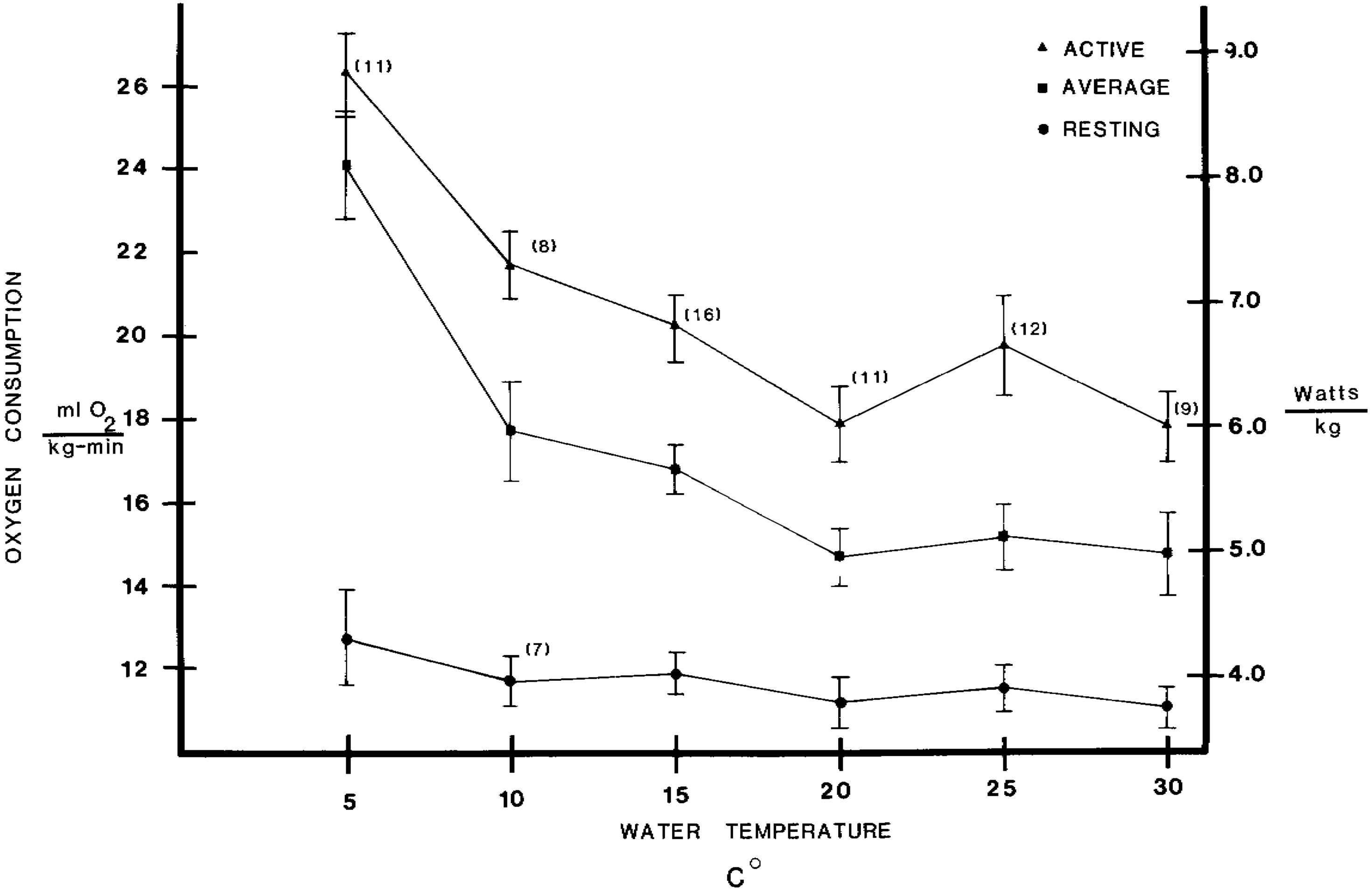

Figure 1. Resting, average and active oxygen consumption are plotted against chamber water temperature for the 5 sea otters studied. 1 standard error is plotted for each point representing the mean of the means for each experiment run. The mean number of experiments used to determine the points on the figure are given in parenthesis.

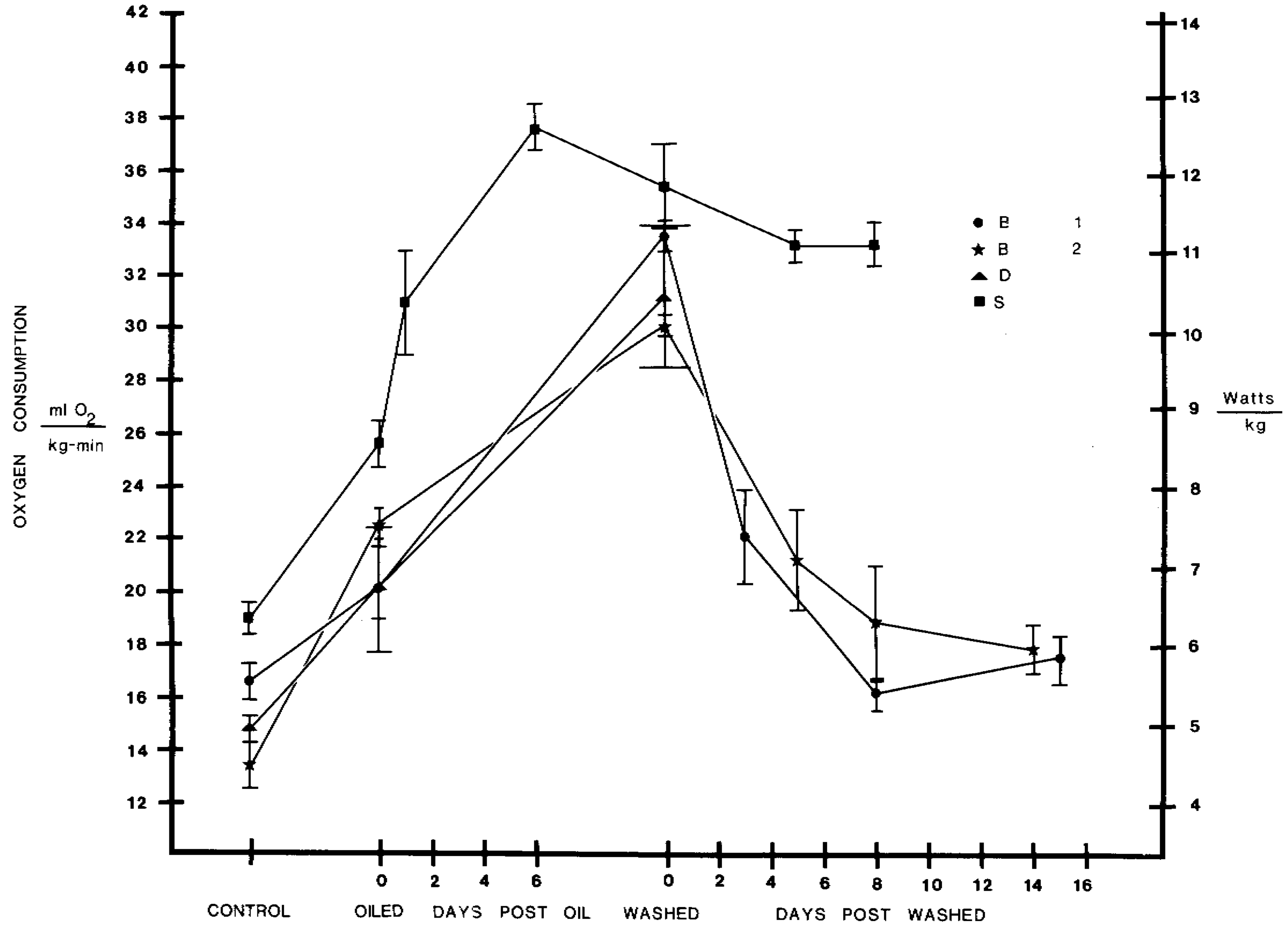

Figure 2. Mean average oxygen consumption for control, oiled, and washed animals are displayed. Days post oiled only refers to treatment of S where the oil was left on 8 days prior to oiling. Otherwise, all animals were washed 8 hrs after oiling except for S. 1 standard error is plotted as bars around the mean. The number of measurements for control runs was 18, B1; 12 B2; 16, D; 24. S. For oiling and washed runs 6, B1; 3, B1; 3 B1; 6 D; 6 S.

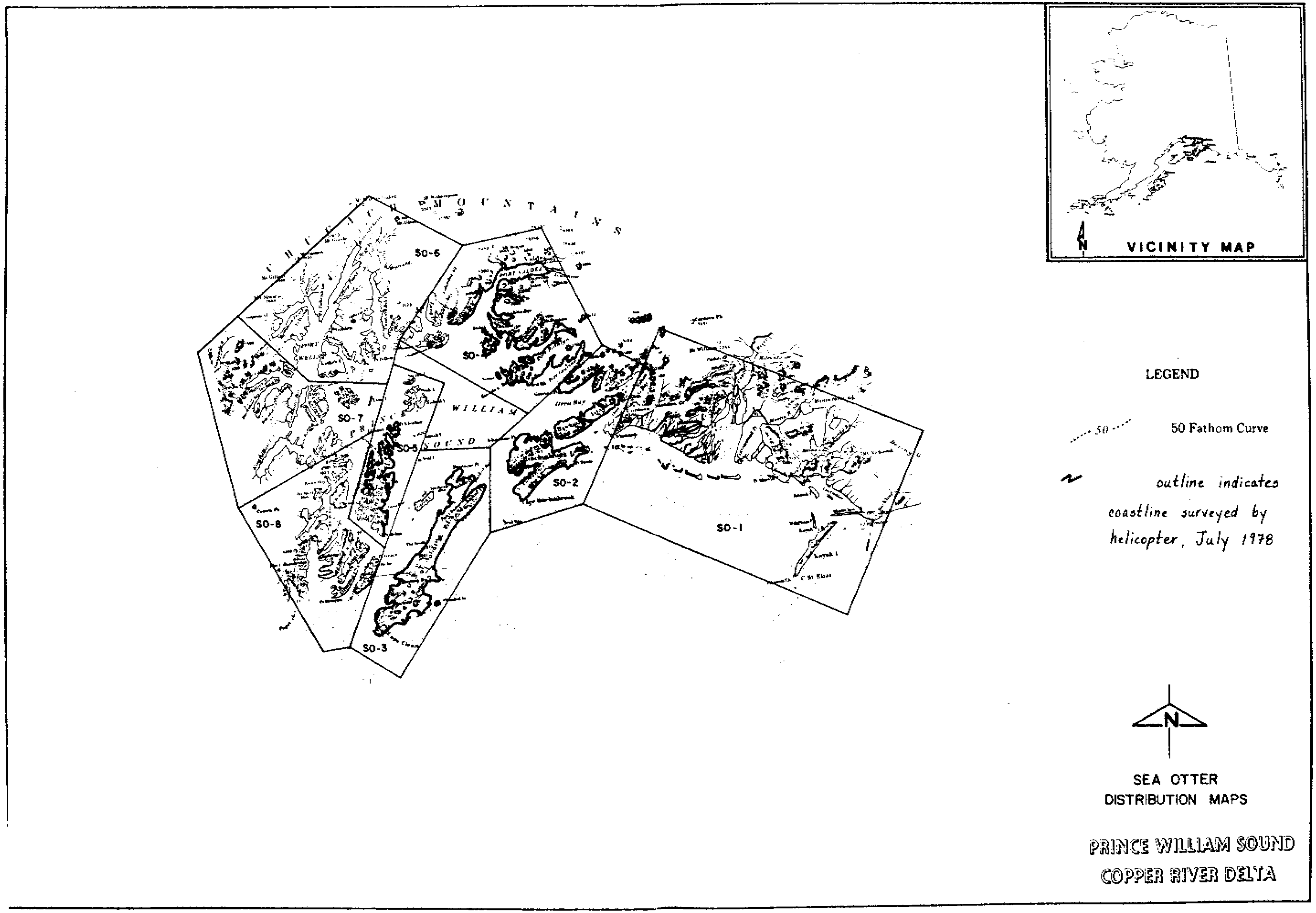

Figure 3. Map of Prince William Sound showing an overview of the AREA SURVEYED FOR SEA OTTERS. The heavy line indicates area surveyed.

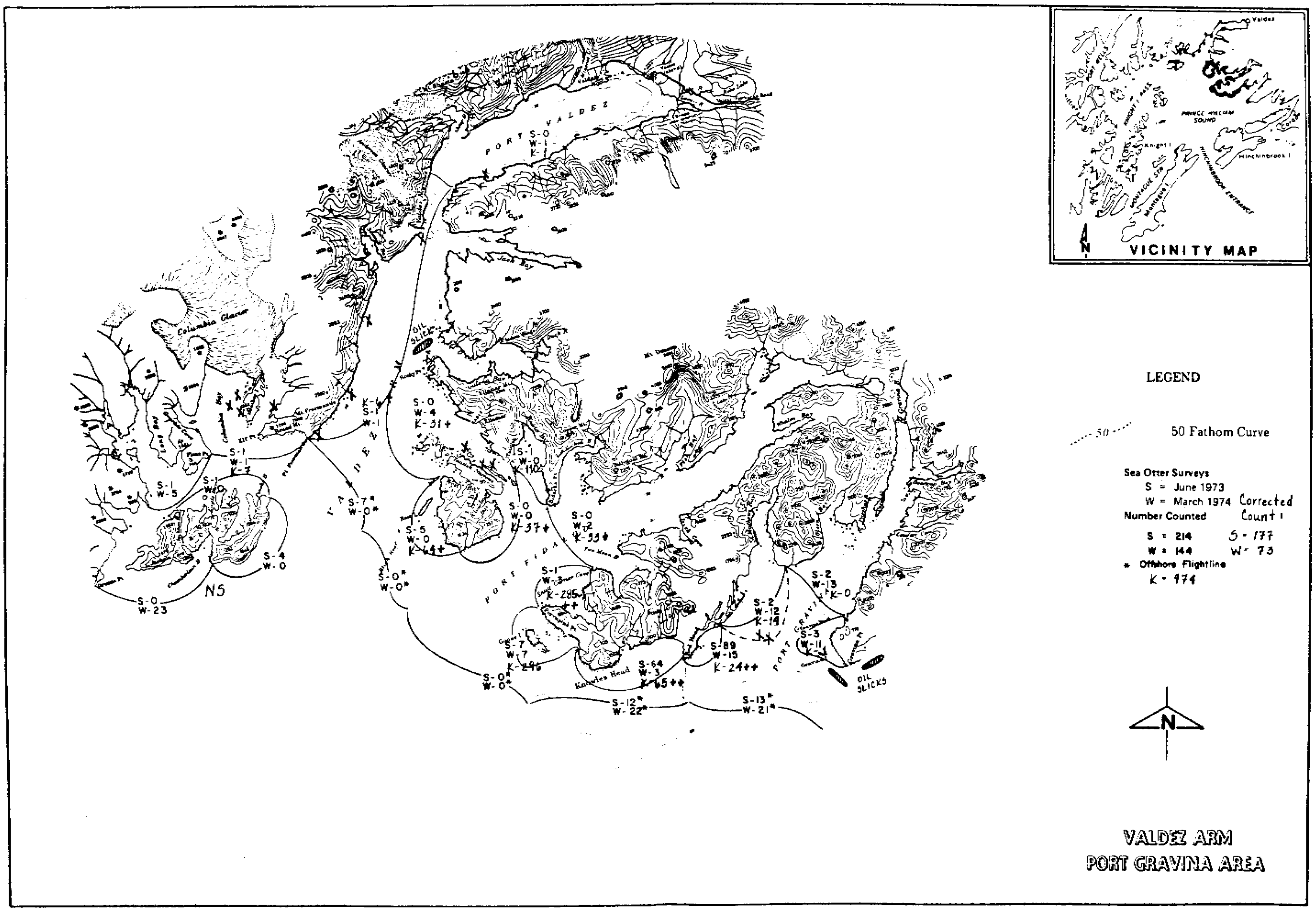

Figure 4. Displays sea otter sightings for Valdez Arm Point Gravina area. S and W are surveys conducted by Calkins, Pitcher and Schneider (1975).

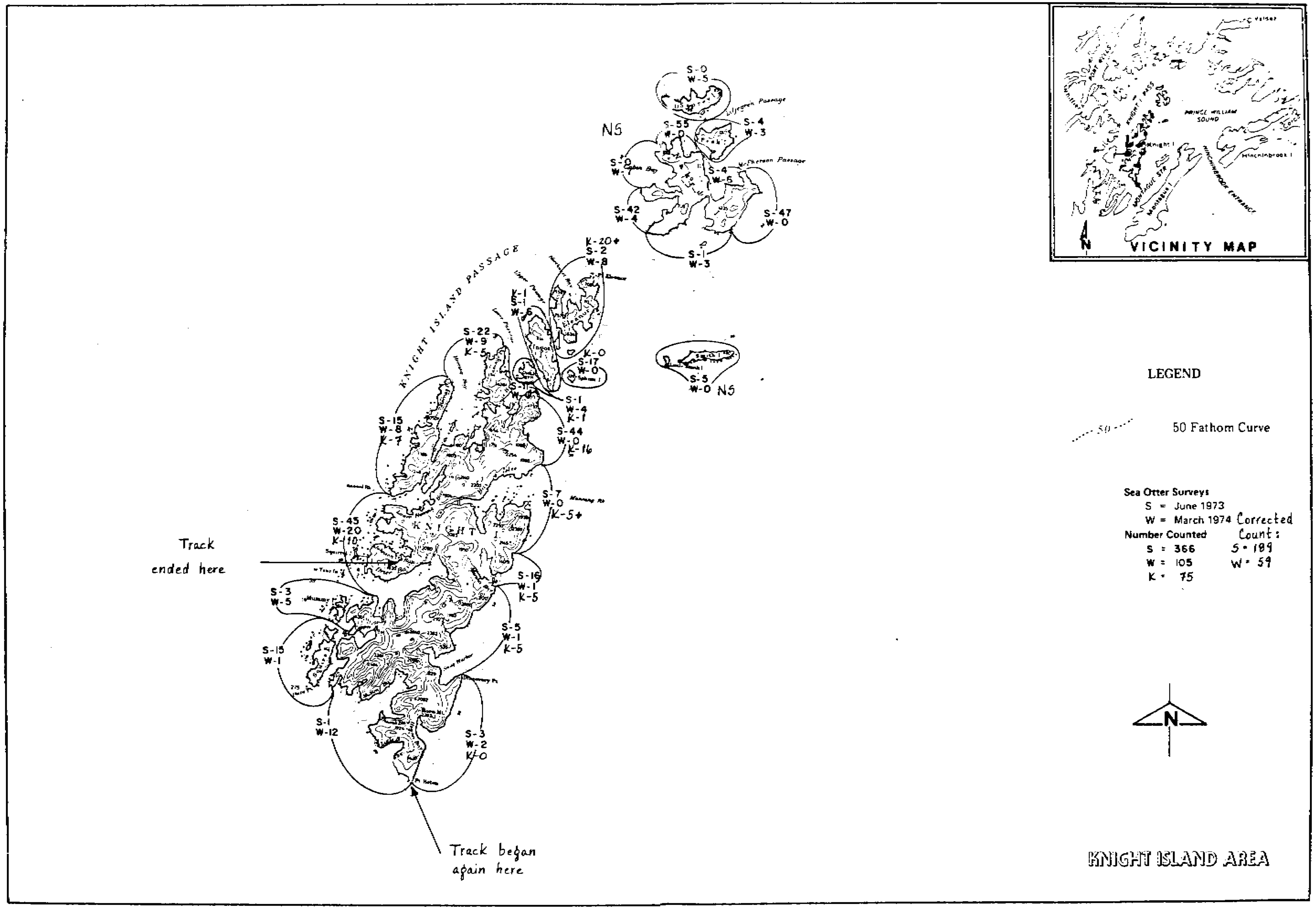

Figure 5. Displays sea otter sightings for Knight Island area. S and W are sighting reported by Calkins, Pitcher & Schneider (1975).

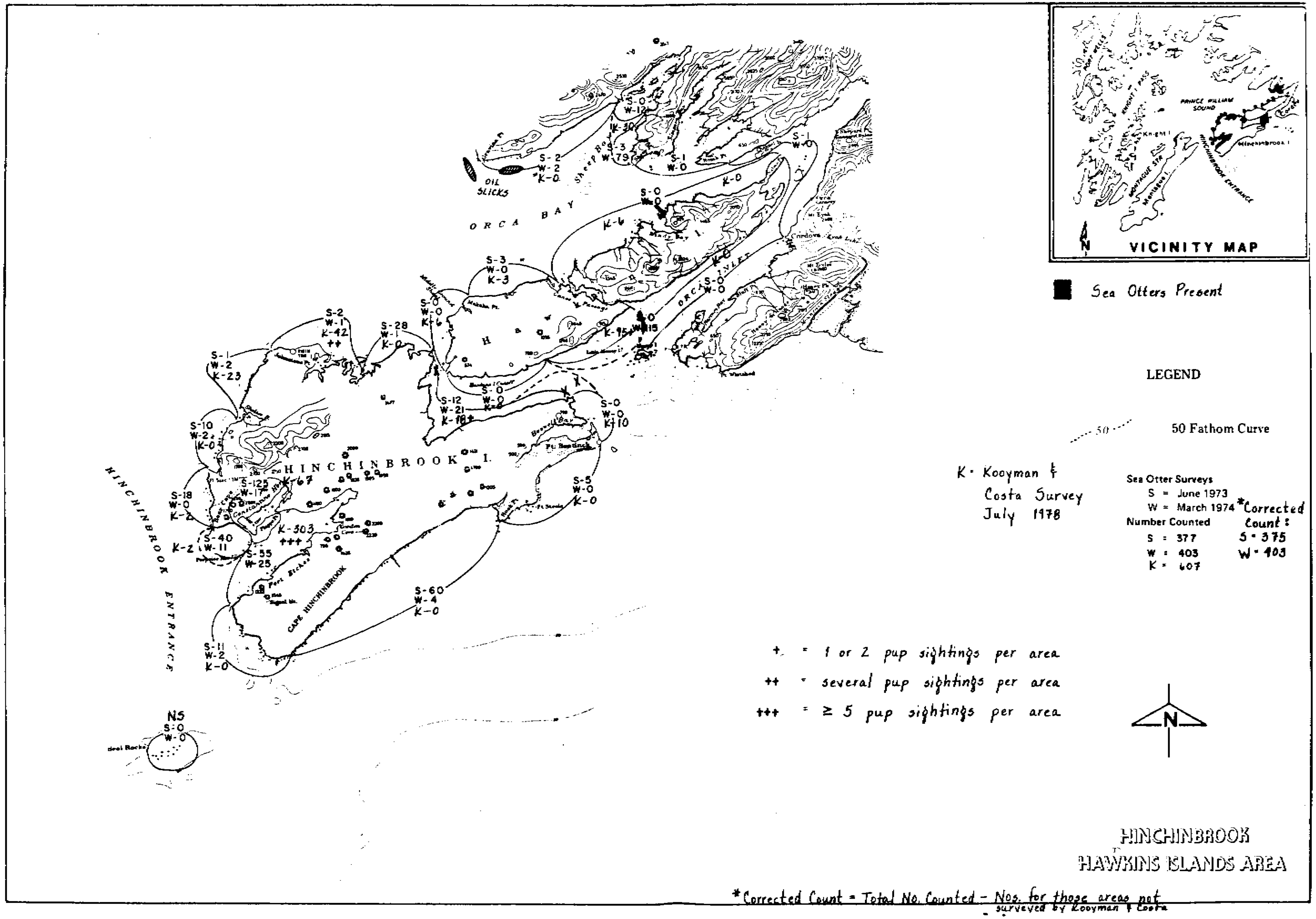

Figure 6. Displays sea otter sightings for Hinchinbrook and Hawkins Islands area. S and W are sightings reported by Calkins, Pitcher and Schneider (1975)

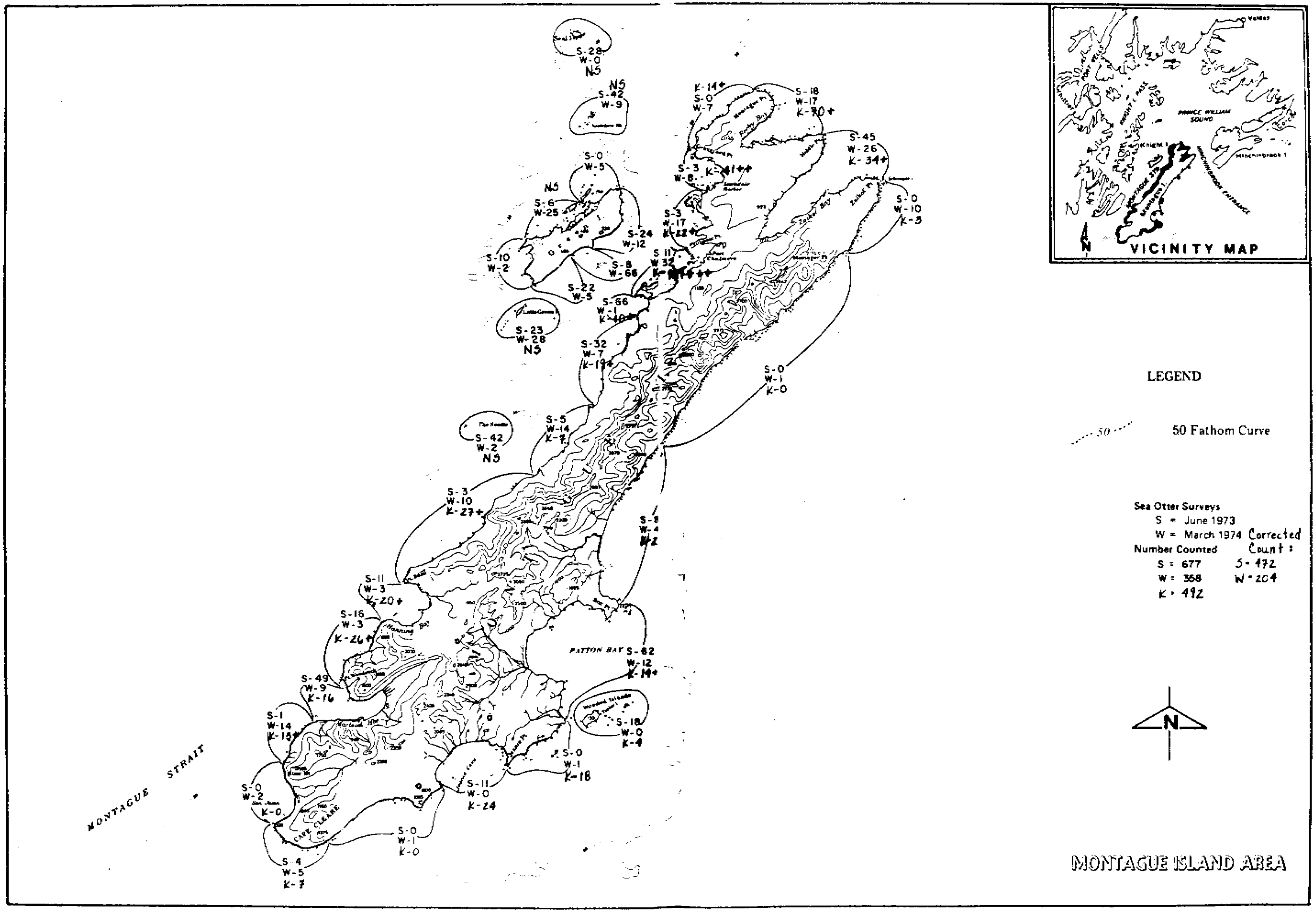

Figure 7. Displays sea otter sightings for Montague Island area. S & W are sightings reported by Calkins, Pitcher & Schneider (1975).

LETHAL AND SUBLETHAL EFFECTS ON SELECTED ALASKAN MARINE SPECIES AFTER ACUTE AND LONG-TERM EXPOSURE TO OIL AND OIL COMPONENTS

by

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Sid Korn

and

John F. Karinen

Research Unit 72

Submitted as the Annual Report, Contract #R7120822
for the period October 1, 1977 to March 30, 1979

OUTER CONTINENTAL SHELF ENERGY ASSESSMENT PROGRAM
Sponsored by
U. S. Department of the Interior
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April 1, 1979

Northwest and Alaska Fisheries Center Auke Bay Laboratory
National Marine Fisheries Service, NOAA
P.O. Box 155, Auke Bay, AK 99821

ANNUAL REPORT

Table of Contents

I. Summary of objectives, conclusions and implications with respect to OCS oil and gas development 3

II. Introduction. 8

- A. General nature and scope of study. 8
- B. Specific objectives. 9
- C. Relevance to problems of petroleum development 10

III. Current State of Knowledge. 10

IV. Progress on FY-78 Studies (October 1, 1977 to September 30, 1978) 11

- A. Accomplishments (Study Title, Objectives, Methods, Status, Results, and Significance) 11

V. Progress on FY-79 Studies (October 1, 1978 to March 30, 1979) 25

- A. Status 25
- B. Milestone Chart. 27
- C. Problems Encountered 28
- D. Estimate of Funds Expended 29

VI. List of Manuscripts, Publications, and Presentations. . . . 30

- A. Publications and Manuscripts 30
- B. Presentations. 34

Summary and Implications of Research

Table 1 summarizes toxicity data from static crude oil bioassays completed in FY 77 and FY 78. Although sensitivity generally increased from lower invertebrates to higher invertebrates, and from higher invertebrates to fish, sensitivity was better correlated to habitat. These data are reported in:

Rice, Stanley D., Adam Moles, Tamra L. Taylor and John F. Karinen. Sensitivity of 39 Alaskan Marine Species to Cook Inlet Crude Oil and No. 2 Fuel Oil, Proceedings 1979 Oil Spill Conference, March 19-22, 1979, Los Angeles, California. Sponsored by EPA, API, and USCG, p.549-554.

Scientific names	Common names	Habitat	°96 h TLm total aromatics
Fish			
1. Clupea pallasi	Pacific herring	pelagic	1.22 (0.88-1.56)
2. Salvelinus malma	Dolly Varden	pelagic	1.55 (1.30-1.80)
3. Oncorhynchus gorbuscha	pink salmon	pelagic	1.69 (1.47-1.83)
4. Theragra chalcogrammus	Walleye pollock	pelagic	1.73 (1.37-2.09)
5. Aulorhynchus flavidus	tubesnouts	pelagic	2.55 (2.06-3.03)
6. Myoxocephalus polyacanthocephalus	great sculpin	benthic	3.96 (3.52-4.40)
7. Platichthys stellatus	starry flounder	benthic	>5.34
8. Pholis laeta	crescent gunnel	intertidal	>11.72
9. Anoplarchus purpurescens	cockscomb prickleback	intertidal	>11.72
Crustaceans			
10. Crangon alaskensis	grass shrimp	subtidal	0.87 (0.83-0.91)
11. Pandalus goniurus	humpy shrimp	subtidal	1.79 (1.53-2.04)
12. Eualus suckleyi	kelp shrimp	subtidal	1.86 (1.66-2.07)
13. Pandalus borealis	pink shrimp	subtidal	4.94 (3.20-5.60)
14. Paralithodes camtschatica	king crab	benthic	3.69 (2.65-4.73)
15. Hemigrapsis nudus	purple shore crab	intertidal	8.45 (8.32-8.58)
16. Pagurus hirsuiticulus	hairy hermit crab	intertidal	>10.58
17. Orchomene pinguis	amphipod	planktonic	>7.98
18. Acanthomysis pseudomacropsis	mysid	planktonic	>9.02
Echinoderms			
19. Cucumaria vega	tarspot	intertidal	>6.84
20. Strongylocentrotus drobachiensis	green sea urchin	intertidal	>10.58
21. Leptasterias hexactis	six-armed starfish	intertidal	>10.58
22. Eupentacta quinquesimita	white cucumber	intertidal	>12.29
Mollusks			
23. Chlamys hericus	pink scallop	benthic	3.94 (3.52-4.39)
24. Mytilus edulis	blue mussel	intertidal	>8.97
25. Protothaca staminea	little neck clam	intertidal	>6.84
26. Collisella scutum	plate limpet	intertidal	8.18 (6.14-10.96)
27. Notoacmaea pelta	shield limpet	intertidal	>8.46
28. Katharina tunicata	leather chiton	intertidal	>8.46
29. Tonicella lineata	lined chiton	intertidal	>8.46
30. Mopalia cilliata	ciliated chiton	intertidal	>8.46
31. Margarites pupillus	purple margarite	intertidal	>8.46
32. Littorina sitkana	Sitka periwinkle	intertidal	>8.46
33. Thais lima	file periwinkle	intertidal	>8.46
34. Colus halli	Hall's colus	benthic	>8.98
35. Neptunea lyrata	ridged whelk	benthic	>10.58
Annelids			
36. Nereis vexillosa	mussel worm	intertidal	>10.58
37. Harmothoe imbricata	scale worm	intertidal	>10.58
Nemerteans			
38. Paranemertes peregrina	purple ribbon worm	intertidal	>10.58
39. Lineus vegetus	brown ribbon worm	intertidal	>10.58

Table 1. Sensitivities of 38 Alaskan marine species to Cook Inlet crude oil—96-h TLm's are in mg/l of total aromatics determined by GC, with 95% confidence intervals in parentheses

Progress on FY '78 studies has been good especially towards determining the contribution of various oil aromatic components to oil toxicity. We have determined that the toxicity of an oil water-soluble fraction is not accounted for by a synthetic mix containing eight principal aromatic components. Oil toxicity is caused by additional components, both aromatic and paraffinic. Interactions of oil components occur in a complex manner to cause synergistic or antagonistic effects. Additional research is needed to reach the objective of being able to predict the toxicity of oil solutions based on analyses of the solution.

Additional progress was made in determining effects of environmental variables on oil toxicity. We have determined that temperature and salinity affect oil toxicity in a complex and nonuniform manner depending on species and oil components tested. There is a marked effect of salinity on oil toxicity to salmon smolts. We tried to determine the causes of increased sensitivity in seawater by studying effects of salinity on respiration rate; uptake and depuration rate of oil aromatics, and blood ionic and osmotic levels. None of the above explained the increased sensivity in seawater. It now appears that the sensitivity increase is related to the ability of the animal to metabolize the aromatic oil component. Several invertebrates were also exposed at different salinities, but we found little difference in TLm's at different salinities.

5

We have demonstrated that reduced temperature increases the sensitivity of salmonids to certain oil aromatics. The effects of temperature on oil toxicity depends on species tested and aromatic oil component. Environmental managers must take temperature into account along with species involved to assess the impact of oil on a locality.

Our tests with egg and larval stages of invertebrates continues to support the conclusion that egg and larval stages are often the most sensitive to oil pollution and the most vulnerable. Tests showed a rapid effect of oil (2 h) with larval stages plus sublethal effects on behavior that would lead to mortality in the field (i.e. loss of ability to swim). We also found that shrimp eggs and gonadal tissue accumulate hydrocarbons rapidly and retain residues for long periods. This may cause effects at hatching.

Tests comparing static and flow-through bioassays showed that animals with high metabolic rates have similar TLm values in both types of tests. They accumulate hydrocarbons rapidly and the greatest mortality occurs within the first 24 h of exposure. In contrast, animals with low metabolic rates and slow uptake are also slow to die. Therefore, static tests are reasonable estimates of acute toxicity for some animals, but are poor estimates for others (e.g. intertidal snails, mussels, etc.).

Implications are that:

(1) Oil effects and responses of organisms to oil are complex, species dependent, and variably modified by environmental factors (temperature, salinity, etc.).

(2) Effects studies are producing a number of observations useful in evaluating the impact of oil in the real environment.

(3) There is a need to test laboratory findings in the field.

(4) Several research findings indicate the need for further effects research, especially with long-term chronic exposures.

(5) Extremely low concentrations of hydrocarbons reduce survival of marine organisms, especially larval stages.

(6) Immediate or delayed death is not necessarily a prerequisite to impact on a life stage; behavioral changes of larvae (nonswimming response) may be just as effective in eliminating the individual (predators) as outright death from oil.

(7) Larvae are susceptible to short-term exposures (2 h).

(8) Much of the research data generated in this program has had immediate application and use by regulatory agencies, e.g. Alaska Governor's Office, legislative committees, and Federal and State Agencies.

There is a need to review the current status of knowledge, take a close look at information gaps, and the direction of future research. In our opinion there is still a great need for effects research information, especially the correlation of effects observed in the laboratory with effects noted in field exposures, and the determination of exposure regimes and tissue burdens in field and laboratory exposures.

8

Introduction

General Nature and Scope of Study

The research is addressed to the general question, "What are the effects of petroleum hydrocarbons on arctic and subarctic biota"? It involves physiological and bioassay tests of applied research on species indigenous to the Gulf of Alaska, Bering Sea, and Beaufort Sea. The major emphasis of research has shifted from strictly descriptive acute toxicity determinations to mechanistic studies, sublethal tests, and long-term exposures that will eventually allow prediction of oil impact on the biota.

Our studies can be broken down into two basic themes. (1) toxicity challenge experiments, where we attempt to identify sensitive species, life stages, factors that affect toxicity, or components that are most responsible for toxicity, and (2) sublethal physiological response, where we attempt to identify, measure, and characterize physiological responses that are indicative of oil stress. Eventually these sublethal studies will provide information useful in identifying exposed animals in the field, an evaluation of how stressed the exposed animals are, and possibly the mode or mechanism of toxic action. We often conduct uptake-depuration studies in parallel to the above tests, to correlate tissue concentrations with effects, which will aid in the interpretation of results.

OCSEAP funding on effects studies at Auke Bay began in the last 2 months of FY '75, continued at significant funding levels through FY '76, '77, '78, and will continue through at least FY '79. This report describes progress associated with OCSEAP funding only, and draws from published or drafted manuscripts and unwritten but completed studies up to April 1979.

General program objectives have remained relatively constant throughout the life of this research unit, although emphasis has changed as information on various aspects of oil impact has accumulated.

Specific Objectives

In FY '78, our program had six themes, with variable emphasis. We began studies looking into which aromatic compounds are most responsible for the toxicity of oil WSF (with a synthetic WSF), and if the major components act synergistically when together. We have continued some larvae studies to determine the sensitivities of several noncrustaceans. We conducted one large experiment to determine why coho smolts are twice as sensitive to oil and aromatics after introduction to seawater, and how long does the sensitive period persist. We attempted to compare the effects of short- and long-term exposures to pink salmon fry with observations on growth and survival. We began experiments measuring sensitivity and uptake-depuration of several intertidal invertebrates that were exposed continuously or with an intermittent air exposure. We began literature search and experimental planning for dispersant tests, but before we began lab tests, we were instructed to reprogram the effort when OCSEAP reassessed its priority on dispersant work.

In FY '79, the program is smaller and centered around only one major theme: What is the sensitivity of arctic animals to oil and aromatics compared to subarctic animals? Which is more important to sensitivity--species or temperature?

Relevance to Problems of Petroleum Development

The FY 79 program on the sensitivity of Arctic animals to oil has a great deal of relevance to problems of petroleum development in Alaska. A significant part of both current and future potential petroleum development in Alaska is taking place and will be taking place in the Arctic. Because low temperature appears to be such an important factor in governing the sensitivity of some subarctic species to oil it is necessary to determine whether this relationship holds for similar Arctic species or Arctic species in general.

Current State of Knowledge

Prior to this research, little was known about sublethal effects on subarctic organisms or the relative toxicity of important oil components, or effects on larvae of noncommercial species. A base of information has now been accumulated on acute toxicity, sublethal effects, relative toxicity of oil aromatics, effects of various environmental factors on these parameters, and effects on larvae; but this is only a small part of the information needed to predict and evaluate the major impacts of hydrocarbons in the marine environment. We now have more knowledge about the effects of temperature and salinity, on the ability of subarctic organisms to metabolize, eliminate or recover from petroleum exposure.

A considerable amount of information has been generated in this effects study and in other effects studies throughout the scientific community.

Progress on FY '78 Studies

(Oct. 1, 1977 to Sept. 30, 1978)

A. Toxic components and synergism of toxic components: This study was initiated to determine the contribution of individual and groups of toxic aromatic components to the toxicity of oil WSF's.

Objective A1. Compare the toxicity of water-soluble fractions (WSF's) of crude oil with synthetically produced WSF's.

Method: Pink salmon fry and *Eualus* shrimp were exposed to several concentrations of Cook Inlet WSF or synthetic solutions containing benzene, toluene, ortho- and para-xylene, naphthalene, methyl naphthalene and dimethyl naphthalene in the same ratio as they occur in the WSF. Tests were flow-through, exposure solutions were analyzed by GC, and 96 h TLm values were calculated.

Status: Data acquisition and analyses are complete. First draft for a scientific publication is in progress now. Results indicate that this is a viable experimental design and more information can be attained with further studies where individual compounds are added and deleted.

Results: The toxicity of the synthetic solutions was less than half the toxicity of the WSF, even though the aromatic components in the synthetic solution comprise over 90 percent (by weight) of the total aromatics in the WSF. These results indicate that there are additional components or possibly classes of components that contribute significantly to oil WSF toxicity.

Significance of Results: With the limited data available, we can say that aromatics contribute significantly to the toxicity of oil WSF's. However, other classes of compounds or small amounts of highly toxic aromatics may also contribute significantly. Additional studies are indicated to determine additional important compounds or classes of compounds that account for the toxicity in the WSF.

Objective A2. Synergistic effects of toluene and naphthalene: Several studies with fish and shrimp larvae strongly suggest that toluene and naphthalene have different mechanisms of toxicity, indicating that the toxicants probably have synergistic effects. If the toxicities are synergistic, this would help explain why simplistic experiments with single compounds have under-estimated the toxicities of WSF's.

Specifically:

a. Determine if toluene and naphthalene have synergistic toxicities to pink salmon fry and Eualus shrimp under flow-through conditions.

Method: Flow-through bioassays were used with toluene, naphthalene and combinations of toluene and naphthalene. Ninety-six hour TLm's were generated.

Status: Tests with Eualus shrimp, pink salmon, Mytilus edulis and Colus jordani were completed. A draft of the manuscript has been delayed because of hiring problems (Office of Personnel Management will not certify C. Misch, the person who collected the data and began a draft before her appointment ran out).

Results: Synergistic action between toluene and naphthalene was indicated in all tests, but the statistical significance is not known at this time.

b. Determine if toluene and naphthalene have synergistic effects on uptake and/or depuration in pink salmon fry and Eualus shrimp;

Method: Pink salmon and Eualus shrimp were exposed to toluene or naphthalene or combination of toluene and naphthalene in continuous-flow exposure. Accumulation was determined by radiometric methods.

Status: Tests and data analyses were completed.

Results: There were no significant differences in accumulation of the aromatics alone or in combination.

Significance of Results: No synergism or antagonism of accumulation was found. Accumulation of aromatics is highly variable and is not a good measurement of subtle changes.

B. Larval Studies

Objective B1. Determine the sensitivity of eggs and larvae from several noncommercial species: barnacles, mussels, snails, starfish, and sea urchins.

Method: Static bioassays were run with the solution changed as needed to maintain stable concentrations of toluene, naphthalene, and Cook Inlet WSF. Death and inability to swim were monitored in the bioassays.

Status: Tests with toluene, naphthalene and Cook Inlet WSF have been completed with the following:

Species	Common Name	Stage
Natica clausa	snail	egg, veliger
Fusitriton oregonensis	snail	egg, veliger
Tochuina tetraquadra	nudibranch	egg
Evasterias troschelii	starfish	egg, larvae(bipinnaria)
	sea urchin	egg, larvae

Other species were tested in FY '78, but the timing was off. Several tests are in progress and/or scheduled for FY '79 to complete the study.

Results: Eggs from the tested species are quite resistant while veligers are more sensitive to the toxicants. Results after 96 min. were similar to 24 h exposures indicating that larvae accumulate toxicants rapidly and are readily affected by brief exposures.

Significance of Results: Generally, larval stages are more sensitive than eggs or adults. Very short-term exposure (less than 2 h to oil may affect larval stages.

Objective B2. Determine the uptake and retention of hydrocarbons into new and old eggs carried by *Eualus* shrimp.

Methods: The uptake of toluene and naphthalene in shrimp gonad, muscle, and hepatopancreas was determined using radiolabeled compounds. This study was repeated on shrimp with newly extruded eggs, and again with shrimp carrying old eggs, just before their release.

Shrimp with new eggs were exposed to Cook Inlet WSF's continuously for 10 days. Samples of eggs and muscle were analyzed by GC-MS by the National Analytical Laboratory, Seattle. The isotope studies determined the rate of uptake for toluene and naphthalene, and the WSF-GC analysis studies determined the concentrations at equilibrium for many compounds.

Status: Studies were completed and manuscript preparation is in progress.

Results: Hepatopancreas accumulated the most followed by gonad or eggs and muscle. Gonad, old or new eggs accumulated similar amounts of hydrocarbon. The aromatics persist in the eggs and gonads for several weeks. GC-MS analyses shows accumulation of mono- and dinuclear aromatics with more accumulation in the gonad than muscle.

Significance of Results: The persistance of aromatics in the eggs and gonads was to be expected due to the high lipid content of these tissues. Effects of aromatic residue on the hatching of the egg are possible and further study is indicated.

C. Sensitivity increase of salmonid smolts in sea water. Through bioassays, we have found that the sensitivity of sea water-adapted pink and sockeye salmon, and Dolly Varden trout, is greater than sensitivity in fresh water in exposures to WSF's, toluene, and naphthalene. First attempts at explaining this phenomenon through uptake and excretion experiments did not completely answer the question.

Objective C1. Determine the uptake of isotopes into tissues of fresh water- and sea water-adapted salmonid smolts. Although whole body uptake was essentially the same, the uptake into different tissues may be different.

Methods: Uptake of oil hydrocarbons between fresh water and sea water smolts was tested in two ways: via water and via oral administration of known quantities. Radiometric methods were used for determination of uptake and depuration in brain, liver, and muscle.

Status: Tests were completed. Manuscript preparation is in progress.

Results: No difference in total uptake was found in liver, brains, and muscle of smolts exposed in fresh- or sea-water. Oral uptake were similar for toluene, but did show some differences for naphthalene. More isotope and a lower percent of naphthalene metabolites was found in the brain and muscle of sea water-adapted animals.

Significance of Results: We are unable to explain the increased sensitivity to aromatics of smolts in sea water vs. fresh water based on differences in uptake. The differences in percent metabolites may be the key. Additional studies looked at other possible mechanisms that could increase sensitivity in sea water and are reported below.

Objective C2. <u>Determine the osmotic and ionic composition of blood in fresh water and sea water-adapted smolts exposed to toluene and naphthalene</u>.

Methods: Continuous-flow bioassays of smolts were conducted in 0, 10, 20, and 30°/oo salinity water with both toluene and naphthalene. Tests were done in 30°/oo at the time of migration (24 h acclimation) and after 12, 22, and 42 days of acclimation. Blood ion and osmotic measurements were taken before and during all assays.

Status: Studies and raw data work-up were completed. Manuscript syntheses has started.

Results: Sensitivity of smolts increased with salinity and remained at the greater level of sensitivity for over 42 days (smolts were fed and grew in sea water, but maintained a relatively high level of sensitivity). Little change was noted in blood ion concentrations at sublethal exposures. Only at the higher concentrations were changes measured.

Significance of Results: Sensitivity persists while in sea water (up to 42 days for coho smolts), and is proportional to salinity. Ion changes in the blood were not observed until animals were severely stressed and in the process of dying.

D. <u>Long-term Exposures</u>: Long-term exposures have recently been possible because of improvements in flow-through exposure techniques. Most previous flow-through tests have been crude attempts, without verification of stable concentrations during exposure. We will conduct long-term exposures and compare the results with species we have previously tested in short-term exposures.

Objective D1. Determine the effects of flow-through toluene and naphthalene exposures on growth and survival of pink salmon fry exposed at different temperatures.

Methods: Tests will be 40 days long, with samples of fish taken at 10-day intervals to measure effects on growth. Tests were to be replicated at three temperatures to determine the influence of temperature on toxicity in long-term exposures.

Status: This study was cancelled after two attempts. The first attempt was terminated after 6 days when the main sea water pump to the lab failed and our sea water low-water alarm also failed, causing a massive fish kill in the experiment and about one-third of the remaining stock of experimental fish. The second attempt was terminated after 8 days when a power outage combined with a failure of our emergency generator caused fish mortalities in the experiment and most of the remaining stock of pink salmon. We then had to cancel the study due to lack of fish. This experiment will be attempted under different funding in FY '79, and with additional "fail safe" modifications.

Objective D2. Determine the survival of two tolerant and two sensitive species to flow-through exposures of toluene and naphthalene.

Methods: Static and continuous-flow bioassays were run on sensitive (pink salmon, shrimp) and resistant (black cucumber, shore crab) animals using toluene and naphthalene.

Status: Tests were completed. The manuscript describing results is ready for laboratory review.

Results: Flow-through tests were more toxic than static tests especially with more resistant animals. *Cucumaria vegae* (black cucumber) could not be killed in the static test but was killed at moderate concentrations in the flow-through test. Sensitive animals showed the least change in TLm between static and flow-through exposure.

Significance of Results: Animals that accumulate hydrocarbons rapidly and have a high metabolic rate (pink salmon) are affected rapidly by exposure to oil. After 24 h the median tolerance TLm levels out and further exposure causes little additional mortality. Ninety-six hr. static tests are reasonable estimates of sensitivity for these animals. Tolerant animals accumulate hydrocarbons slowly and the TLm goes down with increased time of exposure. Static tests with declining concentrations give poor estimates of the long-term sensitivity of these animals to oil. Flow-through testing is needed with tolerant animals.

E. *Test the effect of intermittent air exposures on the sensitivity of intertidal species to toluene, naphthalene, and WSF*. Exposure to air during and after exposure to toxicants may cause an additional stress on intertidal animals and result in decreased survival.

Objective E1. Determine the sensitivity and uptake-depuration by the intertidal shore crab *Hemigrapsus nudis* and other invertebrates to toluene and naphthalene exposures, with and without intermittent exposure to air.

Methods: *Hemigrapsus nudis* crabs and *Thais* sp. snails were exposed to oil aromatics in water and in two different simulated tidal cycles of air twice per day. Standard 96 h TLm were calculated.

Status: Tests were completed for *Hemigrapsus* and *Thais*.

Results: Animals were more tolerant with more air exposure, presumably because less aromatics were taken up.

Significance of Results: Animals in the upper intertidal zone are more tolerant to chemical toxicity (via WSF) than the same species at lower levels. However, the recovery potential of equally exposed animals is not known at this time.

Objective E2. Determine the uptake, and especially the depuration pattern, of intertidal animals exposed to labeled toluene and naphthalene, with and without exposure to air.

Methods: Intertidal animals will be exposed to radio-labeled toluene and naphthalene either continuously or during two different tidal cycles that interrupt exposure.

Status: Ran out of experimental animals and is rescheduled for FY '79 under different funding.

F. Dispersant testing: Literature review and R&D on methods of analysis and exposure will be probed to prepare for expanded testing in FY '79. Emphasis on this project was reduced considerably from original plans, when OCSEAP decided part way through the contract year not to fund dispersant studies in FY '78.

Status: Literature has been accumulated. Stocks of several dispersants have been obtained. The project was then terminated and the effort was reprogrammed into existing studies.

G. Additional Experiments: Some effort was salvaged from the long-term pink salmon exposure that failed and the dispersant tests that were cancelled by OCSEAP. This effort was reprogrammed into the existing studies or into the following two studies which were taken on because animals, labor expertise, etc. were available, and they were compatible with the OCSEAP theme--temperature and salinity.

G1. Effects of temperature on toxicity and uptake-depuration of aromatic hydrocarbons to animals with varying potential to metabolize aromatic hydrocarbons.

Methods: Continous-flow bioassays and uptake studies were run at two temperatures on animals with differing abilities to metabolize aromatic components. Pink salmon juveniles, snails, and shrimp were tested with toluene and naphthalene. Dolly Varden trout were given oral exposures and metabolites were analyzed in several tissues.

Status: Pink salmon, shrimp, snail bioassays were completed last spring. Pink salmon juveniles, shrimp, and snail temperature uptake studies were completed. Oral exposures to Dolly Varden trout were completed, and data has been entered into a computer and analyses of data is continuing. Two manuscripts are in progress.

Results: Pink salmon are more sensitive to low temperatures and shrimp are more sensitive at higher temperatures. Uptake-depuration by fish was not significantly affected by exposure at different temperatures. In contrast, snails accumulate and depurate aromatics faster at higher temperatures. Shrimp tests are in progress. Higher percents of naphthalene metabolites were found in brain and muscle of Dolly Varden exposed orally at 12°C vs 4°C.

Significance of Results: Animals that accumulate and depurate aromatics without metabolizing the aromatics show increased accumulation and depuration at higher temperatures (snails). Animals that metabolize aromatics have processes affected differently by temperature and do not show a clear temperature effect on uptake-depuration. However, the sensitivity varies with temperature and the particular compound tested. The effects of temperature on sensitivity and metabolism of toxicants are not well understood at this time, and further work would be desirable.

G2. Effects of varying salinity on the sensitivity of intertidal invertebrates.

This project parallels the salinity-fish smolt experiments but on a smaller scale.

Methods: Invertebrates were exposed to flow-through toluene and naphthalene exposures at different salinities and after acclimation. Blood ion levels were also monitored.

Results: Sensitivities of *Hemigrapsus*, snails, and sea cucumbers were not affected significantly at 15-30°/oo salinities if the animals were acclimated. Blood ion levels were different for the groups at different salinities, but did not differ significantly between control and dosed animals of one salinity.

Significance of Results: Salinity does not appear to affect the sensitivities of acclimated invertebrates, if salinities are within the normal range that the species tolerate.

Progress on FY '79 Studies

Objective: Determine the sensitivity of arctic species to oil and aromatic hydrocarbons.

Emphasis in earlier years has been with Alaskan species collected in the subarctic. The goal of this project is to determine the sensitivities of arctic species and determine if differences between the subarctic forms are primarily species related or temperature related.

Status: Arrangements and planning for this spring and summer collection of arctic animals have been completed. Animals will be collected with the help of LGL Company and Ken Dunton (both are OCS P.I. working under the Arctic Project Office). The collection trips will be in early May and August using OCSEAP gear and equipment when available. Coordination of efforts is through Dave Norton at the Arctic Project Office. Collection during May will be under the ice at Prudhoe Bay using baited traps and nets. Later collection will be at Simpson Lagoon using fyke nets.

We will be ready to test animals after shipment to Auke Bay in early May. The first series of tests will be completed in June. With the use of experienced field collectors (LGL and Ken Dunton) we have every expectation of collecting a good selection of important arctic fishes and invertebrates for testing.

We have hired one additional chemist and one fishery biologist to assist in the arctic studies. Our temperature control systems have been improved for the holding and testing of arctic animals. We now have six, 500-1000 l tanks with temperature control to maintain arctic animals at 4°C.

Continuous-flow dosing apparatus is set up with temperature control. Current plans call for diverting personnel from other projects to complete arctic tests when the animals are available. In this manner we will minimize the holding time of arctic animals in the laboratory prior to exposure tests.

Milestone Chart

	1st. quarter	2nd. quarter	3rd. quarter	4th. quarter
I. FY 78 Research Goals		Manuscript Synthesis		
II. FY 79 Research Goals				
A. Planning, logistics, animal collection	contact NARL, Dave Norton, LGL, and Ken Dunton plan logistics completed	Assemble collection gear modify wet lab for max. chilling completed	Collect animals scheduled and arranged	Collect animals scheduled and arranged
B. Acute Toxicity			Begin Tests	Tests
1. Determine the toxicity of oil components on arctic animals.				
2. Determine effects of toxicity of oil and oil components to arctic animals.				Tests
C. Long-term Oil Exposures				Start Tests
1. Determine survival to long-term oil exposures				
D. Uptake and Depuration Studies			Begin Tests	
1. Determine accumulation and depuration in arctic animals.				
2. Determine effects of temperature on uptake.				Tests

Problems encountered:

Two major problems this year have been:

(1) The uncertainty and delay in transferring operational funds to the project.

(2) The usual problems and delays associated with hiring temporary personnel.

Fortunately our schedule was such that delays of funding during the first two quarters had minimal effect on actual operations.

Hiring problems, however, have been considerable and have had a definite detrimental impact on manuscript synthesis. Excessive time was required to follow-up and re-initiate personnel requests when communications broke down following reorganization within the Civil Service System. Most personnel problems have now been solved, however, a recent resignation of one of our chemists will require further modification in our working group.

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Presentation and Workshops

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Effects Workshop, OCSEAP, November 15-17, 1978 San Diego, California, Dr. Stan Rice attended.

Exxon Class on Dispersants, August 2-3, 1978, Anchorage, Alaska. Dr. Stan Rice attended.

SUBLETHAL EFFECTS OF PETROLEUM HYDROCARBONS AND TRACE METALS, INCLUDING BIOTRANSFORMATIONS, AS REFLECTED BY MORPHOLOGICAL, CHEMICAL, PHYSIOLOGICAL, PATHOLOGICAL, AND BEHAVIORAL INDICES

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TABLE OF CONTENTS

Page

LIST OF FIGURES iii
LIST OF TABLES v
I. SUMMARY OF OBJECTIVES, CONCLUSIONS, AND IMPLICATIONS WITH RESPECT TO OCS OIL AND GAS DEVELOPMENT 1
    A. Summary of Objectives 1
    B. Summary of Conclusions 1
    C. Implications with Respect to OCS Oil and Gas Development 3
II. INTRODUCTION 4
    A. General Nature and Scope of Study 4
    B. Specific Objectives 5
    C. Relevance to Problems of Petroleum Development 6
III. CURRENT STATE OF KNOWLEDGE 6
    Behavior 6
    Chemistry 7
    Morphology 10
    Pathology 11
    Physiology 11
IV. STUDY AREA 12
V. SOURCES, METHODS AND RATIONALE OF THE DATA COLLECTION 12
    Behavior 12
        Vertebrate 12
        Invertebrate 14
    Chemistry 17
    Morphology 20
    Pathology 20
        Pathological changes in flatfish from exposure to oil-contaminated sediment 20
        Effects of petroleum on fish disease resistance 21
    Physiology 23
VI. RESULTS 25
    Behavior 25
        Vertebrate 25
        Invertebrate 30
    Chemistry 42
    Morphology 54
    Pathology 57
        Pathological changes in flatfish from exposure to oil-contaminated sediment 57
        Effects of petroleum on fish disease resistance 61
    Physiology 62
VII. DISCUSSION 62
    Behavior 62
        Vertebrate 62
        Invertebrate 64
    Chemistry 66
    Morphology 69
    Pathology 70
        Pathological changes in flatfish from exposure to oil-contaminated sediment 70
        Effects of petroleum on fish disease resistance 71
    Physiology 71

Page

VIII. CONCLUSIONS---------- 72
Behavior---------- 72
Vertebrate---------- 72
Invertebrate---------- 72
Chemistry---------- 72
Morphology---------- 73
Pathology---------- 73
Pathological changes in flatfish from exposure to oil-contaminated sediment---------- 73
Effects of petroleum on fish disease resistance---------- 74
Physiology---------- 74
IX. NEEDS FOR FURTHER STUDY---------- 74
General Comments---------- 74
Behavior---------- 74
Chemistry---------- 75
Morphology---------- 75
Pathology---------- 75
Physiology---------- 76
X. SUMMARY OF FOURTH QUARTER OPERATIONS---------- 77
Ship or Laboratory Activities---------- 77
Ship or field trip schedule---------- 77
Scientific party---------- 77
Methods---------- 78
Sample localities/ship or tracklines---------- 78
Data collected or analyzed---------- 79
XI. AUXILIARY MATERIAL---------- 80
A. References Used (Bibliography)---------- 80
B. Papers in preparation or in print---------- 85
C. Oral Presentations---------- 87

APPENDIX---------- 89

LIST OF FIGURES

Page

1. Surface of resting S. drobachiensis, showing large globiferous pedicellariae lying horizontally. 8

2. Surface of S. drobachiensis following stimulation with exudate of P. helianthoides, showing activated globiferous pedicellariae. 9

3. Choice apparatus used in testing avoidance of juvenile English sole to crude-oil-contaminated sediment. 13

4. System used for generating aromatic hydrocarbon solutions used in sea urchin behavior experiments. [Modified from Benville et al. 1978] 15

5. Concentrations of naphthalene and its metabolites in tissues of starry flounder, at 24, 48, and 168 hr after the feeding of 56 μCi of 1-^{3}H-naphthalene. Values are expressed as mean ± S.E. (for number of fish tested at each time period, see Table 12). Values of dry weight of tissues are given below as percent of the wet weight of tissue: stomach (22%), blood (14%), liver (25%), skin (33%), brain (18%), muscle (21%), gills (17%), kidney (18%), bile (12%), intestine (22%), and epidermal mucus (2.8%). Rates of decline in concentrations of naphthalene (N) and total metabolites (M) were calculated using the equation $y=ax^{-b}$. Values for regression coefficient b were for liver b(N)=1.845, b(M)=0.404; for blood b(N)=1.671, b(M)=0.837; and for skin b(N)=1.499, b(M)=0.616. 19

6. Apparatus for weathering of crude oil and subsequent exposure of chum salmon eggs to weathered oil. 24

7. Percent juvenile English sole present on oil-contaminated sediment plotted against the oil concentration (TEPH) and hours in the test apparatus (solid circles). Control data (open circles) represents the % flatfish found on uncontaminated sediment opposite the side of introduction. 29

8. Concentration of the SWSF of PBCO and its effect on the pedicellarial response of the sea urchin. Exposure times: ●=24 hr; ■ = 48 hr; ▲=5-15 min. The 5-15 min exposures are not included in calculation of regression line. Regression equation is: Response Index=132-53 log (ppb SWSF). 31

9. Concentration of toluene and its effect on the pedicellarial response of the sea urchin. Exposure times: ●=24 hr; ■ =1 hr; ▲=5-15 min. The 5-15 min exposures are not included in calculation of the regression line. Regression equation is: Response Index=136-39 log (ppb toluene). 32

10. Concentration of o-xylene and its effect on the pedicellarial response of the sea urchin. Exposure times: ●=24 hr; ▲=5-15 min. The 5-15 min exposures are not included in calculation of regression line. Regression equation is: Response Index=120-28 log (ppb o-xylene). 33

Page

11. Concentration of 1,2,4-trimethylbenzene and its effect on the pedicellarial response of the sea urchin. Exposure times: ●=24 hr; ▲=5-15 min. The 5-15 min exposures are not included in calculation of regression line. Regression equation is: Response Index=294-113 log (ppb trimethylbenzene). 34

12. Concentration of ethyl benzene and its effect on the pedicellarial response of the sea urchin. Exposure times: ●=24 hr; ▲=5-15 min. The 5-15 min exposures are not included in calculation of regression line. Regression equation is: Response Index=355-124 log (ppb ethyl benzene). 35

13. Concentration of 1-methylnaphthalene and its effect on the pedicellarial response of the sea urchin. Exposure times: ●=24 hr; ■=1 hr. Regression equation is: Response Index=124-48 log (ppb naphthalene). 36

14. Concentrations of naphthalene and its metabolites in tissues of rock sole at 24, 48, 168, and 1008 hr after the feeding of 56 μCi of 1-^{3}H-naphthalene. Other pertinent details are given in Figure 5 and Table 12. Regression coefficient for rates of decline of N and M was for liver, b(N)=1.999, b(M)=0.530; for skin, b(N)=0.771, b(M)=0.558; and for blood, b(N)=0.812, b(M)=0.601. 47

15. Concentrations of naphthalene and its metabolites in tissues of starry flounder at 24 and 168 hr after the intraperitoneal injections of 56 μCi of 1-^{3}H-naphthalene. Other pertinent details are given in Figure 5 and Table 12. 48

16. Profiles of metabolites in liver, skin, and bile of a rock sole. 50

17. Profiles of metabolites in starry flounder exposed to dietary naphthalene at 4°C. 56

18. Concentrations of TEPH in PBCO-contaminated sediments from Experiment 1 (silty sediment) and Experiment 3 (sandy sediment). 58

19. Concentrations of major aromatic hydrocarbons in PBCO-contaminated sandy sediments and associated interstitial water from Experiment 3 24 hr after mixing sediment with oil. 59

20. Concentrations of major aromatic hydrocarbons in PBCO-contaminated high-silt sediment and in the English sole and rock sole associated with the sediment at 14 and 29 days. Tissue levels are an average of 10 g muscle samples from 2 fish (Experiment 1). 60

21. Growth of chum salmon control embryos (open circles) and embryos exposed continuously to weathered PBCO (closed circles). Percent survival for control and oil-exposed embryos is shown at top. 63

Page

22. Expected response of sea urchin pedicellaria as determined from addition of response of individual hydrocarbons present in the SWSF (closed circles), and actual response using a model SWSF mixture (open circles). Regression line represents the response index calculated from tests using the total SWSF (same regression as shown in Fig. 8). 65

LIST OF TABLES

1. Conditions of experiments concerned with pathological changes in flatfish from exposure to oil-contaminated sediment. 22

2. Control data. Percent juvenile English sole found in each side of the testing apparatus when no oil was present in the sediment. 25

3. Percent juvenile English sole on each side of the test apparatus when oil-contaminated sediment was present on one side (an initial concentration of 2.5% v/v). Hydrocarbon analysis of sediment by gravimetric method; above-sediment water analysis by GC. 26

4. Percent juvenile English sole on each side the test apparatus when oil-contaminated sediment was present on one side (an initial concentration of 5% v/v). Hydrocarbon analysis of sediment by gravimetric method; above-sediment water analysis by GC. 28

5. Hydrocarbon exposure conditions and sea urchin pedicellarial defensive response. 37

6. Response of sea urchin pedicellariae to starfish extract immediately after exposure to hydrocarbons and again after depuration in clean seawater. 39

7. Effect of starfish exudate stimulus strength on pedicellarial response following exposure of sea urchins to hydrocarbons (benzene and o-xylene). 40

8. Pedicellarial response of hydrocarbon-exposed sea urchins before and after KCl injection. 41

9. Rate of movement of control and toluene-exposed sea urchins in a trough with flowing seawater. 42

10. Percent extension of aboral and lateral podia of sea urchins following exposure to hydrocarbons. 43

11. Hydrocarbon exposure conditions and the number (in percent) of sea urchins eaten by <u>Pycnopodia</u> in predator-prey experiments. 43

Page

12. Total radioactivity (expressed as % administered dose) and distribution of naphthalene and its metabolites in pleuronectids exposed to ^{3}H-naphthalene. 45

13. Naphthalene and its metabolites in naphthalene-exposed starry flounder at 4°C. 46

14. Metabolites in rock sole exposed to dietary naphthalene at 12°C. 51

15. Metabolites in starry flounder exposed to dietary naphthalene at 12°C. 52

16. Metabolites in starry flounder exposed to ^{3}H-naphthalene via intraperitoneal injection at 12°C. 53

17. Comparison of metabolite concentrations in naphthalene-exposed starry flounder at 4° and 12°C. 55

18. LD_{50} values for oil-exposed and control starry flounder and rock sole challenged with virulent *Vibrio anguillarum*. 62

I. SUMMARY OF OBJECTIVES, CONCLUSIONS, AND IMPLICATIONS WITH RESPECT TO OCS OIL AND GAS DEVELOPMENT

A. SUMMARY OF OBJECTIVES

The overall objective of this program was to assess potential effects of petroleum and petroleum-related operations on marine organisms indigenous to Alaskan waters. Several principal objectives were addressed by this research unit (OCSEAP RU 73) during the contract period. These were:

(1) To evaluate the effect of petroleum on sensory systems and behavior of marine species by (a) determining if petroleum in sediment causes flatfish to avoid the contaminated area or interferes with normal feeding and activity patterns, and (b) evaluating the effect of crude oil exposure on defensive behavior of a sea urchin.

(2) To investigate the metabolism and disposition of petroleum hydrocarbons in demersal fish.

(3) To develop and refine ultrastructural criteria for assessing cellular damage in marine organisms resulting from exposure to petroleum.

(4) (a) To detect and characterize pathological changes resulting from the exposure of flatfish to sediments contaminated with crude oil, and (b) to detect effects of petroleum exposure on flatfish disease resistance.

(5) To determine if petroleum-exposed eggs and larvae of salmon and flatfish develop abnormally, and to evaluate the effect of any detected abnormalities on survival.

B. SUMMARY OF CONCLUSIONS

The conclusions of this program are summarized according to disciplinary areas of study. Several aspects of the studies have been completed while others are continuing.

Behavior

Juvenile English sole (Parophrys vetulus) did not avoid sediment contaminated with Prudhoe Bay crude oil (PBCO) at concentrations averaging 8,500 ppm. At these concentrations some mortality did occur, but the majority of flatfish were active and fed readily. Juvenile Dungeness crabs (Cancer magister) also did not avoid the surface of oil-contaminated sediment, but--in contrast to flatfish--did not bury in oil-contaminated sediment unless alarmed.

Low ppb concentrations of the saltwater-soluble fraction (SWSF) of PBCO inhibited the pedicellarial defensive behavior of the sea urchin (Strongylocentrotus drobachiensis). This inhibition is apparently a chemosensory-specific reaction which appears to be a common sublethal effect of petroleum hydrocarbons on a wide variety of lower marine organisms (i.e., bacteria, arthropods, molluscs). A consequence of SWSF exposure of sea urchins was increased predation by the starfish Pycnopodia.

Chemistry

Starry flounder (Platichthys stellatus) and rock sole (Lepidopsetta bilineata) readily accumulated and extensively metabolized dietary naphthalene. The extent of biotransformation of naphthalene and the types of metabolites remaining in tissue (liver) of these flatfish were shown to be greatly influenced by both the mode of exposure and the time which elapsed after the exposure was initiated. The experiments with cold-maintained starry flounder demonstrated that lowering of the environmental temperature resulted in increases in both concentrations and resident times of naphthalene and its metabolites in tissues of fish exposed to dietary naphthalene; however, the increase in concentration was much greater for naphthalene than for the metabolites, indicating that bioconversion of naphthalene was considerably less at the lower temperature. Lowering of the temperature also influenced the relative concentrations of metabolite classes accumulated in tissues of fish.

Thus, the vital importance of including determinations of tissue concentrations and types of metabolites together with the concentration of a parent hydrocarbon, while considering overall toxicity of petroleum to marine fish, was again demonstrated.

Morphology

Morphological aspects, particularly at the ultrastructural level, of the process of cataract formation in rainbow trout (Salmo gairdneri) have been elucidated. It is anticipated that this information will be useful in evaluating potential eye defects in salmonid fishes induced by petroleum exposure. The sequence of changes includes an initial hydration of the cortical fiber cells and subsequent disruption of the fiber cell membranes and internal structures. These changes closely parallel cataract formation in mammals treated with naphthalene or with other cataract-inducing agents.

The normal membrane structures of starry flounder and pink salmon (Oncorhynchus gorbuscha) eggs have been characterized. There are marked differences between these two species in membrane thickness and structure. Contrasting environmental conditions during embryogenesis may correspond to the thin membrane and simple lamellar structure of the starry flounder egg, which is pelagic, and the thick membrane and complex lamellar structure of the pink salmon egg, which is demersal.

Ultrastructural changes in livers from oil-exposed English sole were further characterized. There are indications that they may be reversible (See Pathology section).

Pathology

Pathological Changes in Flatfish from Exposure to Oil-Contaminated Sediment

Experiments have been conducted during the past two years in which three species of adult flatfish, English sole, rock sole, and starry flounder, were exposed to PBCO-contaminated sediments for periods of 2 weeks to 4 months. Initial concentrations of PBCO mixed with sediment ranged from 0.2 to 1.0% (v/v), and two basic types of sediment (sandy and silty) were employed. Release of petroleum hydrocarbons was more than 10-fold greater from the sandy type sediment than from the silty type. Also, the three flatfish species differed substantially in the amount of petroleum-derived aromatic hydrocarbon taken up into tissues. PBCO-related pathological effects were not observed in rock sole or starry flounder exposed to contaminated sediments for one and two months, respectively. Oil-exposed English sole were routinely observed to have extensive hepatocellular lipid accumulation, reduced hemoglobin concentrations, and lower hematocrits during the first month of exposure. These conditions appeared to be reversible.

Effects of Petroleum on Fish Disease Resistance

Sub-adult starry flounder and rock sole exposed to sediments containing up to 2,500 ppm PBCO for periods up to 6 weeks showed no demonstrable changes in susceptibility to a laboratory challenge with the pathogenic bacterium, Vibrio anguillarum.

Physiology

Chum salmon (Oncorhynchus keta) eggs have been exposed to slightly weathered PBCO from 1 day after fertilization through the "eyed" stage at 60 days, and the exposure is continuing. So far there is no detectable effect on embryo survival or on development.

C. IMPLICATIONS WITH RESPECT TO OCS OIL AND GAS DEVELOPMENT

Research findings from this program have clear implications with respect to petroleum effects on aquatic species and consequently to OCS oil and gas development. Most of the studies were designed as laboratory experiments with emphasis on oil exposures of aquatic organisms in flowing-seawater tanks. Controlled studies with experimental designs of the type reported here are indispensible parts of a total program directed at understanding effects of petroleum on the marine environment. The degree to which laboratory results can be directly applied to natural events remains a considerable problem, however. In the absence of a capability for testing target species directly under natural conditions, models, such as those used in present studies, and representative test situations, must be applied.

Implications of studies conducted this contract period with respect to OCS activities are presented below according to disciplinary areas of study.

Behavior

The results of the two behavioral studies reflect markedly different oil concentration-effect relationships. Petroleum hydrocarbons in the water at extremely low levels had an immediate and demonstrable effect on invertebrate chemosensory responses, the disruption of which limits behavioral defensive reactions against predators. In contrast, high levels of oil incorporated in the sediment were apparently accepted by juvenile flatfish without noticeable immediate effects; although there is little direct evidence, it is a reasonable assumption that long-term residence by the fish in a heavily oil-contaminated environment is not compatible with survival.

Chemistry

Extensive metabolism of fed and injected petroleum hydrocarbons occurred in flatfish (pleuronectids) suggesting that large concentrations of potentially mutagenic and procarcinogenic compounds (dihydrodiols and phenols) may accumulate in tissues (liver, muscle). Added to this information is the finding that at low temperatures petroleum hydrocarbons and their metabolites were retained in tissues for long periods. These findings suggest that these demersal fish, especially in colder regions, may accumulate particularly heavy body burdens of potentially damaging xenobiotics from petroleum exposure.

Morphology

There is strong evidence that certain petroleum components (e.g., naphthalene or its metabolites) can induce cataracts in mammals. There is also evidence that petroleum can cause eye damage in fish, although it is not yet clear that eye damage is a serious problem in fish encountering petroleum in the marine environment.

In the present studies, the morphological changes occurring in rainbow trout lenses associated with the process of cataract development have been defined to the ultrastructural level. It is anticipated that this information--particularly that relating to very early deleterious changes--will be useful in determining if potentially serious disruptions of the structure of fish eyes have occurred after petroleum exposures.

Similarly, the normal morphology of membranes of eggs from two fish species representative of important larger groups has been defined and will provide future reference points for detecting abnormalities induced in fish egg membranes by petroleum.

Pathology

Pathological Changes in Flatfish From Exposure to Oil-Contaminated Sediment

Sediment-associated PBCO exposures resulted in few serious pathological effects in sub-adult and adult flatfish of three arctic and subarctic species. Whether or not such oil-exposed fish at various developmental stages can successfully compete for food, reproduce, escape predators, and perform a number of other vital functions and activities is, of course, still not known.

Effects of Petroleum on Fish Disease Resistance

There was no detected effect on bacterial disease susceptibility of sub-adult starry flounder and rock sole exposed to PBCO-contaminated sediments. It is still possible, however, that under conditions of stress induced by multiple contaminants including PBCO, stress from starvation plus PBCO, or in potentially less disease resistance younger life stages, that susceptibility to vibriosis infections may be heightened by PBCO exposure.

Physiology

Although the studies on chum salmon egg and alevin development in the presence or absence of petroleum have been in progress for more than two months and no deleterious effects have been detected, it is still too soon to draw definitive conclusions. Because of the known susceptibility of early developmental stages of various species to contaminants, the importance of the results of these studies to OCS oil and gas development is abundantly clear.

II. INTRODUCTION

A. GENERAL NATURE AND SCOPE OF STUDY

The responses of marine organisms to environmental contaminants are reflected in a number of changes detectable at population and organismal levels, as well as at cellular, subcellular, and molecular levels. The general scope of this study is to evaluate effects at various levels by investigating morphological, chemical, physiological, pathological, and behavioral changes in subarctic and arctic marine animals exposed to petroleum.

B. SPECIFIC OBJECTIVES

In the interdisciplinary approach used in this study, there is a series of objectives to evaluate the effects of petroleum on marine organisms. The specific objectives of research performed during the current reporting period of April 1, 1978 to March 31, 1979 are as follows:

Behavior

Vertebrate

To determine if English sole avoid PBCO-contaminated sediment.

Invertebrate

To evaluate the effect of the SWSF of PBCO and its components on the chemosensory-mediated defensive behavior of the sea urchin Stronglyocentrotus drobachiensis.

Chemistry

To investigate the metabolism and disposition of petroleum hydrocarbons in demersal fish. Particular objectives were to assess influence of several exogeneous factors (e.g., temperature and mode of exposure, time) on tissue concentrations of naphthalene and its metabolic products, and on the profiles of metabolites accumulated in the hydrocarbon-exposed pleuronectids.

Morphology

(1) To describe the process of cataract formation in rainbow trout with reference to petroleum exposure.

(2) To examine and compare the structures of starry flounder and pink salmon egg membranes.

(3) To perform electron microscopic analyses as part of laboratory experiments in pathology and physiology.

Pathology

(1) To determine the frequency and nature of pathological changes occurring in flatfish as a result of exposure to oil-contaminated sediments.

(2) To assess the effects of petroleum hydrocarbons on disease resistance in flatfish.

Physiology

To evaluate the effect of weathered PBCO on chum salmon egg and alevin development.

C. RELEVANCE TO PROBLEMS OF PETROLEUM DEVELOPMENT

When petroleum is transported in or obtained from coastal or offshore areas, inevitably petroleum hydrocarbons and associated trace metals escape into the marine environment. These materials, at some levels, have a potential for producing critical damage to marine resources. This damage by crude oil components can take several forms (Blumer, M., Testimony before Subcommittee on Air and Water Pollution, Senate Comm. on Public Works, Machias, Maine, 8 Sept. 1970):

1. Direct kill of organisms through coating and asphyxiation.
2. Direct kill through contact poisoning of organisms.
3. Direct kill through exposure to water-soluble toxic components of oil at some distance in space and time from the accident.
4. Destruction of the generally more sensitive juvenile forms of organisms.
5. Incorporation of sublethal amounts of oil and oil products into organisms resulting in reduced resistance to infection and other stresses. Also, this may result in failure to reproduce.
6. Destruction of the food sources of higher species.
7. Exposure to long-term poisons, e.g., carcinogens.
8. Low-level effects that may interrupt any of the numerous events necessary for the feeding, migration, and propagation of marine species and for the survival of those species which stand higher in the marine food web.
9. Contamination of marine food resources to make them unfit for human consumption.

Studies of OCSEAP RU 73 are largely concerned with indirect, long-term effects of petroleum such as those detailed in items 4, 5, 7, and 8. These effects are much more difficult to detect and evaluate than those related to acute exposures, but may over a period of time have even greater impact on marine biota.

III. CURRENT STATE OF KNOWLEDGE

BEHAVIOR

Vertebrate

Avoidance of Oil-Contaminated Sediment

It is now well established that marine fishes are able to take up petroleum hydrocarbons from water and sediment and bioconcentrate the hydrocarbons in their tissues (Roubal et al. 1978, Varanasi et al. 1978, McCain et al. 1978). In addition, McCain et al. (1978) reported that flatfish held on oil-contaminated sediment exhibited differences in growth, liver characteristics, and hematological parameters. Unfortunately, the above studies and most others involving the lethal and sublethal effects of petroleum hydrocarbons on fishes have been conducted under conditions where the fishes have been forced to accept the exposure insult. Under certain exposure conditions, such as an oil spill covering an extensive area, this may be true, i.e., fish have few or no cues for differentiating uncontaminated from contaminated areas. In other instances they may encounter a definite gradient of petroleum concentration and may avoid areas of heavy contamination if they so choose.

It is generally accepted, albeit without extensive supporting experimental evidence, that, given the opportunity, mobile marine fishes will avoid areas of petroleum contamination. There are, however, recent field observations which indirectly suggest that this may not be true. Cross et al. (1978) reported dead fish and crustacea following the Amoco Cadiz incident, and MacLeod et al. (1978) cited the presence of Bunker C oil in the stomach of codfish taken near the site of the Argo Merchant spill. In laboratory studies detection and avoidance by fish of water-borne petroleum hydrocarbons have been noted (see review by Patten 1977), but no reports have been found concerning the behavior of bottom-dwelling fish in the presence of oil-polluted sediment.

Invertebrate

Chemoreception is a primary sensory modality among marine invertebrates, and the concentrations of hydrocarbons sufficient to disrupt chemosensory behaviors are in the low ppb range (Johnson 1977). Among the numerous chemosensory interactions between marine invertebrates, the predator-prey relationship of a starfish and a sea urchin is particularly amenable to laboratory study. Urchins are omnipresent in the marine environment, and much is known about their ecological role as a herbivore. When presented with a chemical stimulus from their starfish predator, sea urchins exhibit a defensive response that is consistent and repeatable.

The green sea urchin is preyed upon by the sunflower star, Pycnopodia helianthoides (Phillips 1978; Mauzey, Birkeland, and Dayton 1968). The starfish can move faster than the urchin, but the urchin, if overtaken, possesses a complement of defensive globiferous pedicellariae that are activated by a water-soluble exudate from the starfish. These globiferous pedicellariae are generously distributed over the aboral surface of the urchins, and a typical 3 cm diameter urchin might possess 100 or more. Each pedicellaria articulates on a peduncle and has three jaws, each tipped with a hollow tooth capable of delivering venom when sufficiently stimulated (Campbell 1976).

The normal sequence of the pedicellarial defensive response is depicted in Figures 1 and 2. Prior to stimulation the globiferous pedicellariae lie with jaws closed near the bases of the spines (Fig. 1). When stimulated with starfish exudate the pedicellariae rise to a position perpendicular to the test (shell), and the jaws open to an 180° angle (Fig. 2). If a pedicellaria were to contact a tube foot of Pycnopodia at this point, the jaws would close, inject venom, and produce a rapid (though not necessarily total) withdrawal of the starfish.

CHEMISTRY

With increased exploration for and transportation of petroleum and the inevitability of spills, polycyclic aromatic hydrocarbons (PAH) are becoming more common contaminants of the marine environments. Biological activity (mutagenesis, carcinogenesis) and covalent binding with cellular macromolecules (e.g., DNA) of PAH in terrestrial mammals are largely due to their reactive intermediates, presumably oxygenated metabolites (Magee 1974, Brookes 1977, Jones and Freudenthal 1978); therefore, a detailed knowledge of the metabolism of PAH in aquatic species is essential in assessing consequences of petroleum pollution. Naphthalene--a major component of petroleum--was shown to inhibit metabolism of other PAH [e.g., benzo[a]pyrene (BAP)] and to have an inhibitory effect on skin tumorigenesis induced by BAP in rats (Schmeltz et al. 1978). It was suggested that this inhibitory effect on the metabolism of BAP may be

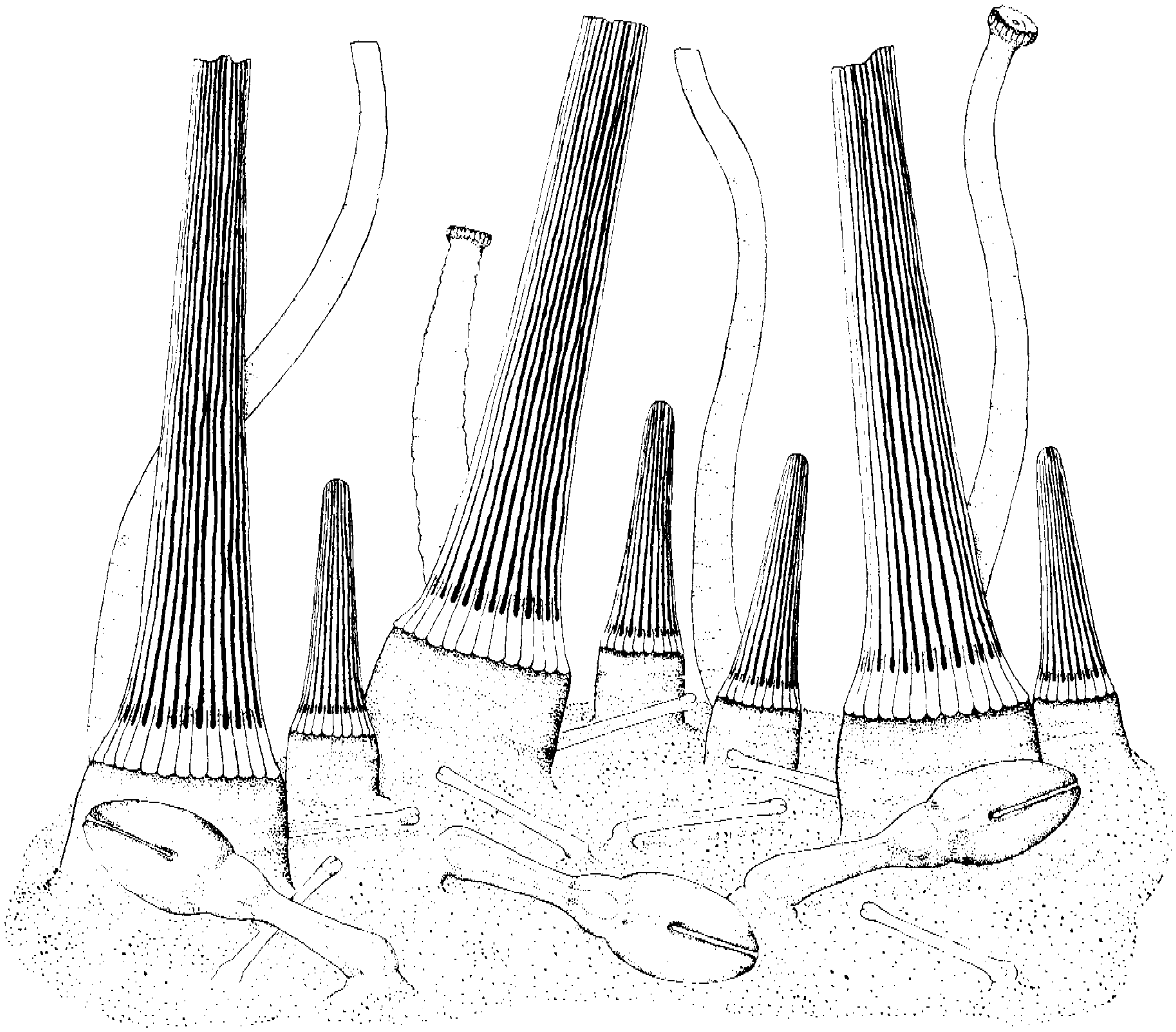

FIGURE 1. Surface of resting S. drobachiensis, showing large globiferous pedicellariae lying horizontally.

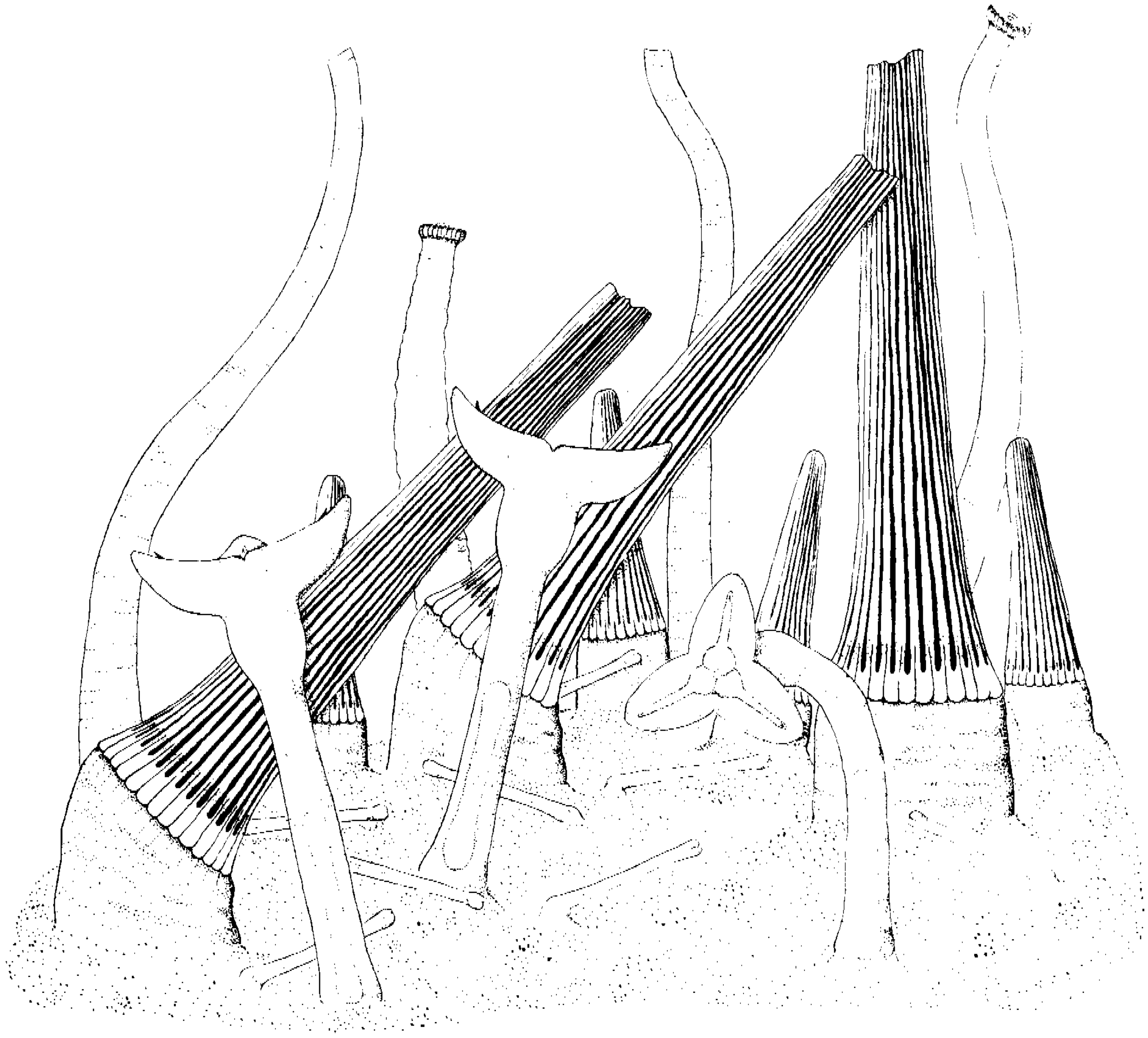

FIGURE 2. Surface of S. drobachiensis following stimulation with exudate of P. helianthoides, showing activated globiferous pedicellariae.

mediated by hydroxylated metabolites of naphthalene. Hepatic and certain extrahepatic tissues of many marine organisms contain hydrocarbon metabolizing enzymes, such as aryl hydrocarbon monooxygenases, epoxide hydrase, and glutathione-S-transferase (Seiber and Adamson 1976, Varanasi and Malins 1977, Malins 1977, Bend and James 1978). Recent studies (Roubal et al. 1977, Varanasi et al. 1978, Collier et al. 1978, Melancon and Lech 1978) show that salmonids (*Oncorhynchus* and *Salmo*) exposed to naphthalene through the diet, in the water column, or via intraperitoneal injection contain considerable concentrations of both the parent hydrocarbon and its metabolic products in various tissues and organs. Varanasi et al. (1978) have reported that the epidermal mucus of salmonid fish is involved in excretion of metabolites of naphthalene.

Because much of the oil spilled in the marine environment ultimately accumulates in bottom sediments (Hyland and Schneider 1976), benthic fishes, especially those in colder regions, may be threatened by petroleum. Pleuronectid fishes are of high commercial value and contribute substantially to the demersal biomass of the continental shelf of the northern Pacific Ocean. Hardly any information is available on the ability of these demersal fish to metabolize PAH. Roubal et al. (1978) reported that, compared to coho salmon (*Oncorhynchus kisutch*), starry flounder accumulated much higher concentrations of aromatic hydrocarbons when exposed to water-soluble fractions PBCO. These results, together with reports (Hodgins et al. 1977, McCain et al. 1977) that certain species of pleuronectids from the same areas have a rather high incidence of liver and skin tumors, make it of considerable importance to investigate hydrocarbon metabolism in these demersal fish.

MORPHOLOGY

Lens hydration and cataract formation in different animals have been attributed to a number of causative factors and agents (Hollwich, Boating, and Kolck 1975). Naphthalene, a component of petroleum, has been studied in mammals and found to be a potent cataract-inducing agent (Van Heyningen and Pirie 1967, 1976). In fish, cataracts have been attributed to nutritional deficiences (Hess 1937, Steuke et al. 1968), sunlight (Allison 1963), and contaminants such as thioacetamide (Sallmann 1966). Petroleum-related eye anomalies have been reported in cunner, *Tautogolabrus adspersus*, exposed to a surface slick of Venezuelan crude oil in a flowing seawater system for six months (Payne et al. 1978). DiMichele and Taylor (1978) investigated the histological effects of naphthalene on *Fundulus heteroclitus* after laboratory exposure of 0.002-30 mg/l for 1-15 days. The organs and the systems which showed major pathological alterations were the neurosensory system, brain, liver, and pancreas; toxicity was apparently related to primary damage within the circulatory system and the ensuing ischemia probably induced the histopathology. No effect was found, however, in the lenses of these fish (DiMichele, personal communication).

Several authors (for review see: Ginzburg 1972) have demonstrated differences in the structure of the intricate outer envelope or "membrane" which covers the teleost egg and developing embryo. Lonning and Hagstrom (1975) state that these differences are species specific, and Ivankov and Kurdyayeva (1974) hypothesize that the morphology of the primary membrane is an indication of the ecological conditions for spawning and egg development. The vulnerability of fish eggs to petroleum exposure has been demonstrated by Kuhnhold (1974) in cod. Kuhnhold and Busch (1977, 1978) have also documented the uptake of naphthalene, benzopyrene and *n*-hexadecane by salmon eggs.

PATHOLOGY

Pathological Changes in Flatfish from Exposure to Oil-Contaminated Sediment

Reports of adverse effects of petroleum hydrocarbons on adult and sub-adult marine fishes exposed for long periods of time have come almost exclusively from a small number of laboratory studies. In previous experiments reported by members of OCSEAP RU 73 (McCain et al. 1978), English sole exposed to sediment-associated PBCO for 4 mo took up substantial amounts of petroleum hydrocarbons and were observed to develop the following apparently oil-related changes: (1) during the first month, when sediment and tissue levels of aromatic hydrocarbons were highest, most of the exposed fish had severe hepatocellular lipid vacuolization (HLV); (2) the number of fish weighing less than their initial weight was higher in the experimental than in the control groups ($P=0.05$) after 4 mo of exposure; and (3) although no control fish died of experiment-related causes and all looked normal during the 4-mo experiment, 3 oil-exposed fish died or were moribund and appeared extremely emaciated. Payne et al. (1978) observed that cunner (Tautogolabrus adspersus) exposed to a surface slick of crude oil for 6 mo had lower testes-somatic indices (0.81) than did controls (1.33). The eye lens diameter of oil-exposed cunner was significantly greater than that of controls. In another study, mummichogs (Fundulus heteroclitus) exposed for 15 days to recirculated seawater solutions of 2.0 to 0.02 µg/g naphthalene (an important component of crude oil) developed histopathology in a variety of organs (DiMichele and Taylor 1978). Major types of damage were neurosensory cell necrosis and localized tissue ischemia. Serum concentrations of glucoside and protein were significantly higher in exposed fish, suggesting a stress response to naphthalene.

Effects of Petroleum on Fish Disease Resistance

Recent studies of host defense mechanisms and disease resistance in salmonid fish subjected to long-term peroral exposure to PBCO showed that no marked alterations occurred (See OCSEAP Annual Report RU 73/74, 1978). It has been shown, however, that various flatfish bioaccumulate petroleum hydrocarbons to a greater extent than do salmonids (Roubal et al. 1978), although their relative capabilities for metabolizing hydrocarbons have not been well studied. This greater tendency to bioaccumulate petroleum hydrocarbons was the rationale for examining the effect of oil exposure on sub-adult starry flounder and rock sole reported here.

PHYSIOLOGY

Of the life stages of an organism, the early developmental stages usually represent the most susceptible period for impact of an environmental pollutant. In early development, particularly during cleavage and differentiation, injury to a single cell can cause death or teratogenesis. In a recent review on the effect of oil on eggs and larvae of marine species, Kuhnhold (1977) points out the astonishingly few reports concerning the effect of oil on this frequently "weakest link" in pollutant resistance of a species.

Several studies have been reported on the effect of petroleum on salmon eggs and alevins (Rice et al. 1975, Kuhnold and Busch 1977/78); however, these investigations have largely concentrated on acute toxicity and the uptake of specific hydrocarbons. No published information has been found detailing effects of weathered crude oil on embryonic and larval development of salmonid fishes.

IV. STUDY AREA

All experiments were conducted either in laboratories or in fish holding facilities at NWAFC, Seattle, and at the NWAFC's saltwater field station at Mukilteo, Washington, on representative subarctic marine and anadromous species.

V. SOURCES, METHODS AND RATIONALE OF THE DATA COLLECTION

BEHAVIOR

Vertebrate

Groups of 20 English sole (0-1 age class, 45-120 mm length) were introduced on one side of a choice test apparatus, and the number on each side determined at intervals of 1 through 15 days. The test apparatus consisted of a 61 x 152 cm box with 20 cm high stand pipes at each end (Fig. 3). In the box were two identical 3,400 cm^2 trays each filled with 15 liters of sediment to a depth of 3.5 cm. A perforated pipe running the width of the box and located 2 cm above the water surface provided seawater at 12 l/min; half of the flow being directed toward each outlet. Dye studies showed that this water flow configuration provided negligible mixing of water between sides of the test apparatus. When the trays were filled with sediment the water volume of the test apparatus was 113 liters with a water replacement flow of 6 times/hr.

In the process of developing procedures to test avoidance of flatfish to oil-contaminated sediment it was decided to evaluate the fishes' feeding responses and use these responses as an index of the fishes' well being, and as a possible measure of chemosensory acuity (See Sutterlin 1975, for a field study on flatfish responses to food extracts). The rationale for assessing chemosensory acuity was that if avoidance of oil-contaminated sediment was chemosensory dependent then impairment of this sensory modality may be relfected in reduced feeding activity or inability to readily locate food sources. In preliminary tests, observations on flatfish behavior indicated that in the test apparatus their perception of diced clam (Saxidomus nuttalli) as a food source was based on visual cues rather than chemosensory stimuli. Thus, nonburrowing juvenile coonstripe shrimp (Pandalus danae), which are primarily chemosensory feeders, were introduced along with the flatfish in each test as another bioassay indicator of chemosensory disruption due to petroleum hydrocarbons in the water column. In addition, at the end of two tests with oil-contaminated sediment, juvenile Dungeness crabs (Cancer magister) were placed in the test apparatus to evaluate the effect of oil-contaminated sediment on the feeding behavior of a burrowing crustacean.

Sediment was collected from a beach near Dungeness, Washington; an area known to have low levels of petroleum contamination in previous assays, and for which sediment characteristics (particle size, organic and metal content) have been determined (McCain et al. 1978). English sole, Dungeness crab (average 8.5 cm carapace width), and coonstripe shrimp (average 3.3 cm from rostrum tip to rear of carapace) were collected together in Puget Sound in less than 1 m of water with a 10 m beach seine.

Control tests were conducted with uncontaminated sediment in both trays of the avoidance apparatus. The sediment was rinsed with flowing seawater in the

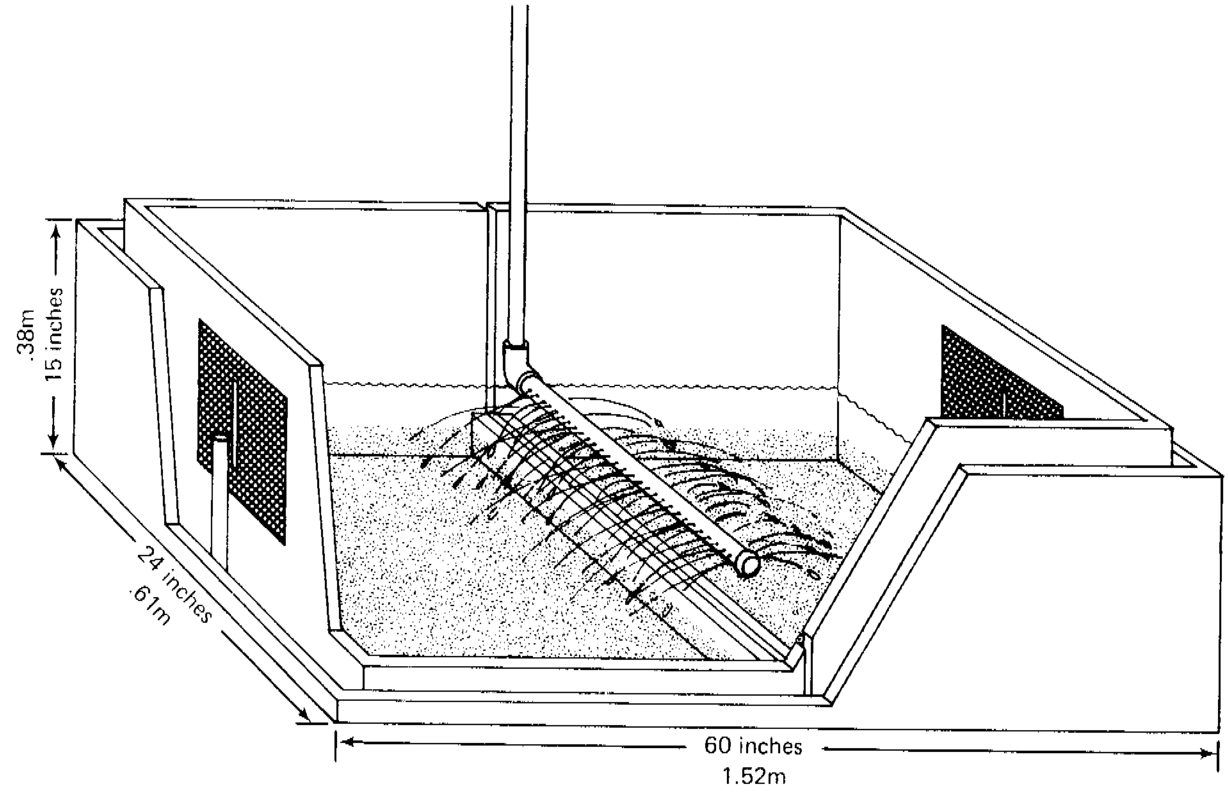

FIGURE 3. Choice apparatus used in testing avoidance of juvenile English sole to crude-oil-contaminated sediment.

test apparatus for 4 to 24 hr and then a group of either 10 or 20 juvenile English sole and 10 juvenile shrimp released on the sediment of one tray; sides for release being alternated between tests. After 19 to 21 hr in the test apparatus the fish and shrimp were fed diced clams and their feeding responses noted. Three hr later the number of fish on each side were counted, measured, visually checked for stomach fullness, and either the test terminated or the fish re-released in the trays where they were recovered and the process repeated the next day.

Prior to testing flatfish avoidance to oil, the sediment in one tray (used in previous control test) was removed and mixed with either 375 or 750 ml of PBCO in a cement mixer for 30 min to give an initial oil concentration of 2.5 or 5% (v/v). After 4 to 24 hr of rinsing, 20 juvenile English sole and 10 juvenile shrimp were released on sediment of the uncontaminated tray. The same feeding and enumeration procedure was followed as described for control tests. In addition, at the termination of each test, or at time of enumeration if the test was continued, a sample of sediment, sediment-interstitial water, and above-sediment water were collected from each side for gas chromatographic (GC) analysis, or for gravimetric determination of total extractable petroleum hydrocarbons (TEPH). The sediment sample consisted of a 150 g composite obtained from the surface of each tray with a 50 g capacity corer 2.0 cm deep. For sampling of sediment-interstitial water an open-ended glass tube (1.7 x 25 cm) was vertically inserted 2 cm into the sediment while holding the upper end closed. After positioning, the upper end was opened and 50 cc of water rising within the tube were removed with a syringe. Above-sediment water was taken by submersing, and then filling, a 315 ml sample bottle containing 3 ml of concentrated hydrochloric acid.

Extraction and analysis of the TEPH in the sediment followed a modified procedure described by MacLeod et al. (1977). Extraction of petroleum hydrocarbons from sediment-interstitial and above-sediment waters was as follows: The water sample was first spiked with a recovery standard (400 µl of 50 ppm, 1,3,5-triisopropyl benzene in methanol) followed by triple extraction with a total of 24 ml of CH_2Cl_2 with 2 min shaking between each extraction. The extract was placed in a separatory funnel with 2.5 ml of Na_2SO_4, laid over a glass wool plug at the bottom of the funnel, and allowed to stand 1 hr. The extract was then drained into a concentrator tube and reduced to 0.8 ml with a tube heater and reflux column. An internal standard (200 µl of 50 ppm, hexamethyl benzene in CH_2Cl_2) was then added, and the extract sealed in a sample vial for analysis using a glass capillary GC column (characteristics described by MacLeod et al. 1977).

The data was treated statistically using chi-square analysis.

Invertebrate

Seawater-soluble fractions of PBCO were generated by the method of Roubal et al. (1977). Solutions containing a mixture of monocyclic aromatic hydrocarbons or single aromatic hydrocarbons were prepared by a modified method described by Benville et al. (1978). In the latter, filtered seawater dripped into a glass reservoir at a constant head from a perforated bucket. Hydrocarbons were introduced continuously near the top of the glass reservoir via a calibrated syringe pump and the saltwater-hydrocarbon mixture was drawn off at the bottom of the reservoir and delivered to a 2 liter glass exposure beaker (Fig. 4). The flow rate of saltwater-hydrocarbon mixture through the exposure beaker was 200 ml/min.

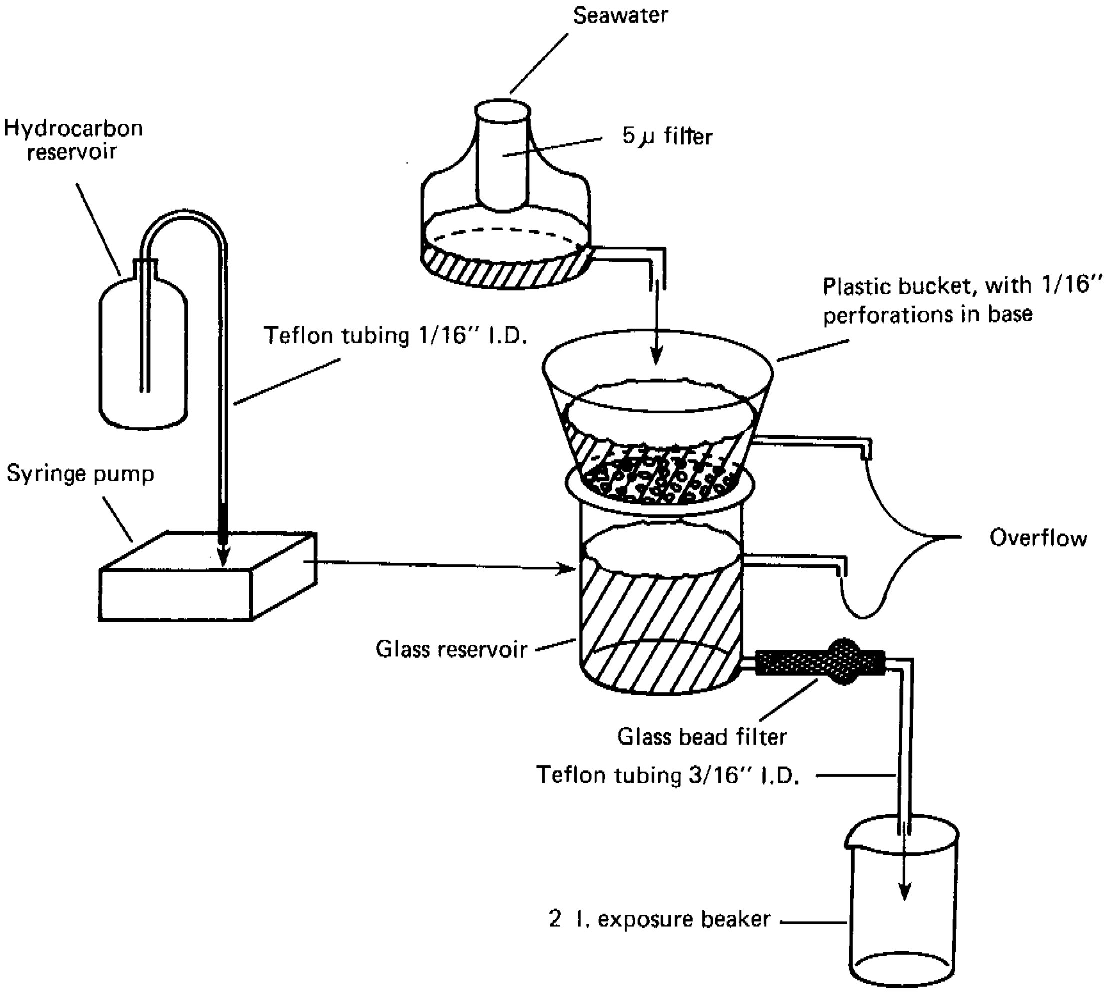

FIGURE 4. System used for generating aromatic hydrocarbon solutions used in sea urchin behavior experiments. [Modified from Benville et al. 1978]

Four tests were conducted using a model mixture of monocyclic aromatic hydrocarbons representative of the SWSF of PBCO. The model mixture consisted of 8% benzene, 57% toluene, 2% ethylbenzene, 26% m,p,o-xylene, and 7% 1,2,4-trimethylbenzene.

For each hydrocarbon concentration used, replicate water samples were taken for GC analysis and extracted following procedures given under methods in the avoidance behavior section. For analysis of benzene, 1 ml of benzene-seawater mixture was placed in a 2 cc GC vial, capped, and allowed to stand 18-20 hr. One ml of air was then extracted from the vial headspace and injected directly into a GC. These results were compared with results of benzene standards prepared by injection of µl amounts of benzene-methanol solutions into GC vials containing 1 ml of seawater, which were then processed in the same manner.

The SWSF hydrocarbon concentrations reported are the summed concentrations of the monoaromatic hydrocarbons toleune, ethyl benzene, xylenes, and trimethylbenzenes. Together with benzene, the above hydrocarbons comprised 95% of the total SWSF of PBCO detected by GC (Roubal et al. 1977); the remainder consisted of naphthalenes (3%) and cyclohexanes (2%). In calculating the SWSF hydrocarbon concentrations, benzene was not included since it was indistinguishable from the solvent front with the GC column employed. The reported hydrocarbon concentrations have not been adjusted for an extraction efficiency which averaged 67.3% (±12.2% S.D.).

Starfish exudate was prepared by placing a *Pycnopodia helianthoides* in its equal volume of filtered (to 5 µ) seawater for 1 hr. The resulting exudate was refiltered (to 5 µ), tested for efficacy in activating pedicellariae, and then frozen in aliquots.

Starfish extracts were prepared twice during these studies. For standardization, serial dilutions of each extract were first made to determine the threshold concentration at which they provoked a pedicellarial response. The second extract preparation was 10 times as potent as the first, and some of it was diluted to 0.1 X for standard bioassays and the remainder kept as 10 X (stimulus) concentrate for competitive inhibition tests. For both preparations, the "standard starfish exudate" used in hydrocarbon bioassays was 10 times greater than the threshold stimulus concentration. Before each test an aliquot was thawed and kept at ambient water temperature.

Prior to behavioral testing, sea urchins (2.5-3.5 cm test diameter) were exposed to hydrocarbons by one of two methods. Most exposures consisted of holding 5 urchins for 24 hr in a 2 liter exposure beaker and then placing them individually in 100 ml beakers containing 40 ml of seawater hydrocarbon mixture. The urchins were left undisturbed for 5-15 min prior to stimulation with starfish exudate. The second method was to expose the urchins individually in the 100 ml beakers for only 5-15 min before testing. Following exposure, 1 ml of starfish exudate was slowly administered with a syringe in a circular motion over each urchin. The defense response assay consisted of counting the number of pedicellariae that open to 180°.

If 75 or more pedicellariae responded to the starfish stimulus, it was considered a total (100%) response; if less than 75 opened a partial response was recorded (0-99%). For each test, the average response of the hydrocarbon-treated group was divided by the average response of the controls to yield a response index for each treatment.

$$\frac{(\bar{x}\ \%\ \text{response of exposed group}}{(\bar{x}\ \%\ \text{response of control group}} = \%\ \text{response index})$$

Each response index reflects results from 10 or more urchins, with at least 5 in the treated and 5 in the control groups. Response indices were plotted against the logarithm of the hydrocarbon concentration and the least-squares linear regression was calculated.

Ancillary observations were made regarding the relative degree to which the tube feet were extended from the urchins, their mobility, and their strength of attachment to the glass substrate. In addition, some groups of hydrocarbon-treated urchins were replaced in clean, flowing seawater and later restimulated to assess reversibility of the behavioral inhibitions.

During the course of these investigations it was found that an injection of 0.5 ml isotonic KCl into the body cavity of the urchins produced a strong pedicellarial response and hyperactivity. Injection of clean seawater produced no response. Consequently, some hydrocarbon-treated urchins that showed reduced defense responses were then injected with KCl to determine whether the pedicellariae were competent to function if artificially provoked.

Four predator-prey experiments were conducted in a 600 liter flow-through fiberglass tank containing 3 Pycnopodia and 10 or more sea urchins in each experiment. The urchins were first divided into control and test groups and each group identified by drilling a characteristic pattern of 1 mm holes in the tests (shells). The test group was exposed to the SWSF of PBCO for 24 hr and then released in the 600 liter tank along with an equal number of controls. After 1.5 to 24 hr the number of urchins eaten by the starfish were determined and each was identified by the marking pattern. Differential predation rates between SWSF exposed and control urchins was compared by chi-square analysis.

CHEMISTRY

Sexually immature starry flounder and rock sole were captured by trawling or beach seining from the mouth of the Columbia River and from Point Pully in Puget Sound, Washington, respectively. The fish (82 ± 30 g) were maintained at experimental temperatures of 12° ± 1°C or 4° ± 1°C in flowing, unfiltered seawater (28 °/₀₀) for a period of two weeks prior to treatment. Fish were fed to satiation on a composite diet of earthworms, euphasiids, and Oregon moist pellets.

Force-feeding study. Test fish of both species mildly anesthetized with tricaine methane sulfonate (50 μg/l) (Crescent Research Chemicals, Phoenix, Ariz.) were force-fed, as described previously (Varanasi et al. 1978), a gelatin capsule (No. 5) containing 56 μCi (sp. activity 198 mCi/mmole) of 1-^{3}H-naphthalene (Amersham-Searle, Arlington Heights, Illinois) dissolved in 25 μl of salmon oil. The fish were then placed in aquaria (≃600 l) supplied with flowing seawater at 12°C. Three to six fish were analyzed at each time period of 24, 48, and 168 hr after the initiation of exposure. Rock sole were also analyzed at 6 wk. Fish were not fed during the first week after the initiation of naphthalene exposure. Another group of naphthalene-exposed starry flounder was kept at 4°C and six fish each were analyzed at 24 and 168 hr.

Injection study. Mildly anesthetized starry flounder were injected intraperitoneally, with 25 μl of salmon oil containing 56 μCi of the tritiated naphthalene. The fish were kept at 12°C under conditions described above, until the sampling time at 24 and 168 hr after the injection.

Sample collection. Fish were killed by a blow to the head and epidermal mucus and skin were collected as described previously (Varanasi et al. 1978, Varanasi and Markey 1978). Samples of muscle, liver, brain, gills, blood, kidney, stomach, intestine, and bile were collected using methods described by Roubal et al. (1977, 1978).

Analytical methods. Radioactivity associated with both naphthalene and total metabolites in each tissue (≃100 mg) was determined by a previously described method (Varanasi et al. 1978). Only radioactivity values (dpm) above one and one-half times the background value were considered. Dry weight of each tissue was obtained by freeze-drying and the values expressed as percent of wet weight of tissue are given in Figure 5. Lipid content of liver, muscle, and skin of starry flounder and rock sole were determined using a previously described method (Hanson and Olley 1963).

Data were statistically analyzed using Student's t test. Also, rates of decline of naphthalene and metabolite concentrations in tissues were obtained by assuming a lognormal distribution and describing the decay of concentration by $y=ax^{-b}$ (Norwich 1977).

The metabolites were isolated from liver, muscle, skin, and bile of the exposed rock sole and starry flounder by the method of Roubal et al. (1977) with the following modifications: The samples (≃200 mg each) were homogenized in 3 ml of methanol and the homogenate was extracted twice with 5 ml of hexane to remove naphthalene. Radioactivity in the hexane phase was due primarily to naphthalene. The homogenate was filtered and the filtrate was collected in a flask kept in ice. The residue was extracted twice with 8 ml aliquots of a mixture of boiling methylene chloride:2-propanol:water (75:25:2, v:v:v) and twice with 8 ml of boiling ethanol:diethyl ether (50:50, v:v). The combined extracts were concentrated at 4°C, under a stream of nitrogen, to minimize any loss of volatile components. Known amounts of radioactively-labeled 1-naphthol were added to control tissues, and recovered radioactivity was determined to assess possible losses of volatile components during extraction. Less than 3% of total radioactivity was lost during the work-up of these samples.

After radioactivity (dpm/μl) in each extract was determined, individual classes of metabolites were separated via thin-layer chromatography (TLC). Non-conjugated metabolites were separated using a solvent system A of p-dioxane: benzene:acetic acid (25:90:4, v:v:v). A glass plate coated with silica gel (0.25 mm thickness, Merck), was kept on a thermo-electric cold plate (Cole-Parmer, Ill.) at 5°C and was spotted with 5 μl of the extract which was mixed with 50 μl each of 0.1% solutions of non-radioactive standards (1-naphthol, 2-naphthol, and 1,2-dihydro-1,2-dihydroxynaphthalene). The TLC plate was then developed in a chamber (Desaga, W. Germany) at 14°C. Several duplicate samples were analyzed to determine reproducibility. Variability among samples from a tissue (e.g., liver) of a single fish was significantly ($P<0.001$) smaller than variability among liver samples from different fish. Superimposition of non-radioactive standards and concomitant development with test samples, which were made visible by previously described staining methods (Boyland and Solomon 1956), made it possible to locate more precisely each class of metabolites in an individual chromatogram than relying merely on R_f values of standards. Conjugates in a sample were separated on a Quantum LQD segmented plate (Kontes, Vineland, N.J.) and developed in a solvent system B consisting of the upper phase of 1-butanol:concentrated ammonium hydroxide:water (80:20:100, v:v:v). Non-radioactive standards, 1-naphthyl glucuronide, 1-naphthyl sulfate (Sigma, St. Louis, Mo.), and 1-naphthyl mercapturic acid (Roubal et al. 1977) were used in a manner described above. According to Roubal et al. (1977) sulfate and glucoside derivatives have the same R_f value and were, therefore, not resolved in this solvent system.

After the determination of the position of the various metabolites the adsorbant was scraped from the chromatograms in 5 mm bands, each of which was placed in a separate scintillation vial with 15 ml InstaGel (Packard Instrument Co., Downers Grove, Ill.) scintillation cocktail. Radioactivity in each sample

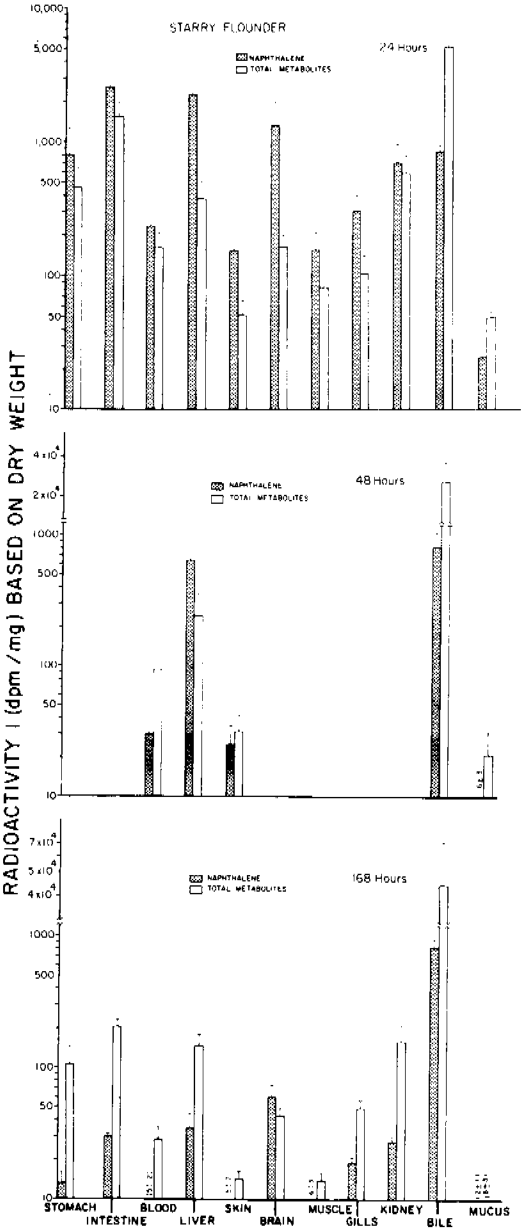

FIGURE 5. Concentrations of naphthalene and its metabolites in tissues of starry flounder, at 24, 48, and 168 hr after the feeding of 56 μCi of 1-^{3}H-naphthalene. Values are expressed as mean ± S.E. (for number of fish tested at each time period, see Table 12). Values of dry weight of tissues are given below as percent of the wet weight of tissue: stomach (22%), blood (14%), liver (25%), skin (33%), brain (18%), muscle (21%), gills (17%), kidney (18%), bile (12%), intestine (22%), and epidermal mucus (2.8%). Rates of decline in concentrations of naphthalene (N) and total metabolites (M) were calculated using the equation $y=ax^{-b}$. Values for regression coefficient b were for liver b(N)=1.845, b(M)=0.404; for blood b(N)=1.671, b(M)=0.837; and for skin b(N)=1.499, b(M)=0.616. [From Varanasi et al. 1979a]

was determined using a liquid scintillation counter (Packard Instrument Co., Ill.). Residual radioactivity in each tissue was also determined.

MORPHOLOGY

For the cataract formation study, rainbow trout were fed PBCO in Oregon moist pellet (OMP) (1 g petroleum/1 kg food) for three years. The food was prepared by dissolving PBCO in trichlorotrifluoroethane and mixing with the pellets. The solvent was allowed to evaporate and the oiled OMP fed to the trout at 2% body weight for five days per week. The reference group of fish received the same amount of OMP treated with trichlorotrifluoroethane but without the added petroleum.

Immediately after sacrificing and exsanguinating the trout, lenses were removed from the eyes and placed in a solution of 0.75% glutaraldehyde, 3% formalin, 0.5% acrolein, in 0.1 M sodium cacodylate buffer with 0.02% $CaCl_2 \cdot H_2O$ and 5.5% sucrose. One lens from each fish was prepared for scanning electron microscopy (SEM) and the other for transmission electron microscopy (TEM).

For the study of egg membranes, ripe starry flounder were stripped and the eggs fertilized and incubated at the NMFS laboratory at Mukilteo, Wash. Pink salmon eggs were fertilized and incubated at NMFS, Auke Bay, Alaska. Eggs were collected 2-3 min after fertilization unless otherwise noted. Flounder eggs were fixed for 24 hr and pink salmon eggs for 1 wk in the aldehyde solution described above. Eggs were subsequently prepared for both SEM and TEM.

Samples of tissue from flatfish exposed to petroleum-contaminated sediment were taken and fixed for electron microscopic examination as detailed in the OCSEAP Annual Report RU 73, April 1978.

PATHOLOGY

Pathological Changes in Flatfish from Exposure to Oil-Contaminated Sediment

In the four experiments performed during the last year, two basic types of sediment (sandy and silty), two initial proportions of PBCO (0.5 and 1.0%), three species of flatfish (English sole, starry flounder, and rock sole), and exposure times ranging from 3 wk to 2 mo were used. Particle size analyses of the sandy and silty sediment types showed that approximately 1.0 and 47.4%, respectively, were composed of silt. Mixtures of PBCO and sediment were prepared using a cement mixer. The sediment was placed in a previously described aquarium (McCain et al. 1978) at a depth of 5 cm. After rinsing the sediment overnight by allowing seawater to flow through the tank, the experimental fish were added. An equal amount of non-oil-contaminated sediment placed in a similarly designed aquarium at the same depth was used for control fish. After adding the fish to the sediment-containing aquaria, the aquaria were examined daily for dead or moribund fish, and the fish were fed to satiation with a combination of frozen euphausiids and live earthworms. Experimental fish were captured by beach seine and otter trawl in relatively unpolluted areas of Puget Sound and the Columbia River estuary.

At intervals of 2 wk to 1 mo, all of the fish were examined for externally visible abnormalities, and they were measured for weight and length. Three to six fish from each group were sacrificed and tissue samples were removed for histological, hematological, morphological, and chemical analyses. For histological examination of each fish, pieces of gill, gonad, fin, skin, gastrointestinal tract, kidney, liver, and eye lens were removed and preserved in appropriate fixatives. Specimens to be examined by light microscopy were embedded in paraffin, sectioned, and stained by a variety of histochemical stains and methods. Procedures used for electron microscopic examinations of tissues are described elsewhere (See Morphology section). Hematological tests were performed for the following: hemoglobin, hematocrit, and total red blood cell and leukocyte counts. Concentrations of serum albumin and total proteins were also measured by standard spectrophotometric methods. Samples of muscle, skin, and liver of the fish were collected for analyses of aromatic hydrocarbons. Muscle samples from each fish were analyzed individually, and skin and liver samples from the three fish in each group were pooled. Tissue samples were frozen at -20°C immediately after they were taken and thawed just before chemical analysis.

Samples of sediment, interstitial water, and water immediately above the sediment were also collected at each sampling interval. Sediment samples were taken from the top 2 cm of sediment with a coring device. Interstitial water samples were obtained by inserting a 2 cm diameter glass cylinder with mesh screen attached to the bottom into the top 3 cm of the sediment, and collecting with a syringe the water which accumulated in the cylinder. The above-sediment water sample was collected by placing a screw cap bottle on its side on top of the sediment, releasing the cap, and allowing the bottle to fill.

Hydrocarbon analyses of sediment, water, and fish tissue were performed by the NOAA National Analytical Facility using a modification of procedures described by Brown et al. (1978) and MacLeod et al. (1977) which involved gravimetric determination of total extractable hydrocarbons and gas-liquid chromatography (GLC) for alkanes and arenes. By substracting the concentration of total extractable hydrocarbons in the non-oil-contaminated sediment, the value of total extractable petroleum hydrocarbons in the oil-contaminated sediment (TEPH) was determined.

The main experimental conditions of the four experiments are given in Table 1.

Effects of Petroleum on Fish Disease Resistance

Sediment for disease resistance tests was collected from near Sequim Bay, Washington and stored at 4°C until used. Petroleum-contaminated sediment (0.5%, v/v) was prepared by emulsifying 250 ml of PBCO in 500 ml of seawater and then thoroughly mixing this emulsion with 50 liters of sediment in a portable, rotary cement mixer. The 50 liters of petroleum-contaminated sediment was placed in a 1.2 M diameter circular, fiberglass tank. An identical tank was set up with 50 liters of non-oiled sediment to serve as a control. Prior to the introduction of fish, flowing seawater was run through both tanks for 48 hr.

Two separate experiments were conducted. In the first experiment, starry flounder averaging 24 g each were maintained for 6 wk on sediment containing an initial concentration of approximately 1,800 ppm PBCO. In the second experiment, rock sole averaging 118 g were exposed for the same length of time; however, the initial concentration of PBCO in the sediment was approximately 2,500 ppm. In both experiments, groups of fish were tested for their ability to survive a laboratory challenge with the marine bacterium, Vibrio anguillarum, after 2 and 6 wk of exposure.

Strain LS 1-73 of V. anguillarum, which was found in preliminary screenings to be one of the more virulent vibrio strains for flatfish, was employed for the challenge. This isolate was maintained on a 50% seawater cytophaga medium and its taxonomic identity was confirmed by biochemical and DNA-homology techniques (Schiewe et al. 1977). For challenge, bacteria were grown to late log phase in a medium of 2% trypticase soy broth (BBL) supplemented with 1% NaCl and 10-fold

Table 1. Conditions of experiments concerned with pathological changes in flatfish from exposure to oil-contaminated sediment

Experiment number	Initial amount of PBCO [% (v/v)]	Fish species	Initial number of animals per group	Sediment type	Duration of experiment (days)	Sampling times (days)
1	0.5	Rock & English sole	41 41	High-silt	29	0,14,29
2	0.5	Rock & English sole	20 30	High-sand	21	0,14,21
3	0.5	Starry flounder	50	High-sand	62	0,13,28,62
4	1.0	English sole	44	High-silt	In progress 120 so far	0,28,61,90

serial dilutions were made in 0.85% NaCl. Bacterial concentration was determined, in triplicate, by standard spread plate techniques. For challenging, 4 groups of 5 fish each from the oil-exposed and control regimes were placed in individual 33 liter aquaria containing aerated seawater at 12°C. Varying concentrations of live *V. anguillarum* were injected intraperitoneally and mortality was monitored daily for 14 days. All dead fish were examined by bacteriological culture techniques in order to reisolate the test bacterium and confirm the cause of death. LD_{50} values were calculated by the procedure of Reed and Muench (1938) and compared.

PHYSIOLOGY

The rationale for design of a weathered oil generator, and the regimen for exposure of chum salmon eggs and alevins to weathered oil, lies in simulating natural environmental conditions and the reproductive biology of chum salmon under laboratory conditions.

Intertidally spawning chum salmon dig redds 20 to 30 cm deep in the beds of streams between tidal intrusions. At this time eggs are deposited in the redds and then covered with gravel as a result of upstream redd digging and stream flow. Subsequently, at least one high tide a day inundates the redds with salt and brackish water; the length of exposure to water of high salinity depending upon redd location. After approximately 50-90 days (development rate is a function of water temperature) the eggs hatch and the chum salmon alevins remain in the gravel for another 30-50 days before emergence and migration to saltwater.

For generating weathered oil a wave machine was constructed consisting of an oblong box with a paddle which was hinged at the bottom and which would oscillate with harmonic motion about a mean vertical position (Fig. 6). This design produces waves in which particle velocity decreases rapidly with depth and the apparatus is suitable for simulating the weathering of oil under offshore conditions. In this flow-through system the following procedure was adopted for weathering of oil and exposure of chum salmon eggs to weathered oil.

Coarse gravel (80% 1-5 cm diameter, remainder fines) was spread 25 cm deep over a perforated pipe at one end of the tank. Over this model of a gravel beach was a removable baffle which isolated the gravel from oil contamination during the weathering process. At the start of a 7-day exposure period, 680 ml of PBCO were layered on the water surface resulting in an oil film 0.9 mm thick and a 4,000 ppm (v/v) initial hydrocarbon concentration. Wave periodicity was set at 48/min, saltwater inflow at 3 l/min for a replacement time of once/hr, and the oil was weathered for 30 hr. During weathering, water overflow was removed 10 cm from the bottom of the tank via an adjustable stand pipe. After 30 hr the baffle was remove, the saltwater inflow reduced in salinity (salinity 16-24 °/₀₀), and the weathered oil allowed to come in contact with the gravel. The wave machine design, though mimicking offshore conditions, is incapable of producing a shallow water wave in which particle velocity is uniform throughout the water column. Thus, the behavior of weathered oil as it contacts the tidal zone under natural conditions is not accurately reproduced in these experiments.

For 3 hr every day for the next 4 days water was taken from under the gravel via a perforated pipe and delivered to a series of troughs containing vials of chum salmon eggs. At the same time, troughs containing eggs not being exposed to weathered oil received non-contaminated brackish water. For the other 21 hr/day all troughs received dechlorinated fresh water. On each fifth day the oil was removed, the apparatus was cleaned with hot water, and the system was flushed for 2 days before repeating the weathering process. During

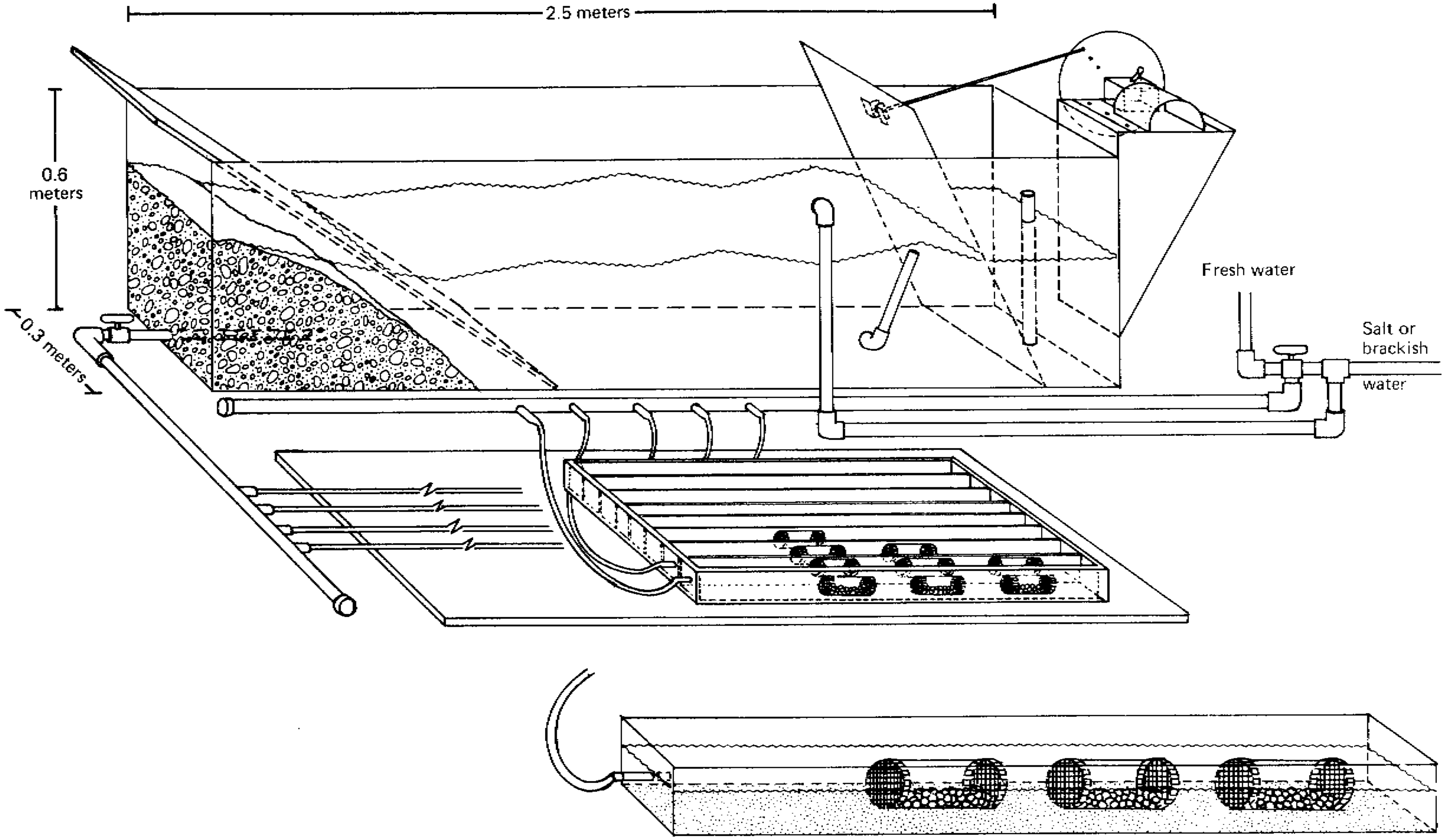

FIGURE 6. Apparatus for weathering of crude oil and subsequent exposure of chum salmon eggs to weathered oil.

the last 2 days the eggs received non-oil-contaminated brackish water for 3 hr each day.

Replicate water samples for GC analysis were taken daily from lines leading into the egg-holding troughs. Extraction procedures for removal of petroleum hydrocarbons from the water are given in the Behavior section of this report.

Chum salmon eggs for this experiment were collected at the Quilcene National Fish Hatchery, Quilcene, Washington on the day of artificial spawning.

VI. RESULTS

BEHAVIOR

Vertebrate

Control tests were conducted with uncontaminated sediment on both sides of the choice chamber apparatus (Table 2). Unequal control groups were used to evaluate the possibility of displacement from one side to the other due to fish density. Though too few control tests were conducted with only 10 fish per group to make a reliable evaluation, the results suggest that the number found on each side were not density dependent. For all control tests combined, the percent fish found on the right side was 52% and on the left side 48%. In the first 15 min after introduction of fish into the test chamber there was considerable activity with the fish frequently passing from one side to another, however, upon enumeration 22 to 24 hr later there was a bias with 63% of fish being found on the side of introduction (54% when only release groups of 20 fish are considered). This bias disappeared when the fish were retained in the test apparatus 48 hr or longer.

Table 2. Control data. Percent juvenile English sole found in each side of the testing apparatus when no oil was present in the sediment.

Test dates	No. fish introduced	Hours in test apparatus	% fish	
			right	left
8/9	20	24	55	45[a]
8/10-11	10	22	100[a]	0
		46	50	50
8/22	10	24	40	60[a]
8/23	20	22	45[a]	55
8/24	20	24	30	70[a]
9/6-11	20	24	55[a]	45
		48	50	50
		76	50	50
		117	45	55

[a] Side fish introduced at start of test.

Three series of tests were conducted with oil-contaminated sediment on one side of the test apparatus; two with an initial oil-sediment concentration of 2.5% (v/v), and one at 5% (v/v). Table 3 presents the results of tests in which

Table 3. Percent juvenile English sole on each side of the test apparatus when oil-contaminated sediment was present on one side (an initial concentration of 2.5% v/v). Hydrocarbon analysis of sediment by gravimetric method; above-sediment water analysis by GC.

Test dates	No. fish	Hours in test apparatus	% fish		Hours oiled sediment in apparatus	Hydrocarbon concentration (ppm)			
						sediment		water	
			right	left		right	left	right	left
8/14	0				0[a]	17.3	11657.9		
8/14	0				2	17.5	8974.8	<.001	.001
8/16	20	23	75[b]	25	46	17.5	8404.0	.026	.003
8/17	20	21	40[b]	60	71	34.1	7140.0	.040	.078
8/18	20	22	55[b]	45	94	43.2	8056.9	--	--
8/29	0				22	8194.3	12.2	.026	.025
8/30	20	22	25	75[b]	46	8496.0	12.2	.037	.032
8/31	20	22	30	70[b]	69	5258.1	13.3	.062	.050
9/1-5	20	23	35	65[b]	93	6350.2	14.7	--	--
		98	65	35	192	6821.8	15.9	--	--

[a] Sediment samples taken before filling test apparatus with seawater.

[b] Side fish introduced at start of test. In each instance fish were initially placed on the non-oil-contaminated side of the apparatus.

375 ml of PBCO were mixed with 15 liters of sediment (2.5% v/v). A sediment sample taken immediately after mixing contained over 11,500 ppm TEPH which decreased by 23% after 2 hr rinsing. Subsequent sediment samples did not show an appreciable decline in TEPH over either a 4 or 8 day period. As expected when 750 ml of PBCO was mixed in 15 liters of sediment (5% v/v) the TEPH concentration was higher (Table 4), however, after 26 hr rinsing, along with flatfish activity, the oil concentration was reduced to 8,300 ppm, and the TEPH remained fairly constant thereafter. Thus, regardless of the initial oil-sediment concentration the carrying capacity for this sediment appears to be about 8,500 ppm.

At the start of each test series the total extractable material from non-oiled sediment was 12 to 17 ppm. During avoidance testing there was a gradual slight increase in extractable material indicating possible transfer of small amounts of petroleum hydrocarbons from the oil-contaminated to uncontaminated trays.

The results from all flatfish avoidance tests showed no statistically significant differences between the number of juvenile English sole on oil-contaminated sediment and the number of fish on uncontaminated sediment. There does, however, appear to be a common pattern of flatfish distribution for each of the first groups of 20 fish introduced into the avoidance chamber which may be indicative of partial avoidance. Prior to initiation of each of the 3 test series the oil-contaminated sediment had not been disturbed, and the percent flatfish found on the side of introduction after 21-23 hr averaged 73% as compared to 54% for control groups of 20 fish. The avoidance results are presented diagramatically in Figure 7 which shows that the pattern of flatfish distribution in control and avoidance test are not identical; again suggesting some initial avoidance of oil-contaminated sediment.

There was no consistent difference in the average length of juvenile English sole found on either side of the choice chamber during both control and avoidance testing. For those fish which were identifiable by length and repeatedly sampled in the test apparatus over a period of several days there was also no predictable pattern for preference of the right or left side even when oil-contaminated sediment was present on one side.

Observations on feeding activity and ability of juvenile English sole to locate a food source were subjective evaluations. There was, however, no difference detected in feeding response of fish on either oil-contaminated or uncontaminated sediment, and visual assessment of stomach fullness at the end of each test indicated that all fish were feeding except for several individuals in the test which extended 15 days with an initial oil concentration in the sediment of one tray at 5%. At termination of this test 24% (4 of 17) fish were not feeding, and there was also a 15% (3 of 20) mortality during the test (See Table 4).

Results of GC analysis show that hydrocarbon content in the above-sediment water was in the low ppb range on either side of the test apparatus when the sediment was undisturbed. However, when fish were present on the oil-contaminated sediment their burrowing activity often raised clouds of oil droplets which formed a highly visible film on the water surface of the oil-contaminated side. Coonstripe shrimp present in the water column above contaminated sediment did not avoid oil droplets in the water caused by flatfish activity, nor did they exhibit a reduction in feeding response or disability to locate food during any of the tests.

Upon termination of two flatfish avoidance tests to oil-contaminated sediment 6 juvenile Dungeness crabs were released on the uncontaminated sediment and their behavior and feeding responses were observed over a 2 to 6 day period. At the time of crab introduction the TEPH in the oil-contaminated sediment was

Table 4. Percent juvenile English sole on each side the test apparatus when oil-contaminated sediment was present on one side (an initial concentration of 5% v/v). Hydrocarbon analysis of sediment by gravimetric method; above-sediment water analysis by GC.

Test dates	No. fish	Hours in test apparatus	% fish		Hours oiled sediment in apparatus	Hydrocarbon concentration (ppm)			
						sediment		water	
			right	left		right	left	right	left
9/18	0				4	17.1	18594.5	.010	.016
9/19	20	21	70[a]	30	26	23.8	8282.8	.079	.081
9/20-	20	21	50[a]	50	46	26.0	9323.9	.062	.266
10/3		91	60	40	96	26.6	8469.5	.014	.074
	(19)[b]	166	42	58	171	28.2	6936.1	.045	.136
	(18)[b]	214	50	50	219	31.8	9668.7	--	--
	(17)[b]	356	59	41	361	33.9	10498.3	.017	.024

[a] Side fish introduced at start of test. In each instance fish were initially placed on the non-oil-contaminated side of the apparatus.

[b] Reduced number of fish due to mortality in initial group of 20 fish.

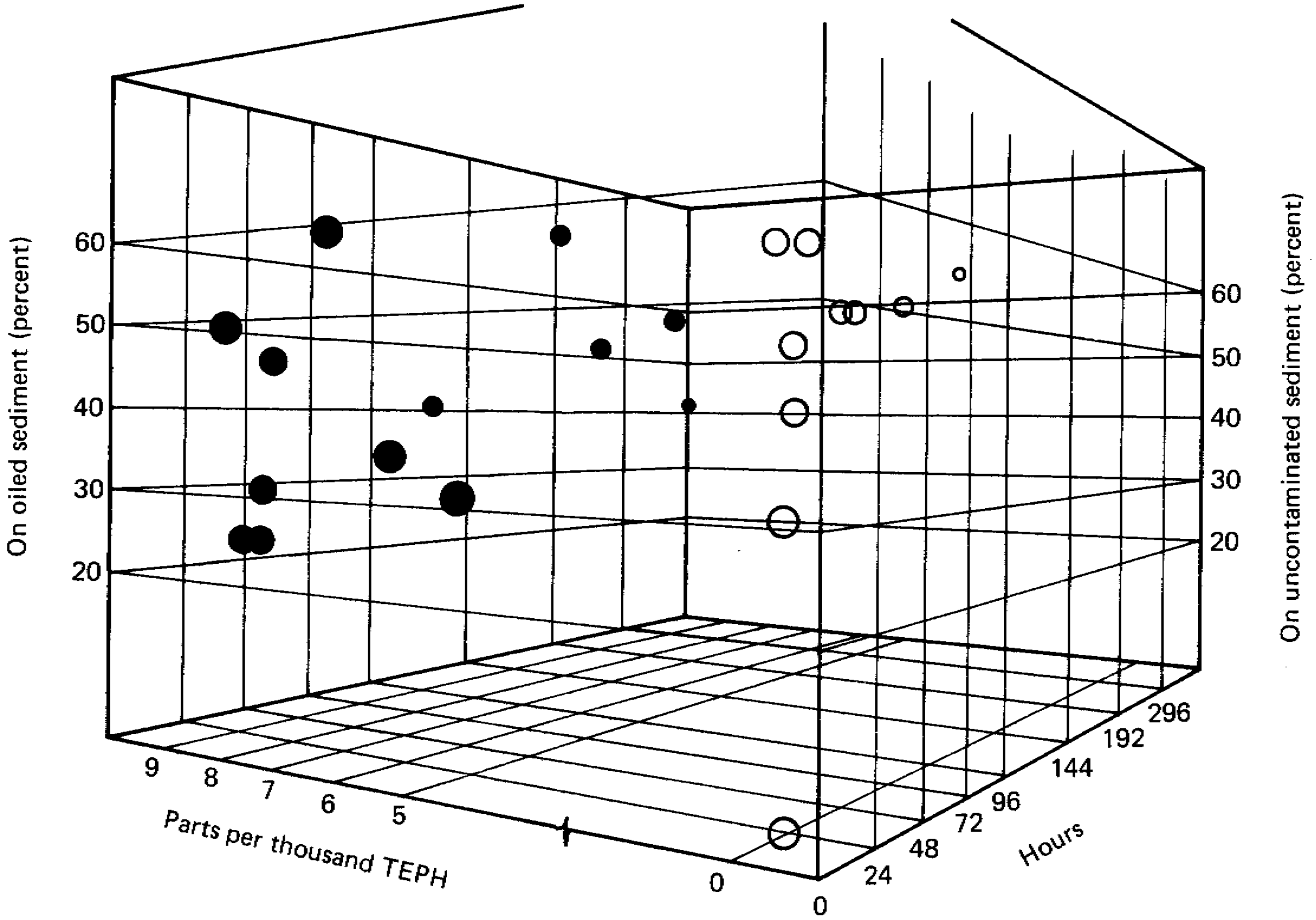

FIGURE 7. Percent juvenile English sole present on oil-contaminated sediment plotted against the oil concentration (TEPH) and hours in the test apparatus (solid circles). Control data (open circles) represents the % flatfish found on uncontaminated sediment opposite the side of introduction.

8,000 to 10,500 ppm, and the TEPH on the uncontaminated side approximately 17 to 26 ppm.

As did the flatfish, the crabs also frequently crossed between the oil-contaminated and non-oiled sediment trays, and readily located and consumed food on the oiled side. However, in contrast to the flatfish, the crabs did not bury themselves in the oiled sediment unless alarmed. Daily observations of crab distribution showed that of the 6 crabs in the test apparatus an average of 1.1 were on the non-oiled sediment surface, 3.4 were buried in the non-oiled sediment, and 1.5 were on the surface of the oiled sediment; none were buried in the oil-contaminated sediment.

Invertebrate

Results of the chemosensory defensive response of the sea urchin when exposed to the SWSF of PBCO for 5 min to 48 hr are presented in Figure 8. The relationship of the pedicellarial response index to the logarithm of the summed concentration of monocyclic aromatic hydrocarbons in the SWSF (toluene, xylenes, trimethylbenzenes, and ethyl benzene) appears linear. Based on the calculated regression, the SWSF hydrocarbon concentration at which the pedicellarial response is inhibited by 50% (EC_{50}) is 35 ppb. This contrasts with the EC_{50}'s for the individual component hydrocarbons toluene, o-xylene, 1,2,4-trimethylbenzene, and ethyl benzene (Figs. 9 through 12; the corresponding data upon which all figures are based is given in Table 5). The EC_{50} for toluene, the major constituent of the SWSF, is 159 ppb. For o-xylene, 1,2,4-trimethylbenzene, and ethyl benzene, the 24 hr EC_{50}'s are 300, 148, and 290 ppb, respectively. Analysis of dissolved benzene concentrations was insufficient to permit a regression analysis. Benzene analyses that were completed ranged from 100-300 ppb ($\bar{x}$=218 ppb), and the average defensive response indices for 24 hr exposures were 32 ± 33%, and for 5-15 min exposure 32 ± 22%.

Four groups of 5 sea urchins each were also exposed to 1-methylnaphthalene (Fig. 13, Table 5). The EC_{50} and calculated regression line for 1-methylnaphthalene are similar to that found for the SWSF. It is doubtful that naphthalenes are responsible for the effects noted in the SWSF tests since their concentrations in the SWSF were found to be generally less than 2 ppb; a concentration which does not appreciably inhibit the pedicellarial response in 24 hr.

In general, 5-15 min exposure periods produced inhibitions of the defensive response equipotent to those following 24-hr exposures. Although the shorter exposures were perhaps slightly less inhibitory with toluene and trimethylbenzene, and slightly more effective with xylene, it can be assumed that the urchins, in terms of their assayed behavior, equilibrate with the hydrocarbons very quickly.

Hydrocarbon-induced inhibition of the pedicellarial response was found to be reversible if the urchins were allowed to depurate in clean, flowing seawater. The results of assays involving various depuration periods and hydrocarbon treatments are tabulated in Table 6. These data show that the hydrocarbon-induced pedicellarial inhibitions diminished much more slowly than they ensued. Recovery rates were highest toward the onset of depuration and tapered off as depuration proceeded.

Benzene- and o-xylene-treated urchins were presented with dilutions of starfish exudate stimulus to determine whether hydrocarbon-induced behavioral inhibition might be overcome. These data are presented in Table 7. The stimulus concentrations are reported as a percentage relative to the strength of the standard stimulus. The data indicate that inhibition of the pedicellarial response is partly overcome by increases in the stimulus concentration (or by

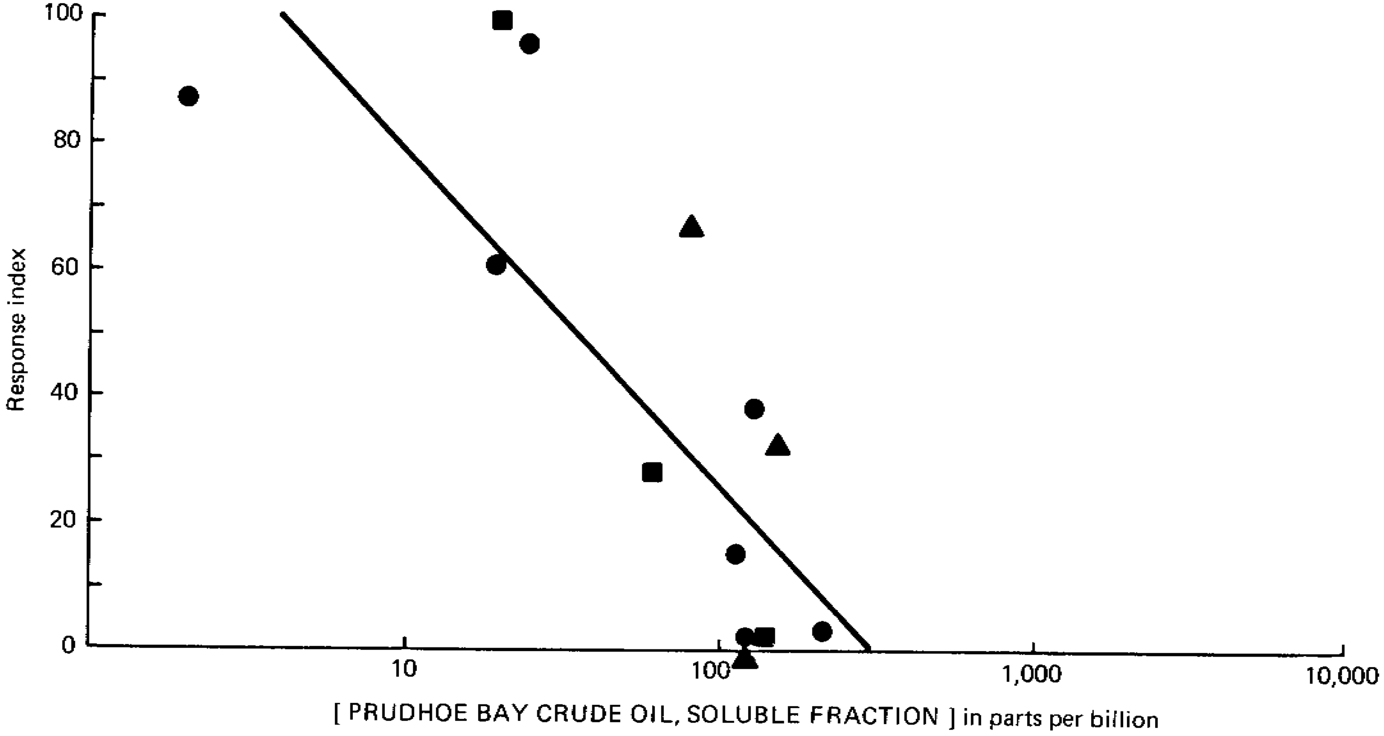

FIGURE 8. Concentration of the SWSF of PBCO and its effect on the pedicellarial response of the sea urchin. Exposure times: ●=24 hr; ■=48 hr; ▲=5-15 min. The 5-15 min exposures are not included in calculation of regression line. Regression equation is: Response Index=132-53 log (ppb SWSF).

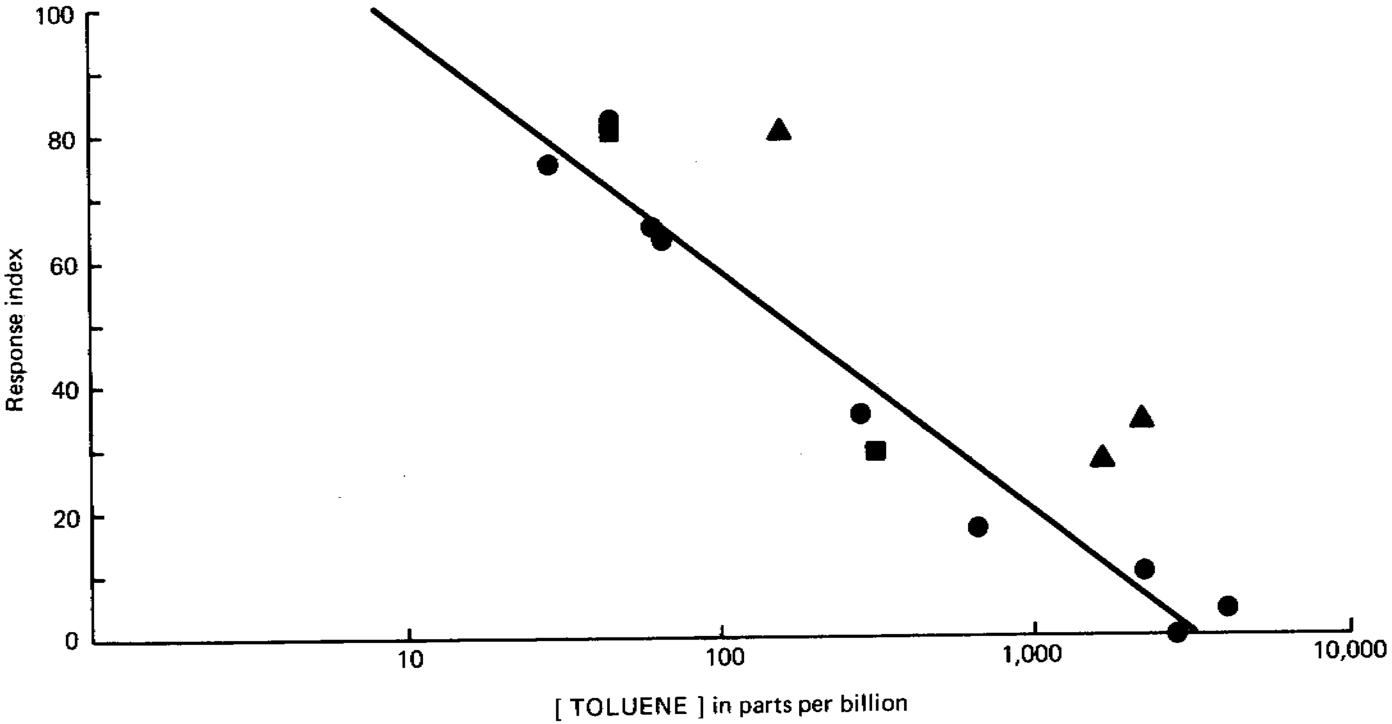

FIGURE 9. Concentration of toluene and its effect on the pedicellarial response of the sea urchin. Exposure times: ●=24 hr; ■=1 hr; ▲=5-15 min. The 5-15 min exposures are not included in calculation of the regression line. Regression equation is: Response Index=136-39 log (ppb toluene).

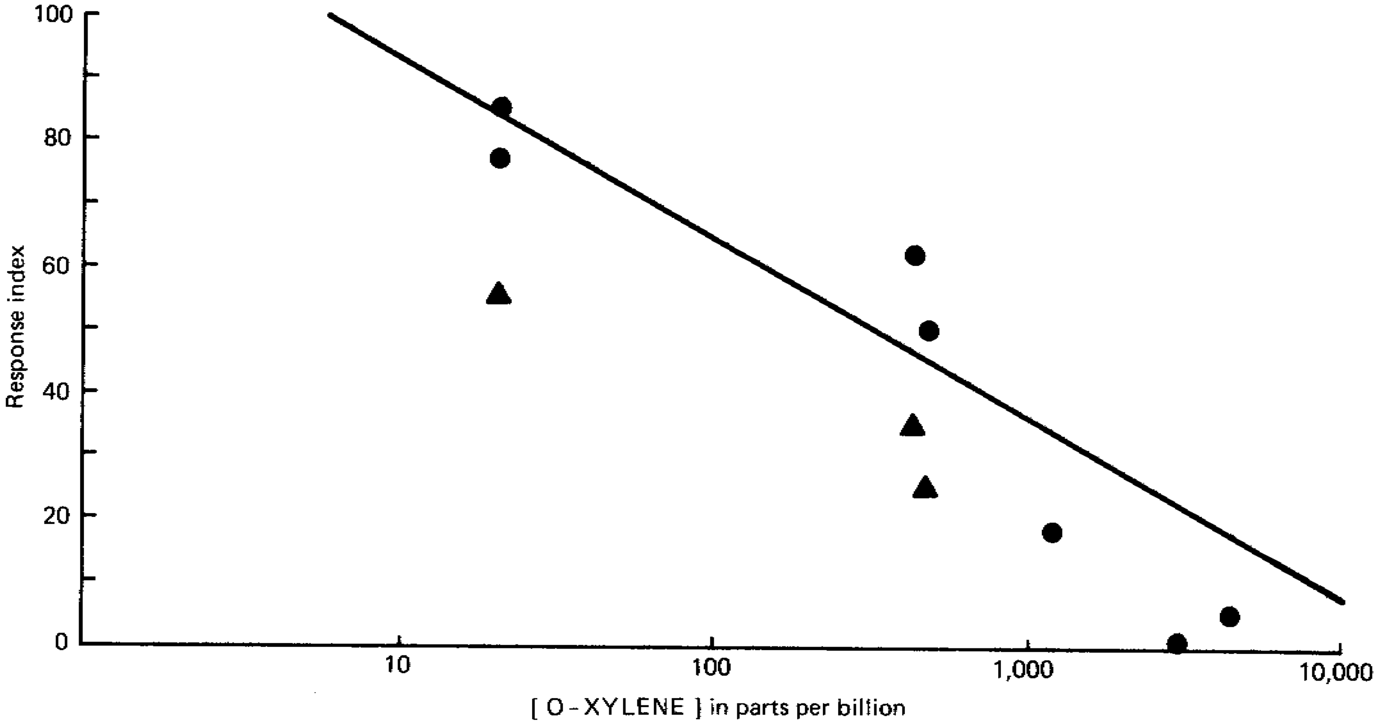

FIGURE 10. Concentration of o-xylene and its effect on the pedicellarial response of the sea urchin. Exposure times: ●=24 hr; ▲=5-15 min. The 5-15 min exposures are not included in calculation of regression line. Regression equation is: Response Index=120-28 log (ppb o-xylene).

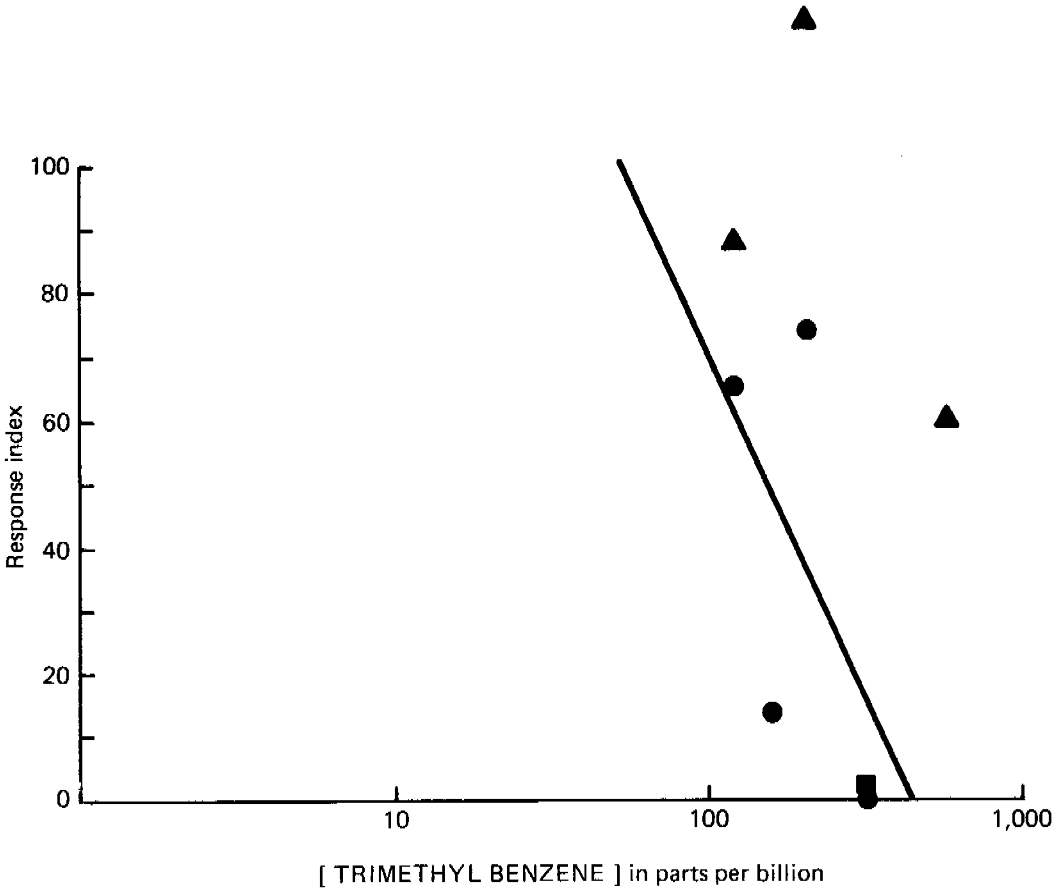

FIGURE 11. Concentration of 1,2,4-trimethylbenzene and its effect on the pedicellarial response of the sea urchin. Exposure times: ●= 24 hr; ▲=5-15 min. The 5-15 min exposures are not included in calculation of regression line. Regression equation is: Response Index=294-113 log (ppb trimethylbenzene).

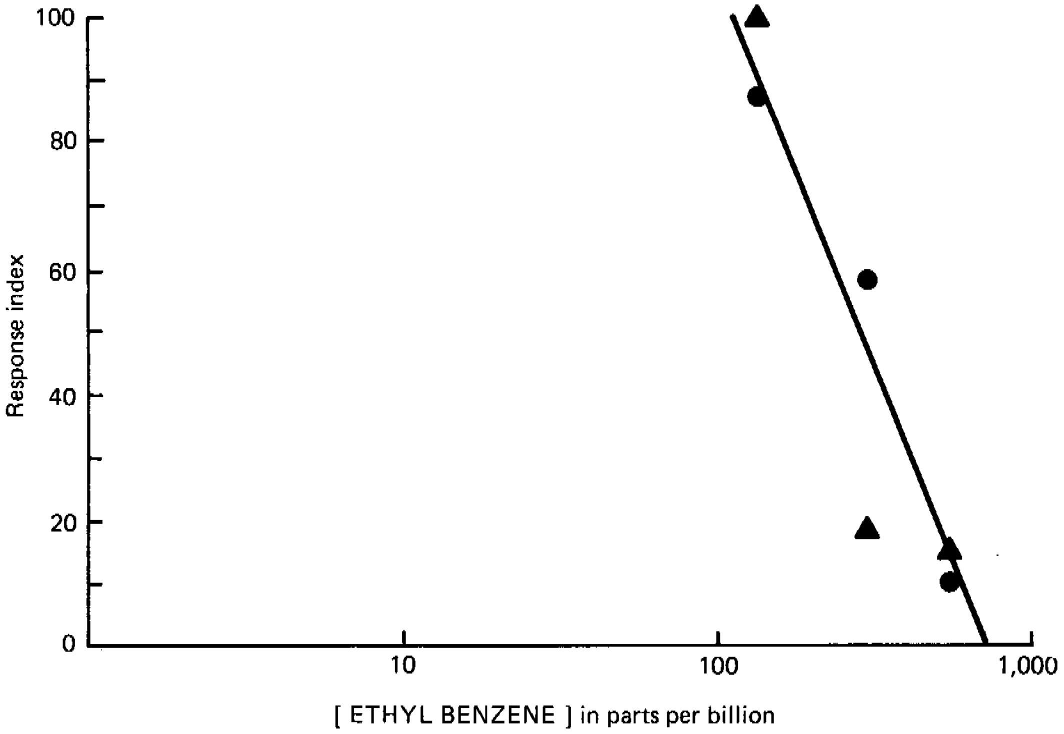

FIGURE 12. Concentration of ethyl benzene and its effect on the pedicellarial response of the sea urchin. Exposure times: ●=24 hr; ▲= 5-15 min. The 5-15 min exposures are not included in calculation of regression line. Regression equation is: Response Index=355-124 log (ppb ethyl benzene).

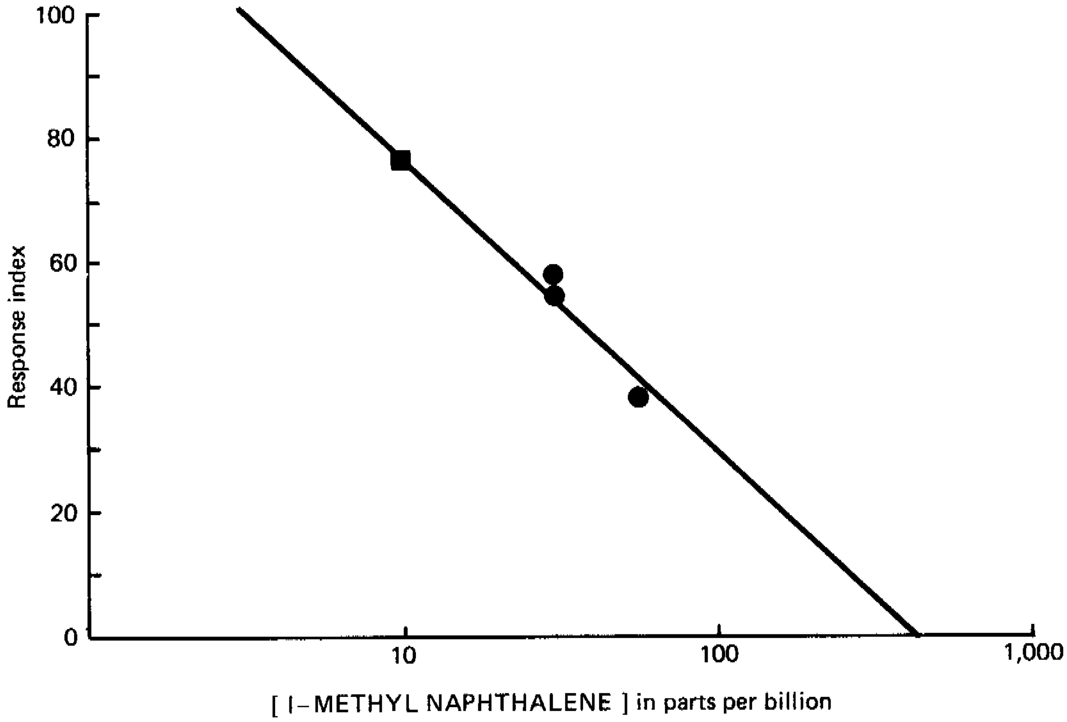

FIGURE 13. Concentration of 1-methylnaphthalene and its effect on the pedicellarial response of the sea urchin. Exposure times: ●=24 hr; ■=1 hr. Regression equation is: Response Index=124-48 log (ppb naphthalene).

Table 5. Hydrocarbon exposure conditions and sea urchin pedicellarial defensive response

Hydrocarbon	Test date	$\bar{x}$ hydrocarbon concentration		Average % response		Response Index $\frac{\bar{x} \text{ treated}}{\bar{x} \text{ control}}$	Exposure hr (min)
		ppm	log	treated	control		
SWSF	11/23/77	112	2.05	13	88	15	24
	12/08/77	62	1.79	25	89	28	48
	01/06/78	19	1.28	41	67	61	24
	02/09/78	130	2.11	29	76	38	24
	02/09/78	24	1.38	73	76	96	24
	02/15/78	140	2.15	1	41	2	48
	02/15/78	20	1.30	42	41	100	48
	02/16/78	2	0.30	68	78	87	24
	08/03/78	119	2.08	0	64	0	(5-15)
	08/04/78	119	2.08	1	53	2	24
	08/18/78	80	1.90	67	100	67	(5-15)
	11/20/78	151	2.18	24	75	32	(5-15)
	11/28/78	212	2.33	2	75	3	24
Toluene	04/07/78	4084	3.61	4	100	4	24
	04/12/78	2827	3.45	0	100	0	24
	04/13/78	662	2.82	11	63	12	24
	04/20/78	282	2.45	29	84	35	24
	04/26/78	62	1.79	51	78	65	24
	04/28/78	66	1.82	45	71	63	24
	05/02/78	694	2.84	22	75	29	1
	05/03/78	2222	3.35	5	49	10	24
	05/03/78	2222	3.35	21	62	34	(5-15)
	05/04/78	1706	3.23	21	74	28	(5-15)
	05/10/78	155	2.19	48	61	79	(5-15)
	05/16/78	14	1.15	48	64	75	24
	05/23/78	22	1.34	78	98	80	1
	05/24/78	22	1.34	78	92	82	24
o-Xylene	06/25/78	4329	3.64	4	77	5	(5-15)
	06/26/78	2954	3.47	0	71	0	(5-15)
	06/27/78	1200	3.08	18	100	18	24

Table 5 . continued.

Hydrocarbon	Test date	$\bar{x}$ hydrocarbon concentration		Average % response		Response Index	Exposure hr (min)
		ppm	log	treated	control	$\frac{\bar{x}\text{ treated}}{\bar{x}\text{ control}}$	
o-Xylene	07/06/78	472	2.67	22	89	25	(5-15)
	07/07/78	509	2.71	23	46	50	24
	07/08/78	435	2.64	62	100	62	24
	07/08/78	435	2.64	35	100	35	(5-15)
	07/11/78	21	1.32	85	100	85	24
	07/13/78	21	1.32	67	87	77	24
	07/13/78	21	1.32	48	87	55	(5-15)
1,2,4-Trimethylbenzene	08/02/78	579	2.76	36	60	60	(5-15)
	08/03/78	315	2.50	0	64	0	24
	08/03/78	315	2.50	1	64	2	(5-15)
	08/04/78	206	2.31	39	53	74	24
	08/04/78	206	2.31	65	53	123	(5-15)
	08/07/78	120	2.08	88	100	88	(5-15)
	08/08/78	120	2.08	52	80	65	24
	08/09/78	250	2.40	11	80	14	24
Ethyl benzene	08/16/78	548	2.74	7	68	10	24
	08/16/78	548	2.74	10	68	15	(5-15)
	08/17/78	296	2.47	26	45	58	24
	08/17/78	296	2.47	8	45	18	(5-15)
	08/18/78	135	2.13	87	100	87	24
	08/18/78	135	2.13	99	100	99	(5-15)
1-Methylnaphthalene	08/24/78	30	1.48	35	65	54	24
	08/25/78	10	1.00	31	41	76	1
	08/30/78	30	1.48	57	99	58	24
	08/31/78	57	1.76	36	96	38	24
Model SWSF mixture	09/07/78	79	1.90	29	77	38	24
	09/08/78	4	0.60	54	69	78	24
	09/13/78	190	2.28	73	100	73	24
	09/14/78	644	2.81	44	100	44	24

Table 6 . Response of sea urchin pedicellariae to starfish extract immediately after exposure to hydrocarbons and again after depuration in clean seawater

Hydrocarbon	Test date (1978)	$\bar{x}$ hydrocarbon concentration (ppb)	Exposure hr (min)	$\bar{x}$ Response (%)	Depuration (hr)	$\bar{x}$ Response post-depuration (%)
Benzene	5/17	250	1	25	24	18
	7/08	150	24	0	24	7
	7/09	150	24	0	48	29
	7/10	150	24	0	72	38
	7/11	150	24	0	96	79
Toluene	3/28	6900	4	0	264	41
	4/14	662	24	17	24	61
	4/19	662	24	17	120	100
	4/27	62	24	51	24	93
o-Xylene	6/26	2954	(5-15)	0	1	5
	6/27	2954	(5-15)	0	24	57
	7/06	2954	(5-15)	0	240	91
1,2,4-Trimethylbenzene	8/04	315	(5-15)	0	24	55
	8/09	120	24	52	24	64
	9/16	120	24	52	192	100
Ethylbenzene	8/17	548	(5-15)	7	24	100

Table 7. Effect of starfish exudate stimulus strength on pedicellarial response following exposure of sea urchins to hydrocarbons (benzene and o-xylene)

Hydrocarbon	Test date (1978)	$\bar{x}$ Hydrocarbon concentration (ppb)	Exposure hr (min)	Test 1		Test 2		Increase (%)
				Stimulus strength (%)	$\bar{x}$ response (%)[a]	Stimulus strength (%)	$\bar{x}$ response (%)	
Control	7/13	0	--	50	87	100	100	17
	7/14	0	--	50	88	100	100	14
Benzene	7/11	150	(5-15)	100	37	1000	79	88
o-Xylene	7/13	21	(5-15)	50	22	100	48	84
	7/13	21	24	50	54	100	67	24
	7/11	21	24	100	85	1000	100	18

[a] Average response of 5 sea urchins per test.

Table 8. Pedicellarial response of hydrocarbon-exposed sea urchins before and after KCl injection

Hydrocarbon	Test date (1978)	$\bar{x}$ Hydrocarbon concentration	Exposure hr (min)	$\bar{x}$ Response (%)[a]	$\bar{x}$ Response after KCl injection (%)
Control	8/03	0	--	64	100
	8/13	0	--	45	75
SWSF	8/03	119	(5-15)	0	100
	8/04	119	24	0	93
o-Xylene	7/13	21	(5-15)	48	100
Trimethylbenzene	8/04	206	24	39	100
Ethylbenzene	8/16	548	24	7	100
	8/17	296	24	26	91
Methylnaphthalene	8/31	57	24	36	100

[a] Average response of 5 or more sea urchins.

repeated stimuli) if the exposure duration is short (5-15 min). Following 24 hr exposure an increase in stimulus strength has a negligible effect comparable to controls.

Experiments were also conducted on excised pedicellariae from control and treated sea urchins. The stimulus concentration required to cause excised pedicellariae to open was at least 800 times greater than that provoking responses in intact urchins. For these tests a stronger starfish stimulus was prepared by freezing Pycnopodia in seawater, then thawing and decanting the resulting mixture. After exposing sea urchins for 24 hr to 1,400 ppb toluene, 50% (10 of 20) of the excised pedicellariae responded as compared with 95% (19 of 20) response for controls. After 24 hr exposure to 282 ppb toluene, 100% (20 of 20) of the excised pedicellariae responded; a response identical to control (100% response of 20 pedicellariae).

In order to determine the competence of the pedicellariae to respond, a KCl solution was injected into the body cavity of the sea urchins. Injections of 0.5 ml isotonic KCl into control urchins caused opening of the pedicellariae. In hydrocarbon-treated urchins that had shown reduced behavioral sensitivity, KCl injection also resulted in pedicellariae opening indicating that the pedicellariae were fully competent to respond if artificially provoked (Table 8).

In addition to the assays of defense behavior considered above, numerous observations of hydrocarbon-treated urchins were made concerning other types of activity. In general, urchins exposed to less than 1 ppm hydrocarbon were able to feed, respond to touch, adhere to the glass substrate, right themselves, and move about in an apparently normal fashion. No urchins were killed by the hydrocarbon treatments employed in this research, and narcosis was generally

Table 9. Rate of movement of control and toluene-exposed sea urchins in a trough with flowing seawater

Test date (1978)	$\bar{x}$ Hydrocarbon concentration (ppb)	Exposure (hr)	N[a]	Test period (min)	$\bar{x}$ Distance moved (cm) control	treated	$\frac{\text{treated}}{\text{control}}$
4/27	4400	24	10	30	5.2	0.3	0.06
4/27	4400	24	10	60	8.0	1.1	0.14
5/03	2222	24	10	15	13.0	9.2	0.71
5/04	1706	24	10	10	7.8	3.8	0.49
5/09	1656	24	10	10	8.2	2.4	0.29
5/02	690	24	20	30	7.3	2.8	0.38
5/02	690	24	17	60	11.0	9.8	0.89
5/10	156	24	10	10	3.2	6.0	1.88
4/28	66	24	10	30	7.4	9.2	1.28

[a] Number tested were equally divided between control and toluene-exposed sea urchins.

evident only at hydrocarbon concentrations approaching or exceeding 1 ppm. Table 9 presents data regarding the average rate of movement of urchins in clean, flowing seawater following exposure to toluene.

One behavioral difference was often apparent between control and hydrocarbon-treated urchins. Shortly after immersion in seawater containing dissolved hydrocarbons the aboral and lateral podia retracted from their normally extended position to an extent that related to the hydrocarbon concentration (Table 10).

In predator-prey experiments there was a significant difference (P=0.01) between the number of hydrocarbon-exposed urchins eaten by starfish and the number of control urchins eaten. Data for each of the four tests is given in Table 11.

CHEMISTRY

Force-feeding (starry flounder) at 12°C. Tissues of starry flounder contained considerable concentrations of both naphthalene and its metabolic products at 24 hr after the force-feeding of naphthalene (Fig. 5). Maxima in concentrations of both the hydrocarbon and its metabolic products occurred during the first 48 hr after the initiation of the treatment and then the concentrations of these compounds began to decline in all tissues but not in bile (Fig. 5). The statistical treatment of the data shows that the rates of decline of naphthalene concentration in liver, skin, and blood were significantly greater than the respective rates* of decline in metabolite concentrations (Fig. 5). At 168 hr, all sites examined, except brain, contained considerably more

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* As will be seen later, average molecular weight of the metabolic fraction increases with time (non-conjugates to conjugates). Therefore, differences between rates of decline in naphthalene and metabolite concentrations calculated on basis of parts-per-billion would be even larger than those calculated on basis of dpm/mg or pmole/mg.

Table 10. Percent extension of aboral and lateral podia of sea urchins following exposure to hydrocarbons

Hydrocarbon	Test date (1978)	$\bar{x}$ Hydrocarbon concentration (ppb)	Exposure hr (min)	% Podial extension (Normal=100)[a]
SWSF	2/15	140	48	0
	2/09	130	24	0
	2/09	24	24	50
	2/15	20	48	50
	2/16	2	24	60
Toluene	3/17	13826		0
	4/07	4084	24	0
	4/12	2827	24	0
	5/03	2222	24	20
	5/09	1656	24	20
	5/02	694	24	5
	4/13	662	24	70
	4/20	282	24	20
	4/28	66	24	100
	4/26	62	24	100
o-Xylene	6/25	4329	(5-15)	0
	7/08	435	24	100
	7/13	21	24	100

[a] Group of 5 or more sea urchins for each test.

Table 11. Hydrocarbon exposure conditions and the number (in percent) of sea urchins eaten by Pycnopodia in predator-prey experiments

Test date (1978)	$\bar{x}$ SWSF hydrocarbon concentration (ppb)	Exposure (hr)	Test period (hr)	Treated		Control	
				N	% eaten	N	% eaten
11/20	151	24	24	5	60	5	40
11/28	212	24	1.5	5	100	5	40
12/01	80	24	2	5	100	5	60
12/07	202	24	2	7	100	7	43
			$\bar{x}$		88		49

radioactivity associated with metabolic products than with naphthalene (Fig. 5, Table 12), more than 70% of the total radioactivity in blood, liver, and skin was associated with the metabolic products. Radioactivity in the epidermal mucus and bile of starry flounder was largely due to the metabolic fraction throughout the experiment.

Force-feeding study (rock sole) at 12°C. Comparison of the data in Figures 5 and 14 revealed that the radioactivity in all tissues of rock sole was considerably greater than the radioactivity in the corresponding tissues of starry flounder at 24 hr. Moreover, values for naphthalene and metabolite concentrations in tissues of rock sole were significantly ($P<0.01$) higher than the corresponding values for starry flounder at 168 hr. Liver, skin, and muscle of starry flounder contained 11.6, 3.0, and 1.7 g of lipid, respectively, per 100 g of wet tissue; whereas, liver, skin, and muscle of rock sole contained 4.3, 1.5, and 1.0 g of lipid, respectively, per 100 g of wet tissue.

Differences between rates of decline in naphthalene and the metabolite concentrations in liver, blood, and skin of rock sole were also measured. As with starry flounder, the rate of decline in naphthalene concentration in each tissue was greater than the rate of decline in metabolite concentration (Fig. 14). It was also determined that the extent of decline of naphthalene in each of the tissues was greater for starry flounder than for rock sole. From 24 to 168 hr, there was 12.4- and 2.3-fold decrease, respectively, in naphthalene and metabolite concentrations in the livers of rock sole; corresponding values for starry flounder were 63.0 and 2.6.

Stomach and intestine of rock sole contained more radioactivity than those of starry flounder at both 24 and 168 hr. At 24 hr, stomach and intestine of the rock sole contained 0.3 and 6.0%, respectively, of the administered dose, whereas, the corresponding values for starry flounder were 0.2 and 1.5.

Because considerable radioactivity was present in the rock sole after one week, some fish were sampled at 6 wk after the treatment. Results (Fig. 14) were that gills and kidney still contained considerable concentrations of metabolic products and bile and liver contained much smaller, but detectable concentrations of metabolic products. Barely any radioactivity was detected in other tissues at this time.

Injection study (starry flounder) at 12°C. At 24 hr after an intraperitoneal injection of tritiated naphthalene (56 μCi) dissolved in salmon oil, livers of starry flounder contained considerably higher concentrations of naphthalene than did livers of the fish in the force-feeding study (Figs. 5, 15). At 168 hr, livers of fish in the injection study contained 16 times as much naphthalene and 1.2 times as much metabolites as livers of the force-fed fish. For a period of 24 hr to 168 hr after the treatment, the decrease in the naphthalene concentration in the liver of fish in the injection study was 9.3-fold and in the feeding study it was 63-fold; the values for decline in the metabolite concentrations were 1.1 and 2.6, respectively (Figs. 5, 15).

Force-feeding study (starry flounder) at 4°C. Data in Table 13 demonstrate that at 24 hr after the initiation of exposure, naphthalene was widely distributed in tissues and body fluids of fish held at 4°C. Tissue concentrations of naphthalene were 1.6 to 15 times higher than those in corresponding tissues of fish at 12°C. At 24 hr, largest differences ($P<0.05$) were observed for liver, stomach, and intestine; for example, 7.8, 9.8, and 15.0 times, respectively, more naphthalene was present in these tissues at 4°C than in those at 12°C. As with fish at 12°C, tissue concentrations of naphthalene and its metabolic products at 4°C were much lower at 168 hr than at 24 hr; however, the rate of decline in naphthalene concentrations from 24 to 168 hr was much greater at 12°C than at 4°C as shown by even larger differences between naphthalene concentrations

Table 12. Total radioactivity (expressed as % administered dose) and distribution of naphthalene and its metabolites in pleuronectids exposed to ^{3}H-naphthalene

Treatment	Species and # of samples		Time after treatment (hr)	STOMACH			LIVER			SKIN			BRAIN			MUSCLE			BILE			INTESTINE		
				% dose	N[a]	M[a]	% dose	N	M	% dose	N	M	% dose	N	M	% dose	N	M	% dose	N	M	% dose	N	M
Force-feeding	R.S.[b]	6	24	0.30[c] ±0.06	55	45	1.8 ±1.5	84	16	1.0 ±0.6	73	27	0.06 ±0.004	85	15	3.4 ±0.5	68	32	1.7 ±0.6	5	95	6.0 ±3.2	63	37
		6	48	--[d]	--	--	0.4 ±0.3	62	38	0.5 ±0.4	57	43	--	--	--	--	--	--	2.2 ±1.6	2	98	--	--	--
		6	168	0.03 ±0.01	29	71	0.12 ±0.05	49	51	0.08 ±0.02	50	50	0.01 ±0.001	74	26	0.3 ±0.04	57	43	1.4 ±0.8	1	99	0.2 ±0.05	65	35
Force-feeding	S.F.	4	24	0.20 ±0.10	64	36	0.7 ±0.5	85	15	0.4 ±0.2	75	25	0.04 ±0.02	89	11	1.3 ±0.4	65	35	0.2 ±0.2	14	86	1.5 ±0.8	62	38
		4	48	--	--	--	0.3 ±0.5	76	24	0.11 ±0.04	45	55	--	--	--	--	--	--	0.9 ±0.4	3	97	--	--	--
		4	168	0.05 ±0.02	5	95	0.02 ±0.01	19	81	0.02 ±0.01	26	74	0.003 ±0.001	59	41	0.09 ±0.02	27	73	0.9 ±0.4	2	98	0.19 ±0.06	9	91
ip injection	S.F.	3	24	--	--	--	3.6 ±0.4	97	3	0.38 ±0.12	84	16	--	--	--	--	--	--	0.49 ±0.04	7	93	--	--	--
		3	168	--	--	--	0.4 ±0.1	76	24	0.06 ±0.01	79	21	--	--	--	--	--	--	2.3 ±0.09	1	99	--	--	--

[a] Relative % of N=naphthalene and M=total metabolites.

[b] R.S.=Rock sole; S.F.=Starry flounder.

[c] Mean ± S.E.

[d] Not done.

[From Varanasi et al. 1979a]

Table 13. Naphthalene and its metabolites in naphthalene-exposed starry flounder at 4°C

Tissue	NAPHTHALENE pmoles/mg dry wt.	NAPHTHALENE $[C_{4°}/C_{12°}]$[a]	NAPHTHALENE % admin. dose[b]	METABOLITES pmoles/mg dry wt.	METABOLITES $[C_{4°}/C_{12°}]$[c]	METABOLITES % admin. dose
	24 hr after feeding ^{3}H-naphthalene[d]					
Liver	35.7 ± 10.8[d]	[7.8]	6.7 ± 1.6	1.2 ± 0.4	[1.4]	0.22 ± 0.04
Muscle	1.9 ± 0.6	[5.6]	5.1 ± 1.3	0.4 ± 0.1	[2.1]	1.10 ± 0.02
Bile	6.2 ± 2.0	[3.3]	0.09 ± 0.01	24.7 ± 6.8	[2.2]	0.39 ± 0.05
Stomach	17.7 ± 8.9	[9.8]	1.30 ± 0.60	2.9 ± 1.4	[2.9]	0.22 ± 0.09
Intestine	86.1 ± 31.2	[15]	30.80 ± 12.7	9.5 ± 1.4	[2.7]	3.07 ± 0.48
Skin	1.2 ± 0.4	[3.6]	1.02 ± 0.3	0.2 ± 0.1	[1.6]	0.16 ± 0.03
Brain	6.5 ± 2.0	[2.2]	0.08 ± 0.03	0.4 ± 0.1	[1.1]	0.005 ± 0.001
Blood	1.1 ± 0.4	[1.9]	---	0.9 ± 0.2	[2.5]	---
Kidney	2.5 ± 0.6	[1.6]	---	1.7 ± 0.5	[1.3]	---
Gills	2.5 ± 0.6	[3.7]	---	0.7 ± 0.2	[3.0]	---
Mucus	0.4 ± 0.1	[5.1]	---	0.3 ± 0.1	[2.1]	
	168 hr after feeding ^{3}H-naphthalene					
Liver	2.75 ± 0.82	[34]	0.57 ± 0.16	0.52 ± 0.18	[1.6]	0.09 ± 0.03
Muscle	0.34 ± 0.11	[26]	1.30 ± 0.58	0.12 ± 0.04	[3.6]	0.33 ± 0.10
Bile	2.42 ± 0.97	[1.3]	0.04 ± 0.01	74.5 ± 35.3	[0.7]	1.21 ± 0.47
Stomach	0.42 ± 0.11	[4.2]	0.03 ± 0.004	0.28 ± 0.08	[0.1]	0.02 ± 0.003
Intestine	0.57 ± 0.16	[3.4]	0.14 ± 0.03	0.53 ± 0.17	[0.3]	0.14 ± 0.04
Skin	0.12 ± 0.02	[10]	1.30 ± 0.03	0.06 ± 0.02	[2.0]	0.06 ± 0.01
Brain	0.77 ± 0.29	[5.6]	0.010 ± 0.004	0.11 ± 0.04	[1.1]	0.0014 ± 0.0006
Blood	0.10 ± 0.03	[9.6]	---	0.36 ± 0.09	[5.6]	---
Kidney	0.29 ± 0.07	[4.8]	---	0.55 ± 0.18	[1.6]	---
Gills	0.28 ± 0.09	[7.0]	---	0.21 ± 0.06	[1.9]	---

[a] Ratio of concentration of naphthalene at 4° and 12°C.

[b] % administered dose was calculated using individual concentration value and total weight of each organ; each value for % admin. dose is mean ± S.E. (6 fish).

[c] Ratio of concentration of metabolites at 4° and 12°C.

[d] Fish were fed 56 μCi (198 mCi/mMole) each of ^{3}H-1-naphthalene.

[e] Average value for six fish ± S.E.

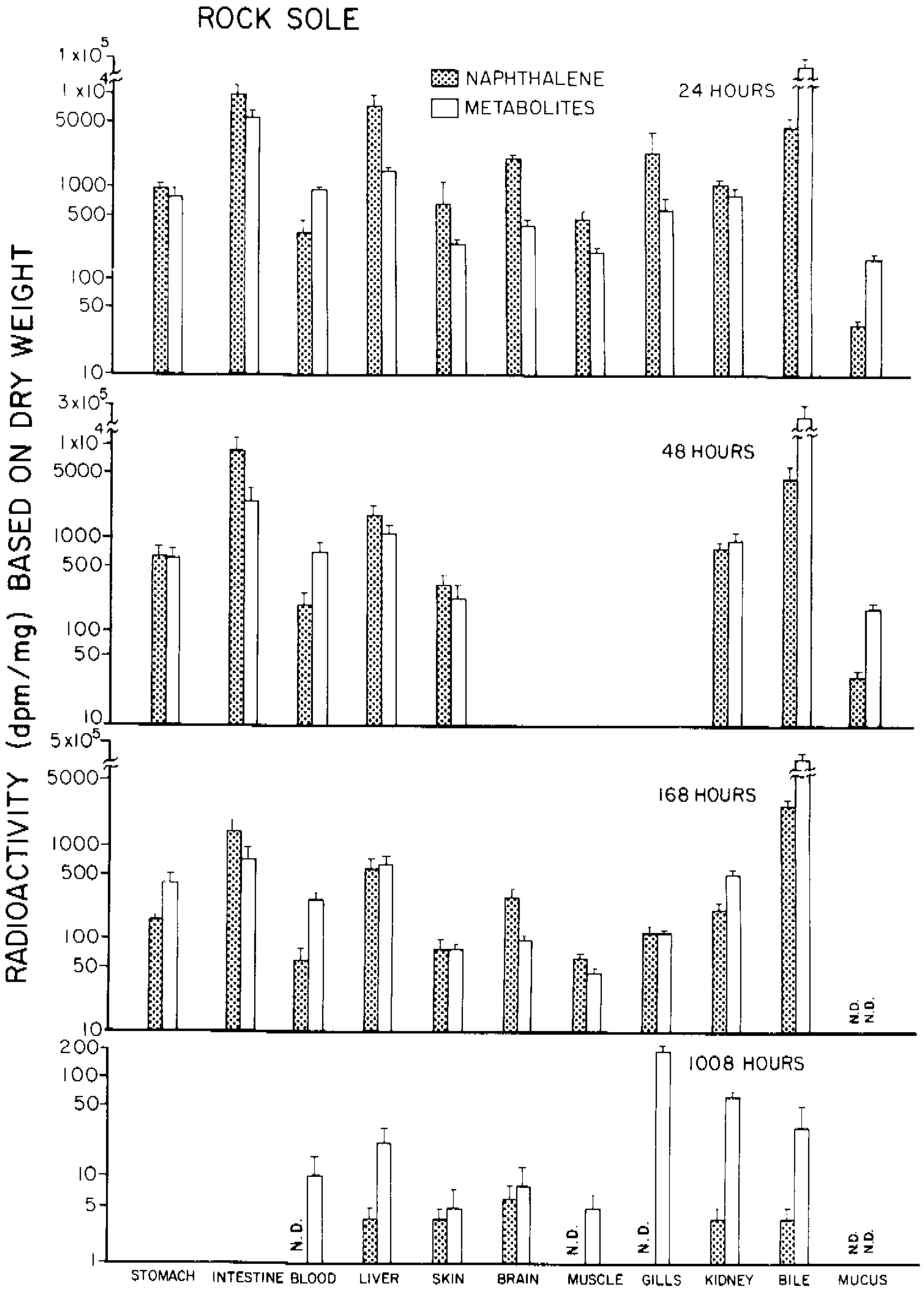


FIGURE 14. Concentrations of naphthalene and its metabolites in tissues of rock sole at 24, 48, 168, and 1008 hr after the feeding of 56 μCi of 1-^{3}H-naphthalene. Other pertinent details are given in Figure 5 and Table 12. Regression coefficient for rates of decline of N and M was for liver, b(N)=1.999, b(M)=0.530; for skin, b(N)=0.771, b(M)=0.558; and for blood, b(N)=0.812, b(M)=0.601. N.D.=not detected. [Varanasi et al. 1979a]

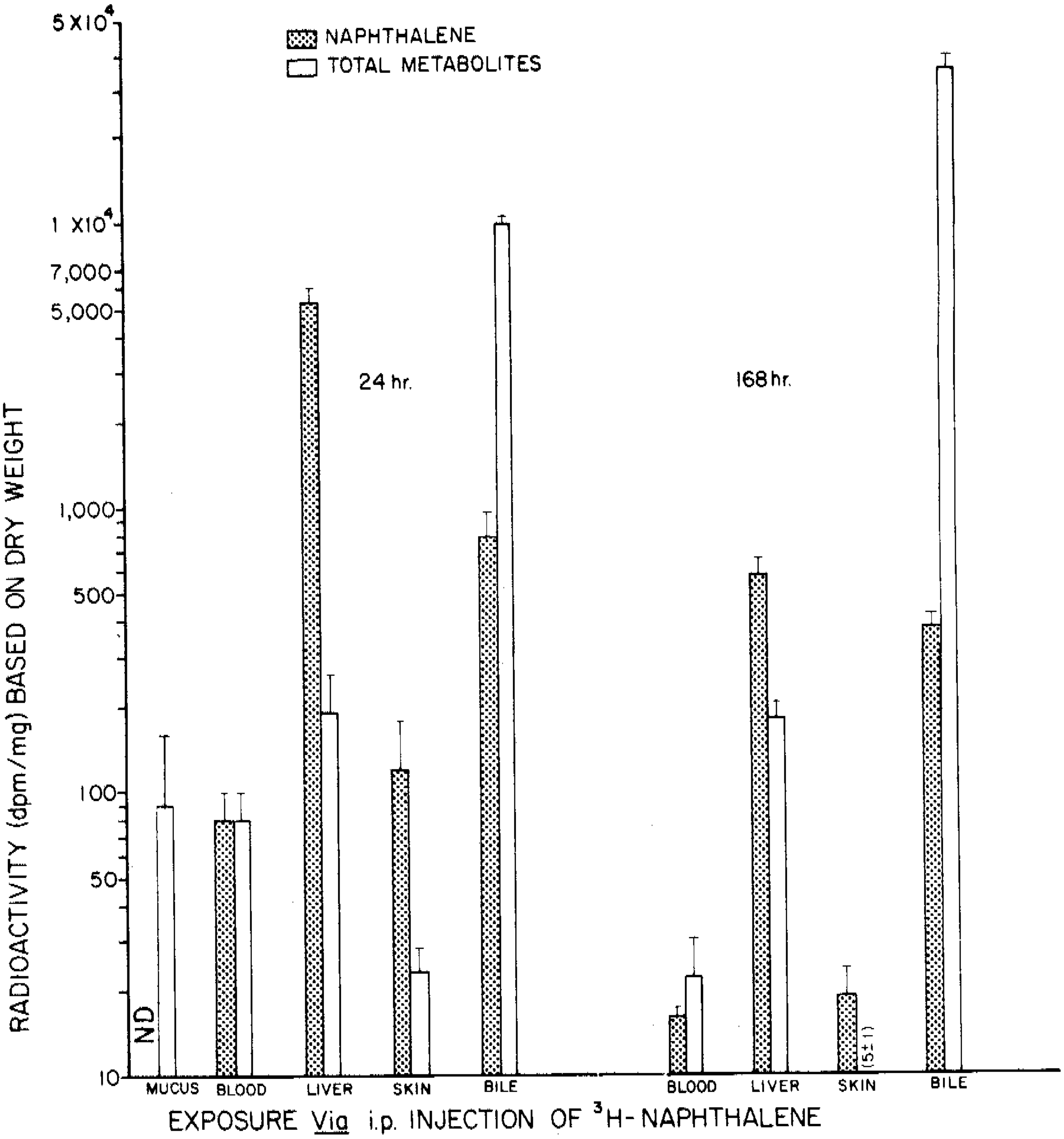


FIGURE 15. Concentrations of naphthalene and its metabolites in tissues of starry flounder at 24 and 168 hr after the intraperitoneal injections of 56 μCi of 1-^{3}H-naphthalene. Other pertinent details are given in Figure 5 and Table 12. [Varanasi et al. 1979a]

in the two groups of fish at 168 hr. For example, at 168 hr, naphthalene concentrations in liver, muscle, and brain were, respectively, 34, 26, and 5.6 times greater in fish at 4°C than those at 12°C (Table 13).

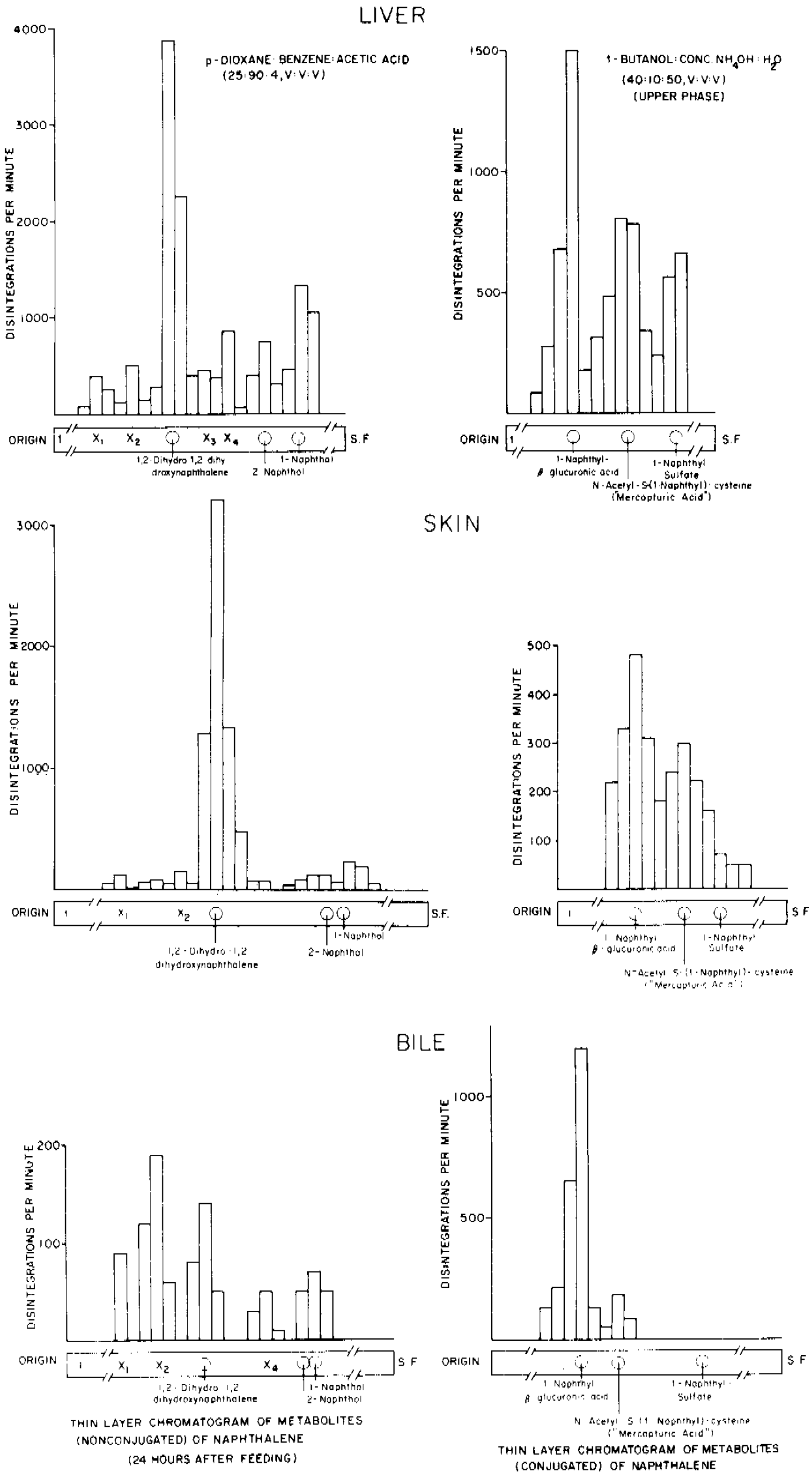
Results show that at 24 hr, concentrations of metabolites (pmole/mg) were not substantially higher in all tissues at the lower temperature. For example, compared to fish at 12°C, muscle, but not liver, of fish at 4°C contained significantly ($P<0.05$) higher metabolite concentrations. An interesting finding was that while ratios of values for naphthalene concentrations in most tissues of fish at 4° vs. 12°C increased markedly from 24 to 168 hr, such an increase was not observed for the metabolite concentrations.

Profiles of metabolites

The chromatograms in Figure 16 show profiles of metabolites in liver, skin, and bile from a rock sole at 12°C. Results in Tables 14 and 15 are given as the mean of four individual samples. The bile from both rock sole (Table 14) and starry flounder (Table 15) contained primarily glucuronic acid derivatives at 24 and 168 hr after feeding of naphthalene. Small amounts of the mercapturic acid derivatives were also detected. The sulfate/glucoside fraction was either not detected or was present in very small amounts in the bile. Non-conjugated metabolites such as 1- and 2-naphthols and 1,2-dihydro-1,2-dihydroxynaphthalene constituted less than 10% of total extracted metabolites. 1- and 2-Naphthols were not always clearly resolved in our solvent system and therefore, combined values for concentrations (pmoles/mg) of these two isomers are given for all samples. No statistically significant changes were observed in the spectrum of biliary metabolites with time (Tables 14 and 15).

In liver of rock sole, 1,2-dihydro-1,2-dihydroxynaphthalene was the major metabolite (38.7%) at 24 hr after feeding of the naphthalene. Considerable proportions (31.9%) of conjugates (e.g., glucuronides, mercapturic acids and sulfate/glucosides) were also present in liver (Fig. 16, Table 14). Although profiles of metabolites in liver and skin were qualitatively similar, 1,2-dihydro-1,2-dihydroxynaphthalene was present in much larger proportions (59.7%) in skin than in liver of rock sole (Table 14). When chromatograms were developed in the solvent system A for resolution of the non-conjugated metabolites, there were four bands (x_1-x_4) whose R_f values did not match with those of the available standards. From 24 to 168 hr, the proportion of the dihydrodiol derivative decreased and that of the conjugates increased in the liver. Therefore, at 168 hr as much as 54.5% of the total metabolites in the liver of rock sole were in the form of conjugates, and the dihydrodiol represented 6.8% of total metabolites. In starry flounder liver, the diol was the major component (39.5%) at 24 hr after feeding; however, the glucuronides also were present in a substantial amount (32.1%) (Table 15). In starry flounder liver, conjugates constituted as much as 42.6% of the total extracted metabolites at 24 hr, and this value increased to 62.3% at 168 hr; the dihydrodiol comprised 12.3% of the total metabolites at this time. Profiles of metabolites in the skin of starry flounder were similar to that in the skin of rock sole (Table 14) and were characterized by the presence of large amounts (44.1%) of 1,2-dihydro-1,2-dihydroxynaphthalene.

Analyses of the metabolites in the liver of starry flounder exposed to the naphthalene via an intraperitoneal injection show that at 24 hr, liver contained primarily non-conjugated metabolites of naphthalene (76.7%), and the 1,2-dihydro-1,2-dihydroxynaphthalene (41.5%) and naphthols (21.3%) were the major components (Table 16). Once again, with time, there was an increase in the proportion of conjugated metabolites in liver; at 168 hr, the liver contained 66.2% of non-conjugated and 33.8% of conjugated metabolites. Comparison of data from Tables



THIN LAYER CHROMATOGRAM OF METABOLITES
(NONCONJUGATED) OF NAPHTHALENE
(24 HOURS AFTER FEEDING)

THIN LAYER CHROMATOGRAM OF METABOLITES
(CONJUGATED) OF NAPHTHALENE
(24 HOURS AFTER FEEDING)

FIGURE 16. Profiles of metabolites in liver, skin, and bile of a rock sole. [Varanasi et al. 1979a]

Table 14. Metabolites in rock sole exposed to dietary naphthalene at 12°C

Metabolites	LIVER[a]		BILE		SKIN	
	% of total[b] metabolites	pmoles/mg dry wt.	% of total[b] metabolites	pmoles/mg dry wt.	% of total[b] metabolites	pmoles/mg dry wt.
24 hr after feeding of ^{3}H-naphthalene						
Total conjugates	31.9±2.7[c]	0.88±0.21	92.8±0.4	172.6±0.8	18.2±9.4	0.08±0.06
Total non-conjugates	68.1±2.7[c]	2.08±0.01	7.2±0.4	13.4±0.8	81.8±9.4	0.3 ±0.1
Glucuronide	12.8±0.6	0.37±0.06	80.7±0.9	150.1±1.6	8.6±4.1	0.04±0.03
Mercapturic acid	14.2±3.1	0.41±0.16	11.0±0.7	19.7±0.2	5.6±1.6	0.02±0.01
Sulfate/glucoside	4.1±1.5[c]	0.11±0.01	1.1±0.2	2.0±0.3	4.1±4.0	0.02±0.03
Dihydrodiol	38.7±5.0[c]	1.19±0.15	3.5±0.2	6.5±0.4	59.7±2.9	0.23±0.09
Naphthols (1- & 2-)	16.1±4.4	0.51±0.13	0.8±0.1	1.5±0.2	10.7±2.7	0.04±0.01
Unidentified (X_1-X_4)	13.4±3.0	0.34±0.03	2.9±0.5	5.4±1.0	11.5±5.9[d]	0.04±0.01
168 hr after feeding of ^{3}H-naphthalene						
Total conjugates	54.5±2.6	0.65±0.06	96.2±0.1	714.3±1.1		
Total non-conjugates	45.5±2.6	0.56±0.10	3.8±0.1	28.2±1.1		
Glucuronide	27.2±6.9	0.32±0.06	85.9±0.9	637.8±6.4		
Mercapturic acid	13.3±2.4	0.16±0.05	8.5±0.8	63.2±5.9		
Sulfate/glucoside	14.0±2.9	0.18±0.07	1.8±0.1	13.4±0.5		
Dihydrodiol	6.8±5.4	0.09±0.08	1.4±0.2	10.0±1.1		
Naphthols	29.3±9.3	0.34±0.09	0.7±0.1	5.6±0.5		
Unidentified (X_1-X_4)	9.5±6.3	0.13±0.10	1.7±0.1	12.6±0.4		

[a] Each value is mean ± s.d. of four samples.

[b] Based on total extracted metabolites, an average of 8, 10, and <0.5% of total radioactivity, respectively, remained in liver, skin, and bile.

[c] Significantly ($P<0.001$) different from corresponding value at 168 hr.

[d] Only X_1 and X_2 were present in skin.

[From Varanasi et al. 1979a]

Table 15. Metabolites in starry flounder exposed to dietary naphthalene at 12°C

Metabolites	LIVER[a]		BILE		SKIN	
	% of total metabolites	pmoles/mg dry wt.	% of total metabolites	pmoles/mg dry wt.	% of total metabolites	pmoles/mg dry wt.
	24 hr after feeding of ^{3}H-naphthalene					
Total conjugates	43.6± 9.9[b]	0.54±0.39	91.8±0.3	4.83±0.01	24.0±1.6	0.04±0.01
Total non-conjugates	56.4± 9.9[b]	0.62±0.21	8.2±0.3	0.44±0.01	76.0±1.6	0.12±0.01
Glucuronide	32.2± 7.2	0.40±0.30	81.6±0.1	4.29±0.01	12.5±0.4	0.02±0.01
Mercapturic acid	9.5± 3.6	0.12±0.10	8.9±0.1	0.47±0.01	9.7±2.1	0.01±0.01
Sulfate/glucoside	1.9± 0.1[b]	0.01±0.03	1.4±0.1	0.07±0.01	1.7±2.5	0.01±0.01
Dihydrodiol	39.7±13.9[b]	0.41±0.04	4.0±0.1	0.21±0.01	44.1±1.3	0.07±0.01
Naphthols (1 & 2-)	10.7± 3.9	0.14±0.12	1.5±0.1	0.08±0.01	11.7±0.4	0.02±0.01
Unidentified (X_1-X_4)	6.0± 0.7	0.07±0.05	2.6±0.3	0.14±0.02	20.3±3.3	0.03±0.01
	168 hr after feeding of ^{3}H-naphthalene					
Total conjugates	62.3± 8.8	0.15±0.03	91.5±0.3	42.6±0.1		
Total non-conjugates	37.7± 8.8	0.10±0.05	8.5±0.3	4.0±0.1		
Glucuronide	16.6± 1.6	0.04±0.01	81.7±0.3	38.2±0.1		
Mercapturic acid	10.9± 6.6	0.03±0.03	8.8±0.1	4.1±0.1		
Sulfate/glucoside	34.8±14.8	0.08±0.02	0.9±0.1	0.4±0.1		
Dihydrodiol	12.4±11.7	0.03±0.05	3.0±0.1	1.4±0.1		
Naphthols	11.5± 3.9	0.03±0.02	2.9±0.2	1.4±0.1		
Unidentified (X_1-X_4)	14.0± 7.1	0.03±0.01	2.6±0.1	0.1±0.1		

[a] See Figure and Table for details.

[b] Significantly ($P<0.05$) different from corresponding values at 168 hr.

[From Varanasi et al. 1979a]

Table 16. Metabolites in starry flounder exposed to ^{3}H-naphthalene via intraperitoneal injection at 12°C[a]

Metabolites	LIVER % of total metabolites	LIVER pmoles/mg dry wt.	BILE % of total metabolites	BILE pmoles/mg dry wt.
		24 hr after the injection		
Total conjugates	23.2±1.7[b]	0.099±0.007	96.9±0.7	21.70±0.16
Total non-conjugates	76.7±1.7[b]	0.328±0.007	3.1±0.7	0.70±0.16
Glucuronide	8.3±0.7	0.036±0.003	88.7±0.1	19.87±0.03
Mercapturic acid	N.D.	N.D.	7.0±0.1	1.57±0.01
Sulfate/glucoside	15.0±0.7	0.064±0.003	1.2±0.1	0.26±0.02
Dihydrodiol	41.5±1.4[b]	0.178±0.006	1.8±0.3	0.42±0.07
Naphthols (1- & 2-)	21.3±0.8	0.091±0.003	0.1±0.2	0.01±0.01
Unidentified (X_1-X_4)	13.8±0.5	0.059±0.002	1.2±0.4	0.28±0.10
		168 hr after the injection		
Total conjugates	33.8±1.5	0.13±0.01	97.5±0.4	108.9±0.5
Total non-conjugates	66.2±1.5	0.25±0.01	2.5±0.4	2.8±0.5
Glucuronide	9.7±0.3	0.04±0.01	89.5±0.5	100.0±0.6
Mercapturic acid	N.D.	N.D.	6.7±0.4	7.5±0.5
Sulfate/glucoside	24.1±0.3	0.09±0.01	1.3±0.1	1.4±0.1
Dihydrodiol	29.1±8.3	0.11±0.03	0.8±0.1	0.9±0.1
Naphthols	20.7±5.2	0.08±0.02	0.6±0.2	0.7±0.2
Unidentified (X_1-X_4)	16.5±4.6	0.06±0.02	1.0±0.3	1.2±0.3

[a] See footnotes under Figure and Table for details.

[b] Significantly ($P<0.05$) different than corresponding values at 168 hr.

[From Varanasi et al. 1979a]

15 and 16 reveals that, whereas profiles of metabolites in the livers of starry flounder from the feeding and injection studies were quite different, biliary metabolites were similar for fish in both studies, and did not change significantly with time.

Data in Table 17 give concentrations and proportions of metabolite classes present in liver, muscle, and bile of starry flounder at 4° and 12°C. From 24 to 168 hr, there was a decrease in the proportion of the dihydrodiol fraction (same R_f value as 1,2-dihydro-1,2-dihydroxynaphthalene) and an increase in sulfate/glucoside fraction in both liver and muscle of fish at 4°C. At 24 hr, muscle of fish at both temperatures contained greater than 75% of total metabolites in the form of the dihydrodiol (Fig. 17). Even at 168 hr, the dihydrodiol constituted approximately half of the total metabolites; at this time muscle of fish at the lower temperature contained larger proportion of the dihydrodiol fraction. Metabolites in bile of both groups of fish at 24 and 168 hr were characterized by high proportions (>85%) of conjugates. Very small proportions (<10%) of the dihydrodiol and naphthols were present in bile at any time.

Comparison of profiles of metabolites in tissues of fish at 4° and 12°C reveal that at 24 hr, liver of fish at the lower temperature contained slightly higher proportion of the dihydrodiol fraction and a lower proportion of the glucuronide fraction. No distinct differences in proportions of metabolites were observed in muscle of fish at 4° and 12°C at this time. At one week after the initiation of naphthalene exposure, both liver and muscle of fish at 4°C contained considerably higher proportion of the dihydrodiol fraction than the proportion present in the corresponding tissues of fish at 12°C. Moreover, proportions of sulfate/glucoside fraction and naphthols were considerably lower in both the muscle and liver of fish at the lower temperature.

MORPHOLOGY

Lenses from an experimental group of laboratory-reared rainbow trout fed petroleum-treated food for three years, and lenses from a parallel control group of fish not fed petroleum were observed using SEM and TEM. Cataracts were found in three of five experimental trout and no lens anomalies were evident in three control fish. Lenses from both groups of fish were approximately the same volume: 0.53 ± 0.29 mm^3 in exposed fish and 0.44 ± 0.14 mm^3 in the controls. The damaged eyes had distinct opaque patches in the anterior equatorial area of the lens which included from 1/4 to 1/2 of the total lens diameter. With light microscopy, these appeared as plaques of uniformly opaque material. In addition there were groups of light-dispersing particles within lobate, translucent vesicles which radiated from a central zone near the opaque areas.

A detailed description and illustration of ultrastructural characteristics of cataractous lenses is presented in the Appendix section of this report.

Starry flounder and pink salmon eggs were examined with SEM and TEM to determine differences in egg membrane structure. In both species, the membrane was composed of a primary layer, the zona radiata, and lacked a secondary membrane or zona pellucida.

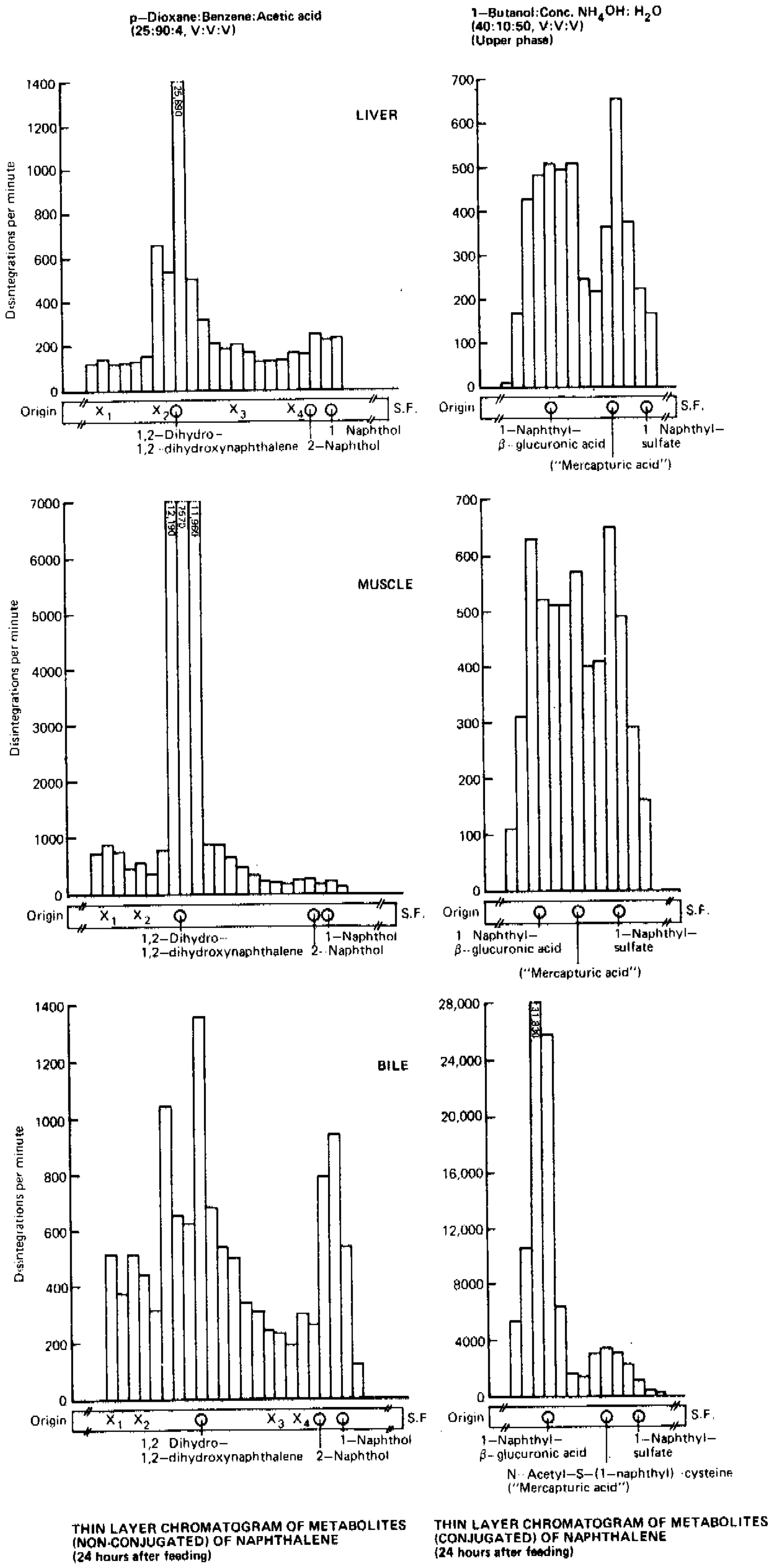
A detailed description of the structure of egg membranes of pink salmon and starry flounder is also presented in the Appendix section of this report.

The major ultrastructural changes found in liver were illustrated in the previous OCSEAP Annual Report for RU 73 and additional plates will not be presented here. See Pathology section of this report for further discussion of these findings.

Table 17. Comparison of metabolite profiles in starry flounder exposed to dietary naphthalene at 4° and 12°C

Metabolites	LIVER			BILE			MUSCLE		
	% of total metabolites		pmoles/mg dry wt.	% of total metabolites		pmoles/mg dry wt.	% of total metabolites		pmoles/mg dry wt.
	4°C[a]	12°C[b]		4°C[a]	12°C[b]		4°C[a]	12°C	
				24 hr after feeding of ^{3}H-naphthalene					
Total conjugates	27.1 ± 1.8[c]	43.6 ± 9.9	0.26[d]	86.5 ± 1.6	91.8 ± 0.3	21.4[d]	11.5 ± 0.3[c]	9.5 ± 0.04[c]	0.04[d]
Total non-conjugates	72.9 ± 1.8	56.4 ± 9.9	0.70	13.5 ± 1.6	8.2 ± 0.3	3.3	88.5 ± 0.3	90.6 ± 0.04	0.30
Glucuronides	15.9 ± 0.4	32.2 ± 7.2	0.15	73.9 ± 0.1	81.6 ± 0.1	18.2	4.6 ± 0.4	5.4 ± 0.9	0.02
Mercapturic acids	11.2 ± 0.4	9.5 ± 3.6	0.11	10.9 ± 0.2	8.9 ± 0.1	2.7	3.2 ± 0.5	2.6 ± 1.1	0.01
Sulfate/glucosides	N.D.	1.9 ± 0.1	N.D.	1.8 ± 0.3	1.4 ± 0.1	0.4	3.6 ± 0.9	1.5 ± 0.2	0.01
Dihydrodiol (1,2-isomer)	48.4 ± 0.2	39.7 ± 13.9	0.46	6.5 ± 1.4	4.0 ± 0.1	1.6	77.3 ± 0.7	80.9 ± 0.5	0.26
Naphthols (1- & 2-)	8.8 ± 0.9	10.7 ± 3.9	0.08	2.8 ± 0.6	1.5 ± 0.1	0.7	1.8 ± 0.1	2.4 ± 0.01	0.01
Uncharacterized (X_1-X_4)	15.7 ± 0.6	6.0 ± 0.7	0.15	4.2 ± 0.5	2.6 ± 0.3	1.0	9.4 ± 0.2	7.3 ± 0.9	0.03
				168 hr after feeding of ^{3}H-naphthalene					
Total conjugates	54.1 ± 1.3	62.3 ± 8.8	0.25	94.6 ± 0.2	91.5 ± 0.3	70.4	28.9 ± 0.5	46.1 ± 0.3	0.03
Total non-conjugates	45.9 ± 1.3	37.7 ± 8.8	0.21	5.5 ± 0.2	8.5 ± 0.3	4.1	71.1 ± 0.5	53.9 ± 0.3	0.07
Glucuronides	32.3 ± 0.3	16.6 ± 1.6	0.15	85.1 ± 0.2	81.7 ± 0.3	63.4	13.1 ± 1.3	23.7 ± 1.4	0.01
Mercapturic acids	11.7 ± 0.2	10.9 ± 6.6	0.06	7.7 ± 0.2	8.8 ± 0.1	5.7	7.2 ± 0.2	8.0 ± 0.9	0.01
Sulfate/glucosides	10.1 ± 0.1	34.8 ± 14.8	0.05	1.8 ± 0.1	0.9 ± 0.1	1.3	8.7 ± 2.1	14.4 ± 0.5	0.01
Dihydrodiol (1,2-isomer)	29.7 ± 0.5	12.4 ± 11.7	0.14	2.5 ± 0.1	3.0 ± 0.1	1.9	47.4 ± 0.4	23.9 ± 0.9	0.05
Naphthols (1- & 2-)	6.2 ± 0.2	11.5 ± 3.9	0.03	0.6 ± 0.1	2.9 ± 0.2	0.5	6.9 ± 1.2	21.6 ± 0.6	0.01
Uncharacterized (X_1-X_4)	10.0 ± 1.1	14.0 ± 7.1	0.05	2.3 ± 0.3	2.6 ± 0.1	1.7	16.7 ± 1.1	8.3 ± 0.4	0.02

[a] Based on total extracted metabolites, an average of 8, 13 and <0.5% of total radioactivity respectively, remained in liver, muscle, and bile at 24 hr.
[b] Taken from Varanasi et al. (1979).
[c] Each value is mean ± S.D. of two samples of pooled homogenates prepared from 4-5 fish.
[d] Values are at 4°C.



THIN LAYER CHROMATOGRAM OF METABOLITES (NON-CONJUGATED) OF NAPHTHALENE (24 hours after feeding)

THIN LAYER CHROMATOGRAM OF METABOLITES (CONJUGATED) OF NAPHTHALENE (24 hours after feeding)

FIGURE 17. Profiles of metabolites in starry flounder exposed to dietary naphthalene at 4°C.

PATHOLOGY

Pathological Changes in Flatfish from Exposure to Oil-Contaminated Sediment

Sediment-Associated Petroleum Hydrocarbons

The type of sediment with which PBCO was mixed greatly influenced the concentrations of petroleum hydrocarbons associated with the sediments. In experiments where the two types of sediment received the same initial amount of PBCO, the sandy sediment lost 77% of the TEPH during the first month, while the silty sediment lost only 16% during the same period (Fig. 18). This difference between the rates of release of petroleum hydrocarbons was also reflected by the concentrations of TEPH in the interstitial water of the sediments (215 μg/ml sandy, and 14 μg/ml silty) 24 hr after being mixed and placed in aquaria with flowing seawater. No detectable levels of petroleum hydrocarbons were found in the above-sediment water samples.

Although the types of sediment influenced the rate of release of petroleum hydrocarbons, the relative amounts of principal aromatic hydrocarbons associated with the sediments were quite similar (Figs. 19 and 20). After the first 14 days of the experiments, the major aromatics in both sediment types were 1- and 2-methylnaphthalene and 2,6-dimethylnaphthalene. The aromatic hydrocarbons found in the sandy sediments were also found in the interstitial water (Fig. 19). The levels of TEPH were too low in the interstitial water from silty sediment to allow GC analyses.

The uptake of petroleum hydrocarbons from PBCO-contaminated high sand sediments by the three species of flatfish has been described previously (McCain et al. 1978, OCSEAP Annual Report RU 73, April 1978). The uptake of aromatic hydrocarbons by English sole and rock sole from similarly contaminated high-silt sediments was predictably lower (Fig. 20). Rock sole muscle tissue contained much higher levels of these compounds than did English sole muscle, and, as was previously reported with high-sand sediment (McCain et al. 1978), the compounds found in highest concentration in the sediment were also highest in muscle tissue.

Biological Effects of Exposure to Oiled Sediments

Of the three species of flatfish exposed to PBCO-contaminated sediments, adult rock sole and starry flounder had no detectable petroleum-associated adverse effects. Adult English sole developed certain histological and hematological changes; however, the importance of these changes to the health of this species is difficult to evaluate. The use of rock sole as experimental animals was unsatisfactory because of their apparent sensitivity to changes in experimental conditions (reduced water flow and resulting lower availability of dissolved oxygen) and their increased susceptibility to infectious diseases during exposure studies. For example, in contrast to the other two species, rock sole could not be identified by cold branding, because the branded skin would often become infected.

Starry flounder exposed to the PBCO-contaminated sandy sediment for 62 days appeared to be more adversely affected by the experimental conditions than were English sole. Both control and oil-exposed starry flounder were similar in the following parameters: (1) their average body weight increased by 35% in 2 mo, (2) approximately 30% of the fish died during the experiment, (3) similar amounts of HLV (ranging from minimal to severe) were observed in the livers, and

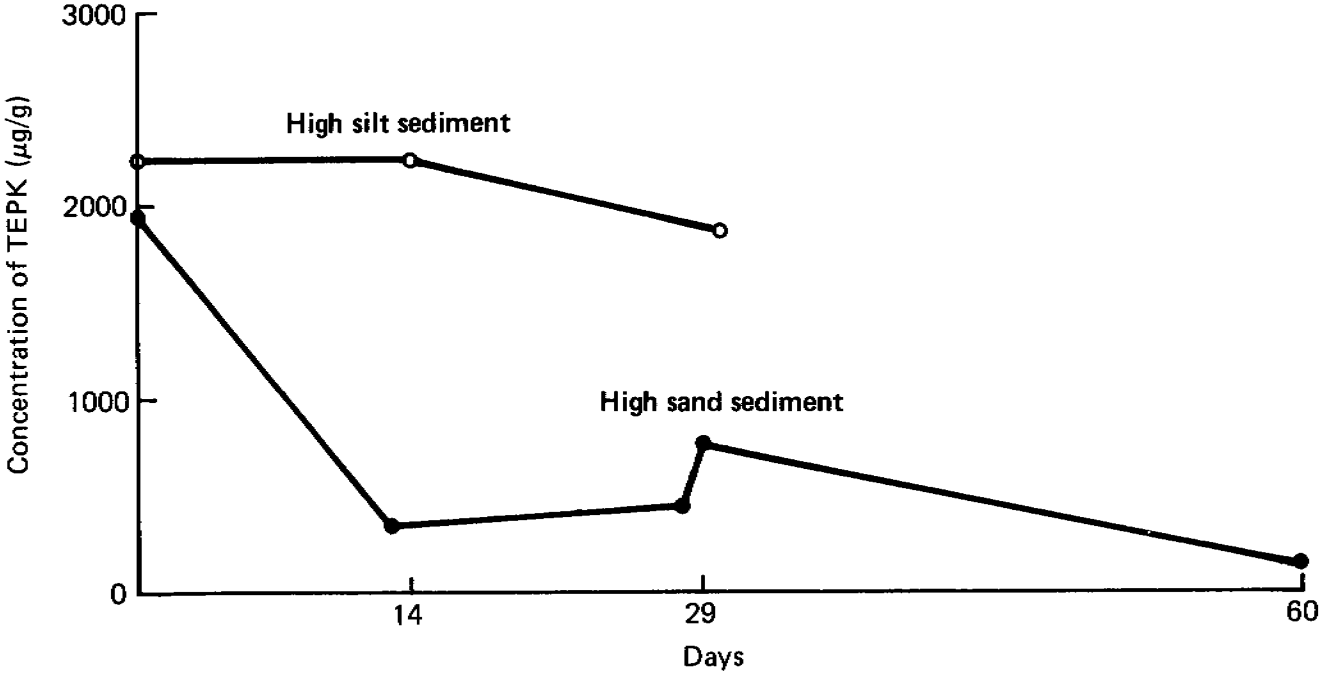
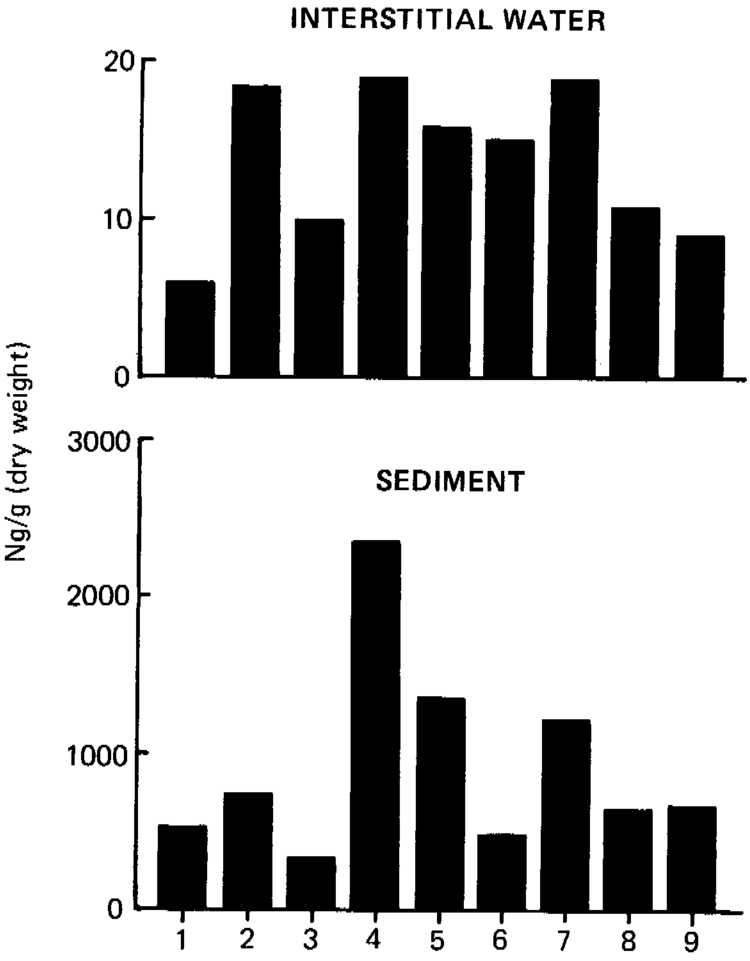
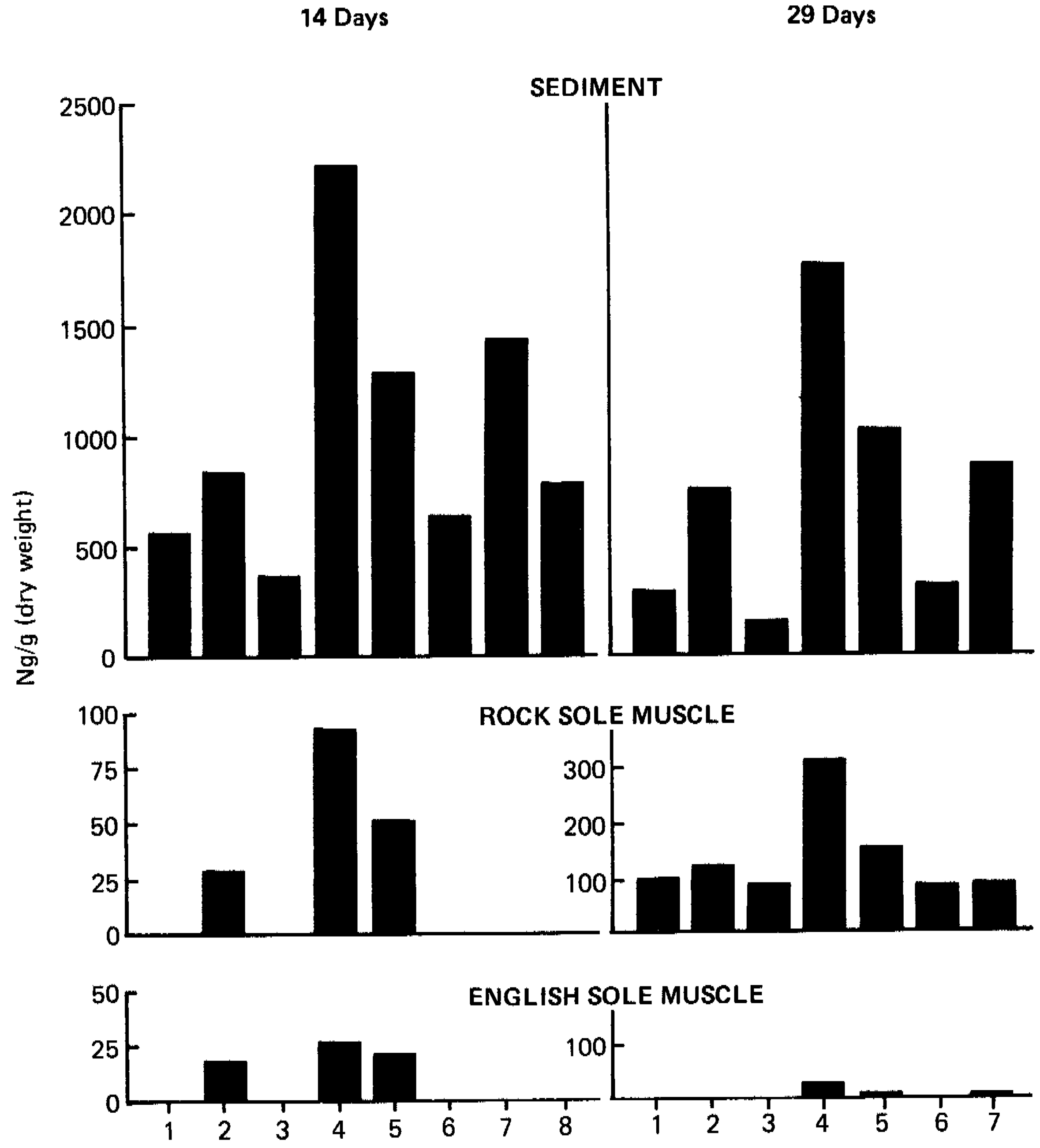


FIGURE 18. Concentrations of TEPH in PBCO-contaminated sediments from Experiment 1 (silty sediment) and Experiment 3 (sandy sediment).



1. 1,2,3,4–Tetramethylbenzene
2. Naphthalene
3. Benzothiophene
4. 2–Methylnaphthalene
5. 1–Methylnaphthalene
6. Biphenyl
7. 2,6–Dimethylnaphthalene
8. 2,3,5–Trimethylnaphthalene
9. Dibenzothiophene

FIGURE 19. Concentrations of major aromatic hydrocarbons in PBCO-contaminated sandy sediments and associated interstitial water from Experiment 3, 24 hr after mixing sediment with oil.



1. 1,2,3,4–Tetramethylbenzene
2. Naphthalene
3. Benzothiophene
4. 2–Methylnaphthalene
5. 1–Methylnaphthalene
6. Biphenyl
7. 2,6–Dimethylnaphthalene
8. 2,3,5–Trimethylnaphthalene

FIGURE 20. Concentrations of major aromatic hydrocarbons in PBCO-contaminated high-silt sediment and in the English sole and rock sole associated with the sediment at 14 and 29 days. Tissue levels are an average of 10 g muscle samples from 2 fish (Experiment 1).

(4) the hematocrits increased significantly at 2 wk and returned to approximately 0-time levels at 1 and 2 mo. The only difference between oil-exposed and control groups was a 26% frequency of hemorrhagic lesions on the lower jaws of control fish after 2 mo exposure, compared to 5% for oil-exposed fish. The significance of these lesions is not known.

Histological, hematological, and physiological changes related to long-term exposure to PBCO-contaminated sediments have been observed with adult English sole. The effects of exposing this species to high-sand sediment contaminated with 0.2% (v/v) PBCO for 4 mo were described previously (see Current State of Knowledge). During the past year, two long-term experiments were performed in which fish of this species were exposed to silty sediment containing 0.5 and 1.0% PBCO; corresponding to Experiments 1 and 4, respectively (Table 1). The levels of TEPH during Experiment 1 are described in Figure 18; and the aromatic hydrocarbon composition of the sediment and the levels of these compounds taken up by the fish are shown in Figure 20. Because Experiment 4 was started in the latter part of 1978, only the levels of TEPH and composition of aromatic hydrocarbons in the sediment are presently available. A TEPH concentration of 4,088 μg/g (dry wt) was present at 0-time, and at 1 mo there was 3,806 μg/g (dry wt), a decrease of only 7%. The most abundant aromatic hydrocarbons were similar to that shown in Figure 20, with 1- and 2-methylnaphthalenes being present at 7.2 and 14.8 μg/g (dry wt), respectively.

Although Experiments 1 and 4 differed in the levels of sediment-associated TEPH, similarities in the types of changes were observed in the English sole. Severe HLV (greater than approximately 60% of the cytoplasm of hepatocytes occupied by lipid vacuoles) was observed in 83% (5/6) of the oil-exposed group in both experiments and in 40% (2/5) and 50% (3/6) of the controls in Experiments 1 and 4, respectively, after 29 days of exposure. Some statistically significant, but transitory, hematological changes were observed in the oil-exposed fish in Experiment 1. At 14 days exposure, hematocrit and hemoglobin values and numbers of red blood cells (RBC) and white blood cells (WBC) were all lower in oil-exposed fish. However, by 1 mo, no hematological differences between the oil-exposed and control groups were found. In contrast, English sole after 1 mo exposure to oiled sediment in Experiment 4 were found to still have the following hematological differences which were significantly different from those of controls: (1) hematocrit, 18.7% for oil-exposed and 21.2% for control ($P<0.001$); (2) percent lymphocytes in blood smears, 71.1% for oil-exposed and 78.5% for controls ($P<0.025$); and (3) hemoglobin, 4.08 g/dl for oil-exposed and 4.44 g/dl for controls ($P<0.05$). No differences were found between the lengths or body weights of oil-exposed or control fish in both experiments.

Effects of Petroleum on Fish Disease Resistance

Results of experiments in which sub-adult starry flounder and rock sole were exposed to oil-treated sediments and then challenged with virulent bacteria are summarized in Table 18. LD_{50} values calculated from mortality data of starry flounder show that exposure of up to 6 weeks produces no marked alteration in disease resistance. Likewise, the data for rock sole show that little or no change in degree of disease resistance could be detected after a 2-week exposure. Declining health of this species (both test and control groups) precluded testing beyond a 2-week exposure.

Table 18. LD_{50} values for oil-exposed and control starry flounder and rock sole challenged with virulent Vibrio anguillarum

	LD_{50} dose of Vibrio anguillarum 2 week exposure	LD_{50} dose of Vibrio anguillarum 6 week exposure
Starry flounder		
oil-exposed (1,800 ppm)	1.1×10^7	1.2×10^7
control	5.6×10^7	6.0×10^7
Rock sole		
oil-exposed (2,500 ppm)	1.5×10^7	N.T.[a]
control	3.8×10^7	N.T.

[a] Not tested, see text.

PHYSIOLOGY

Chum salmon eggs were exposed to weathered oil 3 hr/day, 4 days per week. The oil concentrations in the water varied by one magnitude from 373 to 3,434 ppb with an average of 1,781 ppb. This variation in oil concentration is probably due to oil droplets since a Tyndall effect was noticeable in the water collected for analysis. After 30 hr weathering at 10°C the PBCO showed a general loss of monocyclic aromatics, and an increase in alkanes and unresolved components. (Analysis did not include polar compounds.)

Through 60 days of development the chum salmon embryos exposed continuously to weathered oil did not exhibit any abnormalities or change in growth rate compared to controls (Fig. 21). Survival of oil-exposed eggs is slightly less than controls, but within the range expected for rearing under hatchery conditions.

VII. DISCUSSION

BEHAVIOR

Vertebrate

The first series of tests concerning avoidance of juvenile English sole to oil-contaminated sediment were conducted at initial oil-sediment concentrations of 2.5% (v/v). There was no statistically significant difference in numbers of fish on oil-contaminated versus non-oil-contaminated sediment, nor were there significant differences in the following tests when the oil-sediment concentrations were doubled to 5% (v/v). Analysis of the TEPH in the sediment indicated that the sediment was probably saturated with oil at a concentration less than 2.5%, thus, all tests conducted were actually comparable in total petroleum hydrocarbons to which the fish were exposed. It is somewhat surprising that juvenile English sole do not appear to more actively avoid oil-contaminated sediment even at concentrations which cause visible release of oil when the sediment is disturbed by their burrowing activity. The lack of avoidance by fish to a potentially harmful pollutant has, however, been noted before by others and fish may even show preference for a pollutant at lethal threshold concentrations (Sprague and Drury 1969).

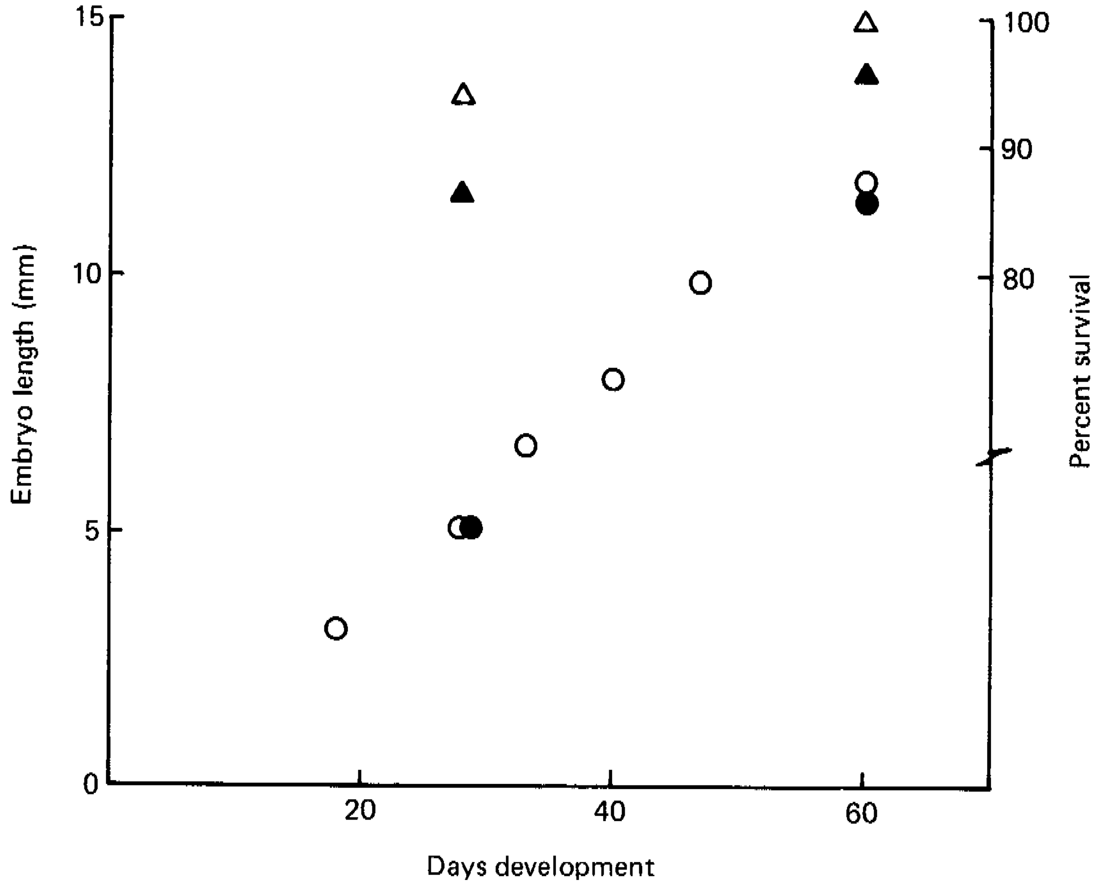


FIGURE 21. Growth of chum salmon control embryos (open circles) and embryos exposed continuously to weathered PBCO (closed circles). Percent survival for control- and oil-exposed embryos is shown at top.

Though the TEPH in the oil-contaminated sediment averaged 8,500 ppm during the avoidance tests, this concentration of oil is not environmentally unrealistic. In a review of the literature on observed concentrations of petroleum in the marine environment, Clark and MacLeod (1977) presented data from a variety of reports which show that though hydrocarbon levels in sediment of polluted coastal areas are usually less than 1,000 ppm, they have been measured at concentrations exceeding 12,000 ppm.

Invertebrate

The pedicellarial defensive behavior of the green sea urchin is mediated by chemical substances released by the starfish, and following exposure of sea urchins to hydrocarbons, this pedicellarial response is reduced. At low hydrocarbon concentrations (less than 1,000 ppb) detected behavioral effects were limited to pedicellarial responses and the activity of the lateral and aboral podia; urchin mobility was not markedly impaired, nor was the competence of the pedicellariae to respond eliminated (as shown by elicitation of pedicellarial response following isotonic KCl injection). The mode of action of hydrocarbons on the pedicellarial system is not known but the results are provocative in several respects. Inhibition of the defense response ensues within 5-15 min and thereafter the response index shows no marked change following continuous exposures of up to 48 hr, indicating that equilibrium is quickly established between pedicellarial response system and the hydrocarbon concentration. In contrast to the rapid onset of inhibition, recovery of the defense response during depuration is relatively slow.

Of the five aromatic hydrocarbons tested individually for defensive behavior responses in the sea urchin only 1-methylnaphthalene approximates the responses elicited by the total SWSF. The concentration of 1-methylnaphthalene found in the SWSF, however, is not sufficient by itself to account for the inhibition of the pedicellarial response. The same lack of sufficient concentration in the SWSF applies to ethyl benzene and trimethylbenzene which, when tested individually, are ineffective at concentrations less than 100 ppb. The greatest concentration reached by either of these latter two aromatics in the SWSF was 21 ppb.

Toluene and xylenes comprise about 80% of the total SWSF hydrocarbons as measured by GC analysis. When the concentrations of toluene and xylenes found in the SWSF are applied to their respective regression equations, as determined from testing of individual hydrocarbons, an expected response index for each of these hydrocarbons is obtained. Addition of the toluene and xylene response indices show that the total expected response is less than the response index observed from total SWSF exposure (Fig. 22). Results of exposure of sea urchins to a model mixture of monocyclic aromatic hydrocarbons representative of the SWSF are highly variable (Fig. 22), but further suggest that the principal components of the SWSF as determined from GC analysis are not totally responsible for pedicellarial inhibition. As pointed out by Malins and Clark (1978) the methods currently being used for extraction and analysis of petroleum hydrocarbons may well be excluding many highly water soluble and high molecular weight components which could account for these differences.

In experiments on interaction between sea urchins and Pycnopodia there was significantly greater predation of oil-exposed urchins. The 80% difference in predation of oil-exposed urchins over controls is probably attributable to the inhibition of the pedicellarial defense response. There is the possibility, however, that Pycnopodia are attracted to, and prefer, oil-tainted urchins. (The attraction to low concentrations of hydrocarbons has been observed in some marine organisms, particularly crustacea.) It is also possible that oil-treated

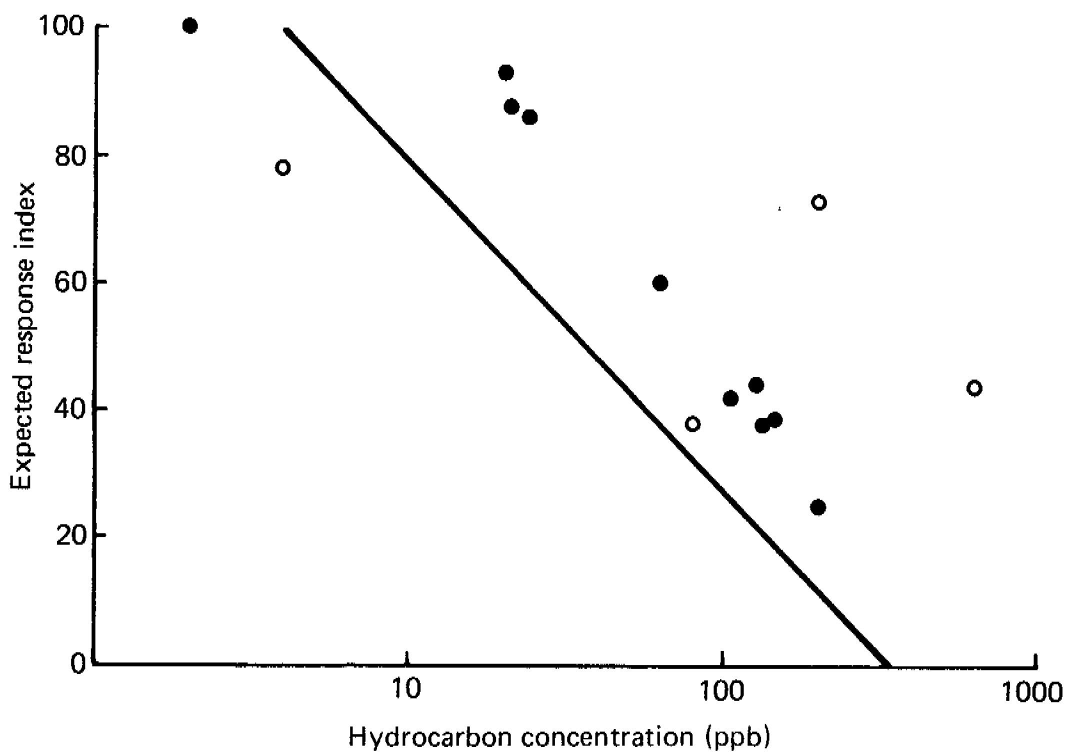


FIGURE 22. Expected response of sea urchin pedicellaria as determined from addition of responses of individual hydrocarbons present in the SWSF (closed circles), and actual response using a model SWSF mixture (open circles). Regression line represents the response index calculated from tests using the total SWSF (same regression as shown in Fig. 8).

urchins are less successful at avoiding the starfish. Regardless of the causative factor, the results show selective predation for oil-exposed sea urchins.

CHEMISTRY

The results show that pleuronectids, like salmonids (Roubal et al. 1977, Varanasi et al. 1978, Collier et al. 1978, Malins et al. 1978), are able to absorb and metabolize dietary naphthalene, and that the naphthalene and its metabolic products are broadly distributed in tissues and body fluids of the exposed fish. Rock sole contained significantly larger concentrations of naphthalene and its metabolites than did starry flounder and almost four times as much radioactivity remained in the digestive tract of rock sole compared to that in the starry flounder at 24 hr after feeding of ^{3}H-naphthalene. The digestive tract of rock sole has pyloric caeca, whereas that of starry flounder does not; it is possible that in addition to other species-specific differences, structural and functional variations in the digestive tracts (Barrington 1968) of these fish are responsible for the observed differences in the levels of accumulated radioactivity. In the present study (Varanasi et al. 1979a), a major fraction of the administered radioactivity may have been directly discharged from the gastrointestinal tract of starry flounder. The support for this observation comes from the results showing that when the same dose of naphthalene was administered to starry flounder via intraperitoneal injection, concentrations of naphthalene in tissues (e.g., liver) of starry flounder were comparable to those obtained for naphthalene-fed rock sole and much higher than those for starry flounder exposed to dietary naphthalene. It may be that infusion of naphthalene over a longer period, from the gastrointestinal tract in the case of rock sole in the feeding study and from the abdominal cavity in the case of starry flounder in the injection study, was responsible for the results showing that the decline in the concentrations of naphthalene from the tissues (e.g., liver, skin, and blood) of these fish was much slower than that for starry flounder exposed to dietary naphthalene. An interesting finding was that the metabolites were lost at a similar slow rate from tissues of both starry flounder and rock sole exposed to dietary naphthalene.

Because of the prevalence of liver tumors and epidermal papillomas in flatfish (Hodgins et al. 1977, McCain et al. 1977), special attention was given in the present work to liver and skin of the test fish. For example, in addition to the total concentrations of naphthalene and metabolites, profiles of metabolites present in these tissues were also determined. The concentrations of naphthalene and its metabolic products in skin were comparable to those obtained for the muscle and were one-tenth of those for the liver of the individual species, indicating that no marked tendency was shown by skin to accumulate the hydrocarbon or its metabolites. In addition to liver, various extrahepatic tissues of marine organisms are shown to possess aryl hydrocarbon monooxygenases (Varanasi and Malins 1977, Bend and James 1978); however, presence of this enzyme system in the skin of fish has not yet been demonstrated. Our results show that the pattern of metabolites accumulated in skin were qualitatively similar to that in the liver of the same fish. However, in both species of fish, the proportion of non-conjugates, specifically 1,2-dihydro-1,2-dihydroxynaphthalene, was higher in the skin compared to that in the liver. If the presence of metabolic products in skin was primarily due to the transport of these compounds from the liver, then certain selection seems to take place in the types of metabolites that are deposited in skin. The results show that edible tissues, such as muscle of starry flounder also preferentially accumulated non-conjugates (e.g., the dihydrodiol derivative) of naphthalene. Whether this is true for carcinogenic hydrocarbons remains an important question to be answered.

Dietary aromatic hydrocarbons are cleared from terrestrial animals primarily via biliary and to a lesser extent, via renal excretion (Daniel et al. 1967, Guarino et al. 1972). The present results showing that bile of the test fish in both dietary and intraperitoneal exposures accumulated large amounts of metabolic products of naphthalene are in agreement with other findings with salmonids (Roubal et al. 1977, Melancon and Lech 1978, Stathem et al. 1978, Collier et al. 1978). This suggests that biliary excretion was one of the major routes by which the hydrocarbon was cleared from these pleuronectids. In the present study, metabolites in the bile of the test fish were characterized by the preponderance of glucuronides (>80%), regardless of species, mode of exposure, or time elapsed after the initiation of naphthalene-exposure. Radioactivity excreted in urine was not measured, but considerable radioactivity was present in the kidney of the test fish over a long period (up to 6 weeks). Excretion of both naphthalene and metabolic products via epidermal mucus (Varanasi et al. 1978) and gills (Roubal, W.T., personal communication) seems to occur in salmonids. The present results showing that epidermal mucus and gills of pleuronectids exposed to naphthalene contained detectable concentrations of naphthalene and, more importantly, its metabolic products, suggest that, in addition to biliary and renal excretion, clearance via epidermal mucus and gills may also take place in these fish. The relative importance of each of these pathways in clearance of xenobiotics in fish remains to be assessed.

In terrestrial mammals, the route of administration can significantly alter the pharmacokinetics of a given compound (Gibaldi and Perrier 1974). The present results reveal that the mode of hydrocarbon-exposure did influence concentrations and relative proportions of naphthalene and its metabolic products, as well as the proportions of metabolites accumulated in fish. Our results show that considerable amounts of metabolites were present in the stomach and intestine of both rock sole and starry flounder in the feeding study at 12°C; the presence of metabolites in the gastrointestinal tract may be due to (a) biliary excretion and/or (b) metabolism of naphthalene by the gut flora or gut mucosa. The presence of both aryl hydrocarbon monooxygenase and epoxide hydrase has been demonstrated in intestinal mucosa of rats (DePierre and Ernster 1978). Gut bacteria are also implicated in the metabolism of hydrocarbons in terrestrial mammals (Sims and Grover 1974). Metabolism of naphthalene in the gastrointestinal tract may be responsible for the observed differences in the pattern of metabolites accumulated in livers of starry flounder in the injection and feeding experiments at 12°C. Thus, it can be speculated that similar differences in pattern of metabolites may occur when main route of uptake of PAH is other than the gastrointestinal tract (e.g., gills or skin when PAH is present in water or sediment). Moreover, if infusion of naphthalene into the liver occurred over a longer period in the injection study compared to that in the feeding study, it may also have influenced the types of metabolites accumulated in liver.

Our findings do show that the types of metabolites accumulated in the liver were dependent on the time elapsed after the administration of naphthalene. With time, the pattern of metabolites changed in the liver of test fish, regardless of species or mode of administration of naphthalene; there was an increase in the proportion of conjugates--specifically sulfate/glucoside fraction--and a decrease in the proportion of 1,2-dihydro-1,2-dihydroxynaphthalene. Burke et al. (1977) reported that the pattern of metabolites changed from a higher proportion of organic-soluble metabolites to a higher proportion of aqueous-soluble metabolites from 10 to 30 min after the addition of BAP in rat hepatocytes.

Because certain dihydrodiols of PAH are precursors of diol epoxides, which are implicated in covalent binding with cellular DNA (Swaisland et al. 1974, Levin et al. 1976), a decreased proportion of the dihydrodiol may imply increased detoxification of the hydrocarbon.

It is possible, therefore, that different exposures (single or continuous) of pleuronectids to PAH (in water, sediment, or food) may result in markedly different degrees of alteration in genetic material because of variability in accumulation of non-conjugated and conjugated metabolites. Some of the non-conjugates are implicated in covalent binding with critical cellular constituents in terrestrial mammals (Miller and Miller 1974) and are shown to have a high biological activity (Kapitulnik et al. 1977, Wood et al. 1977).

The decrease in water temperature (4° vs. 12°C) resulted in substantially higher (2-15 times) concentrations of naphthalene in tissues of naphthalene-exposed starry flounder. These results are in agreement with the results with clams (Fucik and Neff 1977), copepods (Harris et al. 1977) and coho salmon (Collier et al. 1978) indicating an inverse relation between temperature and tissue concentrations of the parent hydrocarbon.

Environmental temperature is known to have a marked effect on the activity of the alimentary canal of fish; both the rate of passage of food as well as the rate of its absorption are much slower in fish at lower temperatures (Barrington 1968). In the present study, substantially larger amounts of radioactivity were present at 24 hr in the gastrointestinal tracts of the fish at the lower temperature. The radioactivity at this time was primarily in the form of naphthalene; therefore, it can be assumed that fish at the lower temperature contained a considerably larger proportion of the ingested dose in the gut. This may contribute, at least partly, to larger concentrations of naphthalene in tissues of fish, as well as to the slower decline in naphthalene concentrations from 24 to 168 hr in fish at the lower temperature. In their study with coho salmon, Collier et al. (1978) did not observe any difference in the amounts of naphthalene in the gut at 4° or 10°C at both 8 and 16 hr after feeding of naphthalene. Thus, it appears that at depressed temperatures the rate of excretion of naphthalene from tissues may be also considerably lower and this may be responsible, in part, for substantially high concentrations of naphthalene in tissues of fish at the lower temperatures.

When compared to the findings at 24 hr, the influence of lowered environmental temperature was even more pronounced at one week after the initiation of naphthalene-exposure. For example, at this time cold-maintained fish contained 30-40 times as much naphthalene as in fish at 12°C. Barely any naphthalene was present in the latter group of fish, hence it appears that cold-maintained animals may retain naphthalene--a potential source of metabolic products--over a much longer period.

In contrast to the findings with naphthalene, the lowering of water temperature did not substantially increase tissue metabolite concentrations. Thus, proportionately much less naphthalene appeared to be biotransformed in the liver at the lower temperature. It should be noted that the decrease in water temperature over the physiological range of a poikilothermic organism is known to increase activities of certain enzymes to compensate for the reduction in body temperature (Hochachka and Somero 1971). Dewaide (1971) reported higher activities of N-demethylase and aniline hydroxylase when liver extracts from cold-acclimated (5°C) rainbow trout or roach were used compared to the corresponding values for animals kept at 18°C. Hardly any information is available on the influence of cold-acclimation on aryl hydrocarbon monooxygenase (AHM) in marine organisms. Our results (Varanasi et al. 1979b) with starry flounder showing that the overall effect of cold-acclimation *in vivo* was reflected in a lesser degree of biotransformation of naphthalene, stresses the need for further studies with poikilothermic organisms to understanding temperature-related changes in xenobiotic metabolism, both *in vivo* and *in vitro*.

Because certain arene oxides, dihydrodiols and phenol derivatives of PAH are implicated in covalent binding with critical cellular constituents, conjugation of these compounds indicates in general a detoxification process. The present results show that the ratio of conjugated metabolites to non-conjugated metabolites increased significantly from 24 to 168 hr in liver and muscle of fish. This finding is in agreement with our previous results (Varanasi et al. 1979) with starry flounder and rock sole (*Lepidopsetta bilineata*) exposed either to dietary naphthalene or via an intraperitoneal injection at 12°C showing that with time the proportion of conjugates, especially sulfate/glucoside fraction, increased significantly and that of the dihydrodiol fraction decreased. Similar influence of time on the type of metabolites was also reported by Burke et al. (1978) for benzo(a)pyrene metabolism in rat hepatocytes. It can be speculated from these results that both the concentrations and types of metabolites will be strongly dependent on whether exposure to PAH is single or continuous.

It appears that the types of metabolites are also dependent on a particular tissue under investigation. For example, in the present work, metabolites extracted from the muscle of starry flounder at both 4° and 12°C contained primarily (>75%) the dihydrodiol derivative of naphthalene whereas livers of the same fish contained much smaller proportion of dihydrodiols (≃40%) and considerable proportion of conjugates. Similar selective disposition of metabolites was also observed by Varanasi et al. (1979) with pleuronectids and by Collier and Malins (personal communication) with rainbow trout (*Salmo gairdneri*). In the latter study, the authors found that in the brain of adult rainbow trout only non-conjugates were characterized, whereas considerable proportion of conjugates, in addition to non-conjugated metabolites, of naphthalene were characterized in liver and blood.

Lowering of environmental temperature did not seem to have a marked effect on the proportions of metabolites accumulated in tissues of fish at 24 hr after the feeding of naphthalene. However, after one week some distinct differences in proportions of metabolites in both liver and muscle of fish at 4° and 12°C were evident. Proportion of the dihydrodiol fraction was considerably high in both the liver and muscle of fish at 4°C compared to those at 12°C. Moreover, proportion of sulfate/glucoside fraction in the liver and muscle of the former group was considerably smaller than that in the latter group. Because the general effect of lowered water temperature is to slow down the activity of alimentary canal of fish, considerably large amount of the ingested naphthalene was retained at 24 hr in the gastrointestinal tracts of the fish at 4°C. It can be assumed therefore that the infusion of naphthalene into the liver of these fish occurred over a much longer period than that at 12°C. This may explain, at least partly, the finding that the influence of lowered water temperature on proportions of dihydrodiol and sulfate/glucoside fractions was opposite to the influence of increased time on these metabolite classes.

MORPHOLOGY

Morphologic changes observed in trout lens fibers during cataractogenesis are very similar to those described in cataract formation in humans and laboratory animals exposed to toxic substances (Hollwich et al. 1975), with senile cataracts (Duke-Elder 1969, Kobayashi and Suzuki 1975), and with sugar-induced cataracts (Unakar et al. 1978). The salient common structural alterations include fibrillar loosening and intrusion of material, probably fluid, between fibers; breakdown and abnormalities in fiber cell membranes, especially in the connecting protrusions; and the appearance of large areas of flocculent, electron-lucent material in the fiber cells. In trout, both the clear and opaque area of damaged lenses have inclusions of flocculent material in the fiber cells. However, the amount of affected area is both greater and more severe in the opaque region. It should be noted, that thioacetamide, while promoting lens fiber cell changes, additionally induces epithelial proliferation (Sallmann 1966) not reported in other forms of cataractogenesis. Epithelial proliferation was also observed in some parts of the opaque areas of trout lenses.

The questions of (1) the relationship of cataracts and other eye damage in fish to petroleum exposure, and (2) the reversibility of lesions observed are pertinent although not definitively answerable at this point. Rabbits fed naphthalene (1 g/kg), however, developed opacities in lenses and retinal degeneration very quickly; pathology in the lens was visible 1-8 days after initial exposure (Van Heyningen and Pirie 1976). Rather than the native naphthalene, metabolic products appeared to be the toxic agents in rabbits. A number of metabolites are carried through the circulatory system to the eye where they are converted to 1,2-dihydroxynaphthalene, which, in turn, is oxidized to 1,2-naphthoquinone (Van Heyningen 1976, Van Heyningen and Pirie 1967, Rees and Pirie 1967). The toxic action of 1,2-naphthoquinone probably involves the affinity of this compound for proteins.

PATHOLOGY

Pathological Changes in Flatfish from Exposure to Oil-Contaminated Sediment

One of the principal experimental results obtained during the two years of subjecting flatfish to PBCO-contaminated sediments has been the importance of species differences, which affect not only the amount of petroleum hydrocarbons taken up into tissues and the presence or absence of oil-related biological changes, but the manner in which the fish react under laboratory conditions. Starry flounder, English sole, and rock sole all took up hydrocarbons from oiled sediment; however, the tissues of the rock sole had levels of the parent aromatic hydrocarbons approximately three times higher than did tissues of the other two species. Whether the tissue levels of metabolic products of these hydrocarbons differed similarly for the three species is not known. As is stated in the Chemistry Section of this Discussion, metabolites of certain aromatic hydrocarbons are known to be more toxic than the parent forms. English sole developed oil-related histological and hematological changes under the conditons of these long-term experiments, while such changes were not detected with rock sole and starry flounder. The importance of species differences in determining the effects of exposure to toxic chemicals and infectious agents is well known. For example, starry flounder and English sole residing in the same polluted estuarine ecosystem were found to differ in that 13% of the flounder and 0.5% of the English sole have fin erosion (Wellings et al. 1976), while 32% of the English sole and none of the other species had detectable hepatomas (Pierce et al. 1978). Lastly, in terms of adaptability to the laboratory conditions employed, English sole were far better experimental animals than were rock sole, with starry flounder being intermediate. The principal limitation of rock sole was their apparent increased susceptibility to infectious diseases. Control and oil-exposed starry flounder also had a much higher mortality rate than did English sole under the same conditions.

Although the physicochemical properties of sediment used in these studies were found to determine the rate of release of contaminating petroleum hydrocarbons into the water, and thus the levels of these hydrocarbons taken up into tissue, the tissue levels of the parent forms of these aromatic hydrocarbons did not appear to relate to the observed biological changes. One example of this lack of correlation was observed in Experiment 1. After 1 mo of exposure, rock sole with individual hydrocarbon concentrations of the seven major aromatic hydrocarbons ranging from 81 to 309 ng/g (dry wt) in muscle tissue (Fig. 20) had no detectable histological changes; however, English sole in the same experiment with detectable levels (9 to 31 ng/g) of only three of the seven hydrocarbons in muscle tissue (Fig. 20) had a 43% higher incidence of severe HLV than did controls. As was previously mentioned, this example of lack of correlation between tissue levels and petroleum-related changes may be related to species differences. When these results with English sole from Experiment 1, which employed silty sediment, are compared to results of the previously described experiment (McCain et al. 1978) involving the same species exposed to PBCO-contaminated sandy sediment, a lack of correlation is again observed. In Experiment 1, no aromatic hydrocarbons were detected in the livers of oil-exposed fish, while during the same exposure period in the other experiment levels of individual aromatic hydrocarbons listed in Figure 20 in liver tissue were 278 to 1,500 ng/g (dry wt). Nevertheless, both groups of oil-exposed English sole had severe HLV. Two explanations which may account for this observation are: (1) low, marginally detectable, levels of certain sediment-associated petroleum compounds, such as non-volatile aromatic hydrocarbons, or microbially or chemically produced products of aromatic hydrocarbons, may be able to induce extensive lipid accumulation in Englsh sole livers, and (2) some petroleum compounds which cause liver changes may be quickly metabolized and are therefore undetectable by conventional GC/MS.

The significance of severe HLV as an indicator of long-term exposure to petroleum hydrocarbons is questionable. Although this condition has been repeatedly observed to occur at a higher frequency in crude oil-exposed English sole, it was observed at approximately the same frequency in both oil-exposed and control rock sole and starry flounder. Excessive HLV can be induced by a variety of causes, including nutritional deficiencies (Snieszko 1972), exposure to pesticides (Couch 1975), and to contact with polluted environments (Pierce et al. 1978). Also, under the experimental conditions described above the severe HLV appears to be a reversible condition.

Effects of Petroleum on Fish Disease Resistance

Tests designed to assess the effects of petroleum exposure on disease resistance of sub-adult flatfish failed to demonstrate any marked impairment. After exposures of up to 6 weeks duration, oil-exposed and non-exposed flatfish showed a comparable pattern of mortality following a laboratory challenge with V. anguillarum. Whether or not a lowered host resistance could occur under other stress and exposure conditions and to different diseases cannot be decisively predicted from the present data. These data do strengthen the concept, however, that this may not be a major problem for adult pleuronectids of these species.

PHYSIOLOGY

Slightly weathered PBCO did not have a detectable adverse effect on chum salmon embryo development or survival over a 60 day exposure period. Studies by

Rice et al. (1975) concerning the effect of the WSF of PBCO on pink salmon (O. gorbuscha) eggs and alevins indicated that the eggs were resistant, and that mortalities occurred primarily at hatching and at the time of alevin emergence from the gravel (following yolk sac absorption). It is presently intended that exposure of chum salmon eggs and alevins to weathered oil will be continued through hatching and until the yolk sac is absorbed.

VIII. CONCLUSIONS

BEHAVIOR

Vertebrate

Observations on juvenile English sole in a laboratory situation indicate that they remain buried in sediment 60 to 85% of the time. Prolonged contact with hydrocarbons in the sediment at concentrations of 400 to 700 ppm has been observed to cause both physiological and pathological abnormalities in English sole (McCain et al. 1978). In the behavioral tests reported here, though the TEPH in the sediments were over one order of magnitude greater than that shown to have adverse effects, the fish fed actively and buried readily in oil-contaminated sediment. Juvenile Dungeness crabs did not avoid the surface of heavily oiled sediment, and there is no information to date on the effect of chronic exposure to oiled sediment for these crustacea. These results are in contrast to statements in the literature in which it is generally assumed that mobile marine organisms avoid oil-contaminated areas.

Invertebrate

Inhibition of the sea urchins' defensive behavior following exposure to the SWSF of PBCO and its major aromatic components have several important connotations: (1) The principal components of the SWSF as determined by GC analysis are not responsible for the total inhibition observed, (2) The pedicellarial defense inhibition resulting from hydrocarbon exposure is apparently a chemosensory specific reaction and not general narcosis, and (3) SWSF-exposed sea urchins are preyed upon by Pycnopodia to a greater extent than non-exposed urchins.

The biological significant of these results is that low ppb concentrations of petroleum components in seawater disrupt chemically mediated behavior. These disruptions ensue within minutes of exposure to the hydrocarbons and recovery in clean seawater is prolonged. Crabs and bacteria also show reversible inhibition of chemosensory behavior by petroleum hydrocarbons (Johnson 1977), with recovery of chemosensory behavior of crabs in clean seawater requiring several days.

CHEMISTRY

In conclusion, the results with pleuronectids (Varanasi et al. 1979b) were that lowering of environmental temperature resulted in increases in both concentrations and resident times of naphthalene and its metabolites in tissues of fish exposed to dietary naphthalene. However, the increase in concentration was much greater for naphthalene than for the metabolites indicating that bioconversion of naphthalene was considerably less at the lower temperature. Lowering of the temperature also influenced the proportions of metabolites accumulated in tissues of these fish.

The studies demonstrated that the extent of biotransformation of naphthalene and the types of metabolites remaining in tissues (liver, muscle) of flatfish were greatly influenced by both the mode of exposure and the time which elapsed after the exposure was initiated. It appears therefore, that different exposures (e.g., in water, food, or sediment; and as a single or continuous exposure) of pleuronectids to polycyclic aromatic hydrocarbons may result in different degrees of alteration of genetic material because of variability in accumulation of nonconjugated metabolites, some of which are implicated in covalent binding with DNA in terrestrial mammals. Thus, it is vital importance to include determinations of tissue concentrations and types of metabolites together with the concentration of a parent hydrocarbon while considering overall toxicity of such xenobiotics to marine fish.

MORPHOLOGY

1. Morphological aspects of the process of cataract formation in rainbow trout have been described. It is anticipated that this information will be useful in evaluating potential eye effects in fish from petroleum exposure. The sequence of changes includes an initial hydration of the cortical fiber cells and subsequent damage to the fiber cell membranes and internal structures and closely parallels cataract formation in mammals treated with naphthalene as well as other cataract-inducing agents.
2. The normal egg membranes of starry flounder and pink salmon differ markedly in membrane thickness and structure. The contrasting environmental conditions during embryogenesis of these two species may correspond to the thin membrane and simple lamellar structure of the pelagic starry flounder egg and the thick membrane and complex lamellar structure of the pink salmon egg.
3. Ultrastructural changes in livers from oil-exposed English sole were further characterized. There are indications that they may be reversible (See Pathology section).

PATHOLOGY

Pathological Changes in Flatfish from Exposure to Oil-Contaminated Sediment

Exposure of flatfish to PBCO-contaminated sediments appears to be a good method to evaluate the effects on these species of not only seawater-soluble petroleum hydrocarbons, but of a wide spectrum of soluble and insoluble crude oil components. After two years of experimentation employing this technique with two basic types of sediment, a variety of oil concentrations, and three species of flatfish, the results suggest that under the limits of these experimental conditions adults of the species so far tested develop at most a low incidence of detectable, permanent pathological changes. Oil-exposure-related mortalities and emaciation were observed in an experiment with English sole which lasted 4 mo; however, few effects from oil exposure were detected in the other species (starry flounder and rock sole) and in other experiments.

Due to the interdisciplinary nature of these experiments, significant contributions were made to the understanding of interactions of PBCO with sediment and the uptake and fate of sediment-derived petroleum hydrocarbons by flatfish. Chemical analyses by GC/MS of sediment, water, and tissues have demonstrated (1) dramatic differences between the uptake and release of petroleum hydrocarbons by different sediment types, (2) species-related differences in the amounts of petroleum hydrocarbons bioaccumulated by flatfish, and (3) tissue-related differences in the levels of bioaccumulated hydrocarbons.

Effects of Petroleum on Fish Disease Resistance

Sub-adult starry flounder and rock sole exposed to oil-contaminated sediments for up to six weeks did not show any marked alteration in disease resistance.

PHYSIOLOGY

Chum salmon eggs which were exposed continuously (4 days/week for 9 weeks) to weathered PBCO did not show any pronounced differences in rate of embryo development or survival when compared with controls.

IX. NEEDS FOR FURTHER STUDY

GENERAL COMMENTS

Although considerable progress has been made in understanding interactions between petroleum, petroleum-related activities, and marine species and ecosystems, most aspects of these interactions remain at best poorly defined. Some of the greatest progress made has been in recognizing the high degree of complexity of many of the problems faced, and in determining that simplistic, cosmetic approaches will not suffice.

Some suggestions for future investigations are listed by discipline in the following sections.

BEHAVIOR

Most studies on acute and chronic effects of pollutants on mobile marine organisms have been initiated with little consideration for the behavioral response of the organism coming in contact with the pollutant. In evaluating the effect of petroleum hydrocarbons on certain marine biota it is logical that the first experiments should be designed to determine if the organism is likely to avoid the hydrocarbons if a possibility to do so exists. This is not an easy question to definitively resolve in a laboratory situation because of numerous factors in the natural environment that cannot be duplicated in the laboratory. As an example, Rice et al. (1975) have shown that pink salmon fingerlings will avoid the SWSF of PBCO, and suggests that this may cause them to move into offshore waters where food supplies are less abundant and increased predation may occur--a situation which may promote return to an oil-contaminated area. It is evident, in any event, that without consideration of behavioral parameters, predictions of effects of petroleum hydrocarbons on many marine organisms may be grossly exaggerated or, conversely, overlooked. Further research is needed, both under controlled laboratory conditions and, as feasible, in field situations, to better define the existence of avoidance responses to pollutants, and factors modifying them, for a variety of mobile marine species at different developmental stages. This information is of vital importance for designing experiments and setting priorities for future effects studies.

CHEMISTRY

Studies conducted under this program have demonstrated that aromatic hydrocarbons are converted to a variety of metabolic products in marine biota. These biotransformations are often rapid and extensive. Other conversions (chemical and microbiological) yield a host of additional conversion products that increase the complexity of petroleum pollutants in exposed marine environments (Malins 1977). Accordingly, a need exists for developing information on the nature and levels of such products in marine systems and the potential these derivatives have for bringing about alterations in the health of arctic and subarctic organisms and ecosystems. Priority should be given to the application of presently available analytical procedures for identifying oxidized structures in the marine environment. Moreover, efforts should be made to study the toxicity of fractions of conversion products so that some idea can be obtained about their impact on marine life.

With regard to a logical extension of the work specifically described in this report, it appears that continuous exposure of fish to petroleum hydrocarbons may result in the accumulation of high proportions of non-conjugated metabolites which are implicated in covalent binding with macromolecules in cells. Thus, studies should be carried out to assess the types of metabolites that accumulate in tissues of fish exposed to hydrocarbons in the water column or sediment. Moreover, studies should be carried out to determine the extent of binding of metabolites with DNA, RNA, and protein to better evaluate the biological implications of the accumulation of potentially mutagenic and procarcinogenic metabolites. Studies on the metabolism of low and high molecular weight PAH should also include larval and juvenile fish to evaluate metabolic differences which may reflect differential susceptibilities of various life stages.

MORPHOLOGY

Two studies are indicated as extensions of the lens study. One involves short-term exposures of several species of marine fish to petroleum as would be encountered in a spilled-oil situation and assessing lens damage using morphological criteria (particularly for early changes) described in this and previous OCSEAP reports. This would explore incorporating eye examinations into monitoring techniques as well as providing data on eye damage resulting from natural exposure situations. The second study would focus on identifying specific compounds that cause eye damage, including oxygenated petroleum hydrocarbon products.

Egg and larval fish studies should be continued to define morphological changes induced by petroleum exposure in various species as appropriate. Fish egg membranes and larvae should be particularly examined at the time of hatching (as part of Physiology studies in progress, for example), as these appear to be sensitive stages in the life cycle to damage from petroleum.

PATHOLOGY

Pathological Changes in Flatfish from Exposure to Oil-Contaminated Sediment

Because larval and juvenile forms of marine species appear to frequently be more sensitive to the effects of pollutants than adults, continuation of experiments initiated during FY 79 involving the exposure of these life stages of flatfish to PBCO would be advantageous. Flatfish larvae are available in early spring, and the very young juveniles first settle into the shallow beaches where they can be captured in early summer. Therefore, these types of studies are seasonal and will be initiated during the latter part of FY 79. Due to the long-term nature of these experiments, it may be necessary to continue them into the first part of FY 80. Additional experiments employing a variety of sediment types, oil concentrations, and species could be continued for the remainder of FY 80.

An area of major concern involves the fact that urban-associated marine environments which receive petroleum contaminants are often polluted with toxic chemicals, such as heavy metals and polychlorinated biphenyls (PCBs). The cumulative and/or synergistic effects of such mixtures of pollutants on resident marine animals are poorly understood. Since many of these pollutants accumulate in bottom sediments, experiments designed very much like the oil-contaminated sediments studies described above, but involving benthic invertebrates as well as flatfish exposed to mixtures of contaminants which include petroleum, would increase our knowledge concerning the bioaccumulation, biological, and pathological effects of these mixtures.

Effects of Petroleum on Fish Disease Resistance

While the data reported here do not identify a detrimental effect of oil exposure on disease resistance among sub-adult flatfish, very early developmental stages of these fish have not been examined. It is conceivable that juvenile fish, with possibly less developed anti-bacterial defense mechanisms, might show an altered response to pathogenic microorganisms following petroleum exposure. Moreover, exposures to multiple contaminants, as described above, should be undertaken.

PHYSIOLOGY

Studies currently being conducted, or projected under the present OCSEAP proposal, concern the effect of weathered oil on salmon and flatfish eggs and larvae. There is one other fish family (Osmeridaie) of sports and commercial importance whose spawning habits are different and render their eggs particularly susceptible to onshore oil pollution. The surf smelt (Hypomesus pretiosus) and capelin (Mallotus villotus) are representative of Osmeridaie, and both species spawn intertidally on exposed sand and pea-gravel beaches. The eggs are adherent to the beach substrate and are usually inundated at least once or twice a day by tidal influx during their 1-2 week embryonic stage. Surf smelt eggs are available in Puget Sound from late summer through December and laboratory techniques for hatching of eggs and rearing of larvae are presently developed (Misitano 1977). A preliminary study evaluating the effect of weathered PBCO on surf smelt eggs was conducted this year and severe abnormalities were noted in the embryos. It is recommended that studies with weathered oil and weathered oil-dispersant mixture be undertaken using surf smelt eggs and larvae as a representative of these beach spawning fishes.

In another area of physiological research, considerable number of studies have addressed the effect of petroleum hydrocarbons on the physiology of crustacea. These studies have primarily involved zoea and larval forms and their response to the SWSF of crude oil and selected hydrocarbons such as benzene, toluene, or naphthalene (OCSEAP Annual Reports Summary, 1977). The results of these investigations indicate considerable bioaccumulation and transformation of hydrocarbons in tissues, and in juvenile forms a disruption of physiologic processes as reflected by respiratory and heart rate depression. Also, at SWSF concentrations approaching acute toxicity levels, appendage autotomy was noted in post-molt crabs. None of these studies, however, have been concerned with chronic exposure of crustacea to oil-contaminated sediment, especially with regard to the physiological process of molting.

Most of the economically important crustacea are bottom dwellers, and many of these crustacea, such as Dungeness crabs, spend a considerable amount of time buried in the sediment. Juvenile Dungeness crabs, in particular, reside in shallow waters where the potential of petroleum contamination of the sediment is likely to be pronounced. In laboratory studies on avoidance by flatfish of oil-contaminated sediment (See Behavior section of this report) observations were also made on juvenile Dungeness crabs. Several of the crabs did molt on oil-contaminated sediment within 2-3 days after introduction into the test apparatus indicating that molting can occur in the presence of oil. In this situation, however, the physiological preparation for molting may have been too far advanced for hydrocarbons to have an inhibitory influence. The molted individuals were preyed upon by other crabs in the test apparatus--a not uncommon occurrence under laboratory conditions. This could reflect unwillingness of the molted crabs to seek shelter in oil-contaminated sediment or possible impairment of post-molt responses.

As noted in toxicity studies on larval crustacea exposed to petroleum hydrocarbons, the most sensitive stage is at molting, and molting is often severely inhibited by sublethal hydrocarbon concentrations. There is no information, however, concerning the effect of petroleum on the molting of crustacea at more advanced stages. Molting is an easily measureable quantity which generally reflects the integration of and performance of all bodily systems from one molt to the next. It is recommended therefore, that future studies include chronic exposure studies to evaluate the effect of oil-contaminated sediment on the success of molting in the juvenile Dungeness crab, with consideration of both physiological and behavioral aspects.

X. SUMMARY OF FOURTH QUARTER OPERATIONS

SHIP OR LABORATORY ACTIVITIES

Ship or Field Trip Schedule

Several trips were made by small boat or via car to various areas of Puget Sound to collect animals for testing. Research activities were conducted at the NWAFC, Seattle and the Mukilteo facility of the NWAFC.

Scientific Party

The scientific party consists of scientists and technical personnel in several major study areas. The overall supervision of the research is carried out by Dr. Donald C. Malins, P.I., Director of the Environmental Conservation (EC) Division, NWAFC, Seattle, Wash. The scientific party also consists of the following persons from the EC Division, NWAFC:

Behavior

Douglas D. Weber, M.S., Fishery Research Biologist; principal investigator in charge of behavior and physiology studies.

Fred Johnson, M.S., Fishery Research Biologist; graduate student working part-time on studies of effects of petroleum on chemosensory systems.

Desmond Maynard, Fishery Research Biologist; graduate student working part-time on studies of fish avoidance of petroleum.

Chemistry

Neva L. Karrick, M.S., Supervisory Research Chemist, Assistant Director, EC Division; role of principal investigator.

William T. Roubal, Ph.D., Research Chemist; investigator of biotransformations of petroleum hydrocarbons.

Usha Varanasi, Ph.D., Research Chemist; investigator of biotransformations of petroleum hydrocarbons.

William D. MacLeod, Ph.D., Manager, NOAA National Analytical Facility (NAF); in charge of analytical services to the study.

Donald W. Brown, M.S., Assistant Manager, NAF; supervisor in charge of analytical services to the study.

Dennis Gmur, M.S., Chemist; assistant to Dr. Varanasi.

Morphology

Joyce W. Hawkes, Ph.D., Fishery Research Biologist; principal electron microscopist and investigator in charge of morphological studies.

Carla Stehr, Fishery Research Biologist; part-time assistant to Dr. Hawkes.

Pathology

Harold O. Hodgins, Ph.D., Supervisory Fishery Research Biologist; principal investigator in charge of pathological studies.

Bruce B. McCain, Ph.D., Microbiologist; part-time investigator in charge of work on petroleum in sediments and their effect on flatfish pathology; co-investigator with Dr. Hodgins.

William D. Gronlund, M.S., Fishery Research Biologist; assistant to Dr. Hodgins and co-investigator with Dr. McCain.

Kenneth V. Pierce, M.S., Fishery Research Biologist; part-time assistant to Dr. McCain.

Linda D. Rhodes, Biological Aide; part-time assistant to Dr. McCain.

Michael H. Schiewe, M.S., Fishery Research Biologist; investigator of effects of petroleum on fish disease resistance.

Physiology

Douglas D. Weber, M.S., Fishery Research Biologist; principal investigator in charge of behavior and physiology studies.

David Misitano, M.S., Fishery Research Biologist; conducts physiology studies.

Teresa Scherman, Physical Science Technician; part-time, prepares samples for chemical analysis.

Methods

The research is conducted through laboratory studies primarily, and not through systematic field sampling. Except for slight modifications the methods used have been described in previous OCSEAP reports.

Sample Localities/Ship or Tracklines - N/A

Data Collected or Analyzed

Behavior

Behavioral studies were completed for the current reporting period prior to the January-March Quarter. Considerable time was spent, however, during this quarter, on collating and analyzing the data which is reported in the current Annual Report.

Chemistry

Juvenile English sole exposed to oil-contaminated sediments were sampled for metabolism and DNA-binding studies (for details of study see Pathology section). Methods for investigating benzo(a)pyrene metabolism in these fish are being standardized.

Morphology

Normal ovaries with eggs were collected and processed for electron microscopic examination from 5 C-O sole (Pleuronichthys coenosus), and olfactory organ, lens, and liver tissues from 16 oil-exposed and control English sole were collected and fixed for subsequent electron microscopic analyses (See Pathology section).

Pathology

An experiment involving long-term exposure of English sole to PBCO-contaminated sediment (1.0% v/v) was initiated during 1978 using the facilities and protocols described in the accompanying Annual Report. During this quarter the 61 and 90 day samples of fish tissue and of sediment were taken for histological hematological, and analytical chemical analyses.

> Numbers and Types of Samples: Blood for hematology (30); Sediment samples for hydrocarbon analyses (7); Tissue samples for hydrocarbon analyses (72); Tissue samples for histological analyses (303).
>
> Numbers and Types of Analyses: *HEMATOLOGY*--Hematocrit (27); Hemoglobin (30); Total blood cell count (13); Differential white cell count (18). *HISTOLOGY*--Microscopic examination of histological specimens (303). *CHEMICAL ANALYSES FOR AROMATIC HYDROCARBONS*--Sediment samples (5).

Physiology

Replicate water samples from the weathered-oil generator have been taken daily 3 times/week in January-March, and the petroleum hydrocarbons extracted. One of each replicate was analyzed by GC for total hydrocarbons. In addition, replicate samples of the weathered oil were taken simultaneously with the water samples to correlate compositional changes in the oil and water samples.

Control and oil-exposed chum salmon eggs have been collected periodically for both developmental analysis and hydrocarbon uptake.

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MALINS, D.C. "Metabolic Fate of Hydrocarbons in Marine Fish: Evidence for Metabolite Formation." Presented at the 8th Annual Symposium of the Analytical Chemistry of Pollutants, Geneva, Switzerland, April 1978.

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SPARKS, A.K. "The Ultrastructure of Cells Associated with Proliferative Disorders in Mussels, *Mytilus edulis*, from Yaquina Bay, Oregon." Presented at the Society for Invertebrate Pathology, Prague, Czechoslovakia, October, 1978.

STEHR, C. "A Comparative Study of the Chorion and Associated Pore Structure of Starry Flounder, *Platichthys stellatus* and Pink Salmon, *Oncorhynchus gorbuscha* Eggs." Presented at the 29th Alaska Science Conference, AAAS, Fairbanks, Alaska, August 1978.

VARANASI, U. "Metabolism and Disposition of Naphthalene in Starry FLounder (*Platichthys stellatus*)." Presented at the 62nd Annual Meeting of FASEB, Atlantic City, N.J., April 1978.

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APPENDIX

CHARACTERISTICS OF CATARACTOUS LENSES OF RAINBOW TROUT

At high magnification with light microscopy and with electron microscopy, damage to lenses was observed to be limited to the epithelium and peripheral fiber cells (See Figs. 1 to 14). In opaque regions of affected lenses, the subepithelial areas appeared to be a locus of major damage. A proliferation of epithelial cells was apparent in some zones but was not uniform throughout the opaque region. In other areas, the epithelium formed a normal, single layer of cells, but the fiber cell zone directly beneath was abnormal in that there was no definition of individual cells. Within the region normally occupied by about ten successive layers of fiber cells there were disrupted membranes, large expanses of electron-lucent material and a variety of inclusions.

Regions of the cataractous lenses that remained clear had numerous damaged fiber cells interspersed with normal appearing cells. The area of affected fibers was not as extensive as in the opaque regions nor was the degree of disorganization of membranes as pronounced. The lateral projections, however, were disrupted in lens fiber cells which also had cytoplasmic changes.

With scanning microscopy it was evident that there was considerable loss of surface structure from both the clear and opaque areas of the lens. The most noticeable change was the loss of ball-and-socket structures on the fiber surface. In addition, lateral projections lost their uniform pattern, and in some areas of the opaque region individual filaments were almost indistinguishable.

MORPHOLOGY OF EGG MEMBRANES OF STARRY FLOUNDER AND PINK SALMON

The zona radiata of the starry flounder consisted of six continuous horizontal lamellae of approximately equal thickness (See Figs. 15 to 19). Numerous pore canals penetrated the zona radiata. A 0.1 μm triple-layered border formed the outer surface of the zona radiata and shaped a slightly depressed lip as it circumvented the openings to pore canals. An outer 0.02 μm electron-opaque dense layer, a center 0.04 μm electron-transparent layer, and an inner 0.04 μm electron-opaque layer composed the border. Beneath the pore openings a space or widening of the canals occurred, which viewed from the surface, appeared as blind openings. Surface observations with SEM revealed the openings of circular pore canals and the micropyle which tapered to 5-6 μm farther inside the canal. The thin surface border formed an edge which surrounded the micropyle, and within a 8-10 μm area, contained pore openings as small as 0.3 μm. The area containing the terminal aperture of the micropyle, as observed in a single specimen, appeared as a protuberance 23 μm in diameter with a center depression 9.5 μm across. Numerous 0.5 μm pores spaced about 1.6 μm apart bordered the outside edge of the depression. A centrally-located protrusion 3.6 μm across occurred within the depression and in the area where the terminal opening to the micropyle would be expected.

The pink salmon egg membrane was composed of numerous short, discontinuous lamellae (See Figs. 20 to 27). An irregular coating 0.2-1.5 μm thick covered most of the surface of the zona radiata and the openings of the pore canals. An osmophilic border about 1.0 μm thick formed the outer boundary of the zona radiata. Electron dense inclusions or invaginations of the border were situated just below the surface of the zona radiata. Occasional gaps in the coating revealed pore canal openings, some of which were slightly raised with a centrally located protrusion. Pore canals penetrated the zona radiata, which produced a columnar-like appearance of the lamellae when viewed in cross section. The micropyle was surrounded by an irregular edge formed by the thin outer coating. Protrusions 0.6-0.8 μm in diameter were incorporated into the coating, which formed a 30-50 μm area surrounding the micropyle. Occasionally, small secondary openings of varying sizes were observed within the area of protrusions. These openings passed through the outer coating into the zona radiata; however, the extent of penetration was not known. The inside surface of the egg membrane contained the terminal aperture of the micropyle which appeared as a two-level protuberance. The diameter of its base was 20-30 μm, and the uppermost level was approximately 10 μm across. A central 5-6 μm crater-like depression contained the 2 μm terminal aperture of the micropyle. A plug-like structure was seen in the aperture three minutes after combination of sperm with the egg.

LIST OF FIGURE CAPTIONS

1. Scanning electron micrograph of lens fibers from the trout. The surface aspect of the fiber cells is apparent on the left and the broken edges of successive layers at 90° on the right (900 X).

2. Detailed view of three fiber cell layers. The surface architecture of indentations and projections that nestle the fibers together as well as the intricate patterns of the interlocking lateral projections are evident (5,000 X).

3. Transmission electron micrograph of cortical fibers from normal lens. These complex fibers includes numerous attachment structures and organelles such as mitochondria (3,300 X).

4. Nuclear fibers from normal trout lens. There is not only a change in dimensions (see text) but reduction in attachment elements and further loss of typical subcellular organelles (24,000 X).

5. Light micrograph of lens epithelium and cortical fiber cells from opaque area of lens. The fibers directly beneath the surface epithelium are disrupted and there is a proliferation of epithelial cells (1,100 X).

6. Transmission electron micrograph of the opaque area of a cataractous lens. Fiber cells in the subepithelial region have a number of abnormal, disrupted membranes, dense vesicles and clear vacuoles (4,700 X).

7. Fiber cells from a clear area of a cataractous lens. There is a decrease in electron density in the abnormal fiber cells (5,500 X).

8. Scanning electron micrograph of surface changes in fiber cells from the clear area of a cataractous lens. The surface ball and socket structures are reduced in number and the lateral interdigitations are irregular (1,000 X).

9. Area of extensive disruption in the clear region of a cataractous lens (3,000 X).

10. Opaque zone of a cataractous lens. The individual filament cells are degenerated and have lost both dorso-ventral and lateral membrane integrity (2,000 X).

11. Opaque region of cataractous lens. There is such extensive degradation of the fiber cells that their borders are nearly indistinguishable (2,000 X).

12-14. Effects of hydration on lens filament surface with scanning electron microscopy.
    12. Micrograph of a normal lens for comparison (2,400 X).
    13. Lens hydrated in distilled water. Osmotic swelling of the fibers is followed by shrinkage and wrinkling during processing (2,400 X).
    14. Lens hydrated in distilled water with loss of structure in the lateral projections (4,800 X).

15. Comparison of pink salmon (on the left) and starry flounder (on the right) egg membrane and associated structures.

16. Transmission electron micrograph (TEM) of a starry flounder egg membrane. Pore openings and portions of a canal penetrate the six lamellae (30,000 X).

17. Scanning electron micrograph (SEM) of a starry flounder egg membrane broken edge. The fine structure of the lamellae are not distinguishable with SEM (15,000 X).

18. Micropyle of a starry flounder egg (SEM) 2 minutes after sperm was added to the eggs. A sperm lies beside the micropyle. The sperm head diameter is 2.0 µm. Material in the micropyle canal may be debris or a plug formed as a result of fertilization changes in the membrane (4,500 X).

19. The terminal aperture of the starry flounder micropyle (SEM). The internal face of the membrane is relatively smooth, correlating with the homogenous structure of the lamellae forming this surface (2,400 X).

20. Pink salmon egg membrane (TEM) (1,300 X).

21. Pink salmon membrane surface, enlarged from top circle of Figure 6 (TEM). Electron dense inclusions or invaginations of the border form at the opening to the pore canals (12,000 X).

22. Lamellar structure at the internal face of the membrane, enlarged from bottom circle of Figure 6 (TEM). Microvilli are still present in this area of the pore canals (4,700 X).

23. Cross section of a pink salmon membrane (SEM). Different densities of lamellae form three zones (a, b, and c) (1,000 X).

24. (Insert) High magnification (SEM) of a short discontinuous lamellae. Spaces aligned perpendicular to the lamellar structures are pore canals (4,200 X).

25. Pink salmon egg surface (SEM). Except for the micropyle area, the irregular coating (on the left) contains no protrusions. A gap in the coating reveals pore canal openings containing an unknown structure, perhaps remnants of microvilli or extrusions that may form the coating. Sperm lying on the surface average 2 µm in diameter (4,600 X).

26. Pink salmon micropyle (SEM) 45 seconds after sperm was added to the eggs. A single sperm occupies the micropyle canal. Protrusions surround the micropyle, and a secondary opening occurs on the left (5,000 X).

27. Terminal aperture of the pink salmon micropyle (SEM). The lamellar structure and pore canals form the filamentous and porous appearance of the internal membrane face. Extraneous bacteria lie to the side (5,000 X).

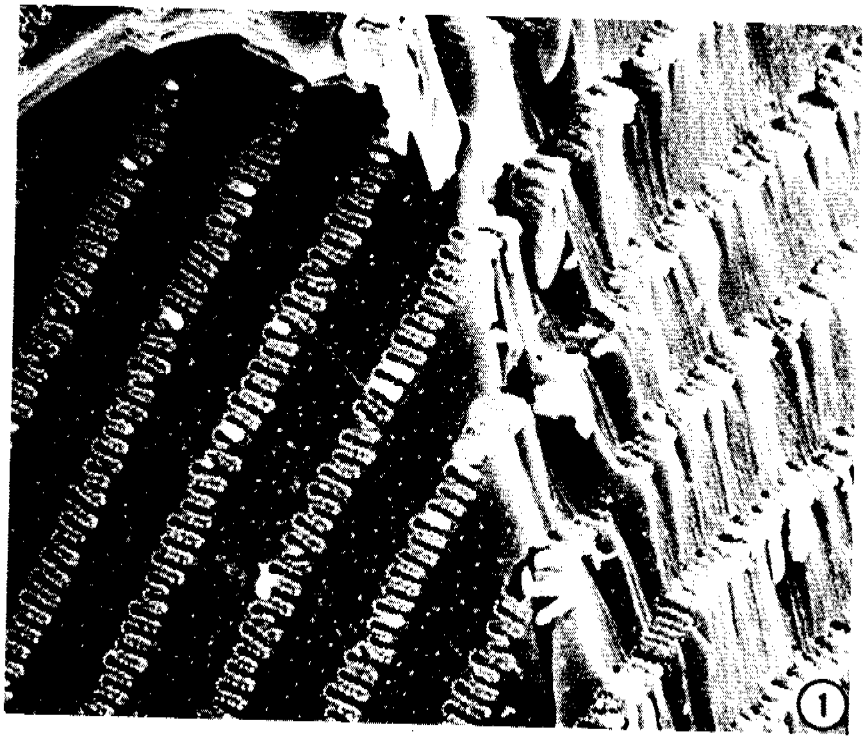


Figure 1. Scanning electron micrograph of lens fibers from the trout. The surface aspect of the fiber cells is apparent on the left and the broken edges of successive layers at 90° on the right (900 X).

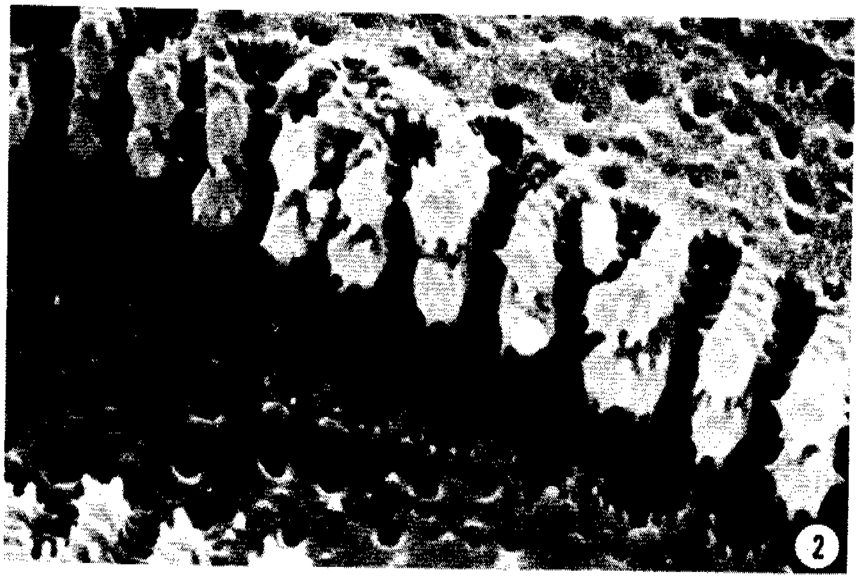


Figure 2. Detailed view of three fiber cell layers. The surface architecture of indentations and projections that nestle the fibers together as well as the intricate patterns of the interlocking lateral projections are evident (5,000 X).

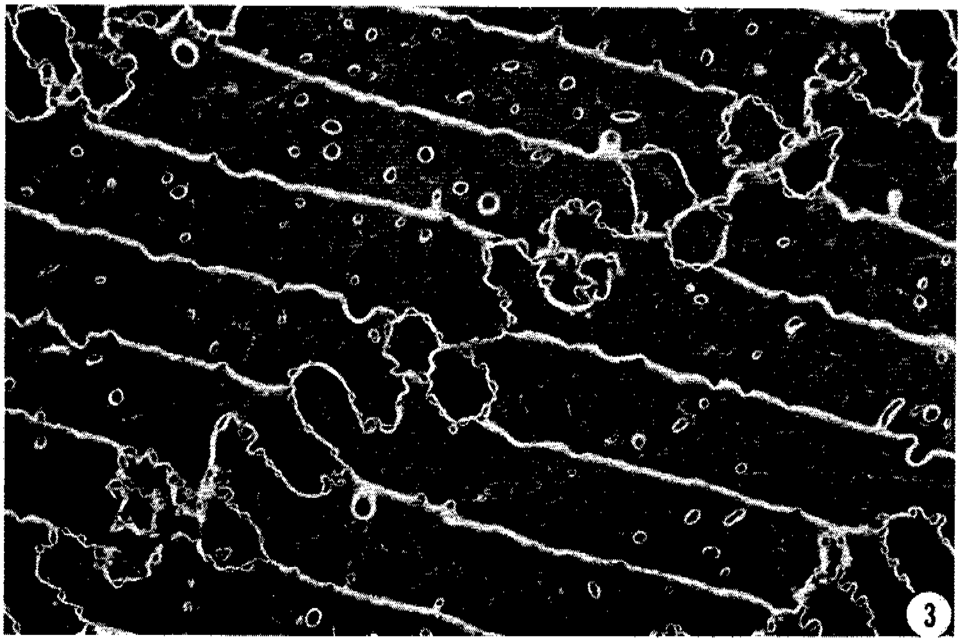


Figure 3. Transmission electron micrograph of cortical fibers from normal lens. These complex fibers includes numerous attachment structures and organelles such as mitochondria (3,300 X).

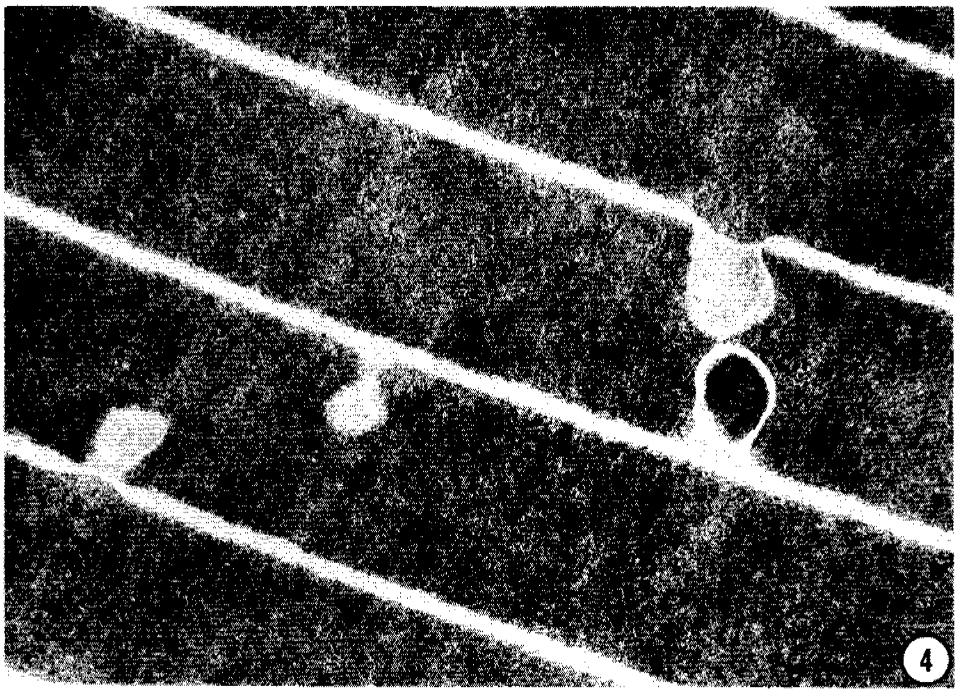


Figure 4. Nuclear fibers from normal trout lens. There is not only a change in dimensions (see text) but reduction in attachment elements and further loss of typical subcellular organelles (24,000 X).

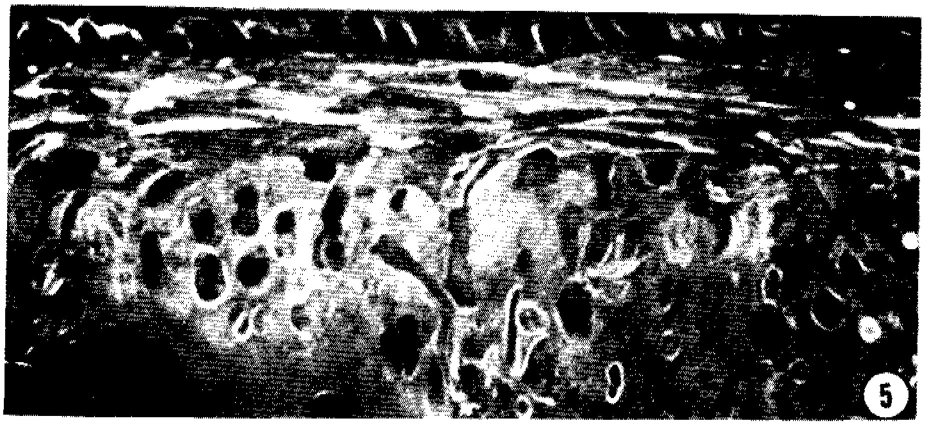


Figure 5. Light micrograph of lens epithelium and cortical fiber cells from opaque area of lens. The fibers directly beneath the surface epithelium are disrupted and there is a proliferation of epithelial cells (1,100 X).

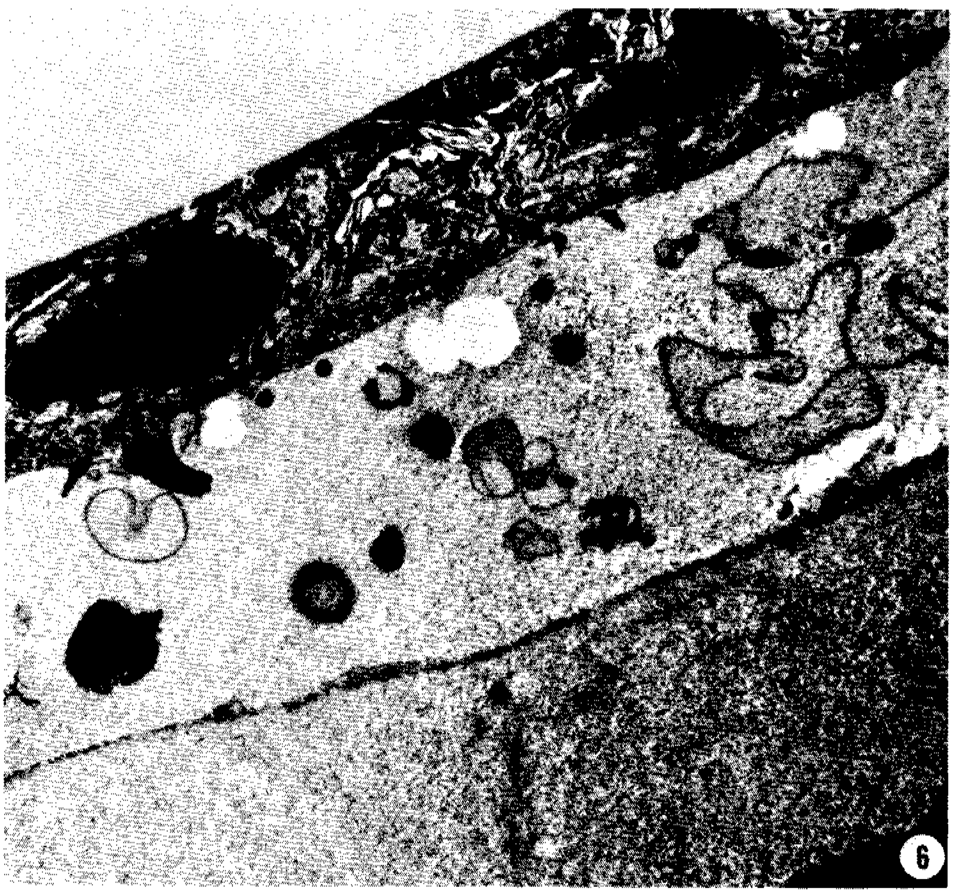


Figure 6. Transmission electron micrograph of the opaque area of a cataractous lens. Fiber cells in the subepithelial region have a number of abnormal, disrupted membranes, dense vesicles and clear vacuoles (4,700 X).

Figure 7. Fiber cells from a clear area of a cataractous lens. There is a decrease in electron density in the abnormal fiber cells (5,500 X).

Figure 8. Scanning electron micrograph of surface changes in fiber cells from the clear area of a cataractous lens. The surface ball and socket structures are reduced in number and the lateral interdigitations are irregular (1,000 X).

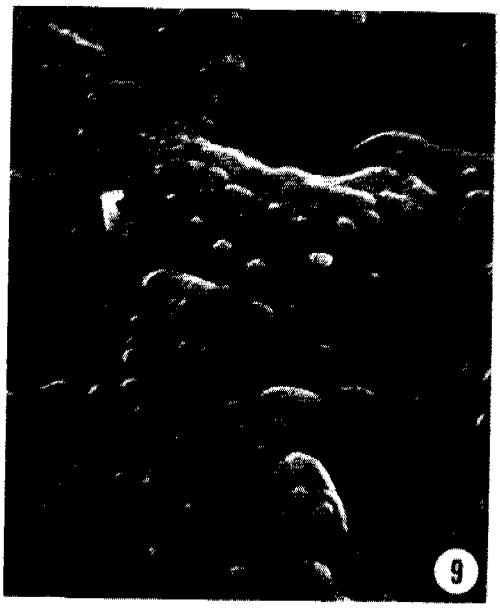


Figure 9. Area of extensive disruption in the clear region of a cataractous lens (3,000 X).

Figure 10. Opaque zone of a cataractous lens. The individual filament cells are degenerated and have lost both dorsoventral and lateral membrane integrity (2,000 X).

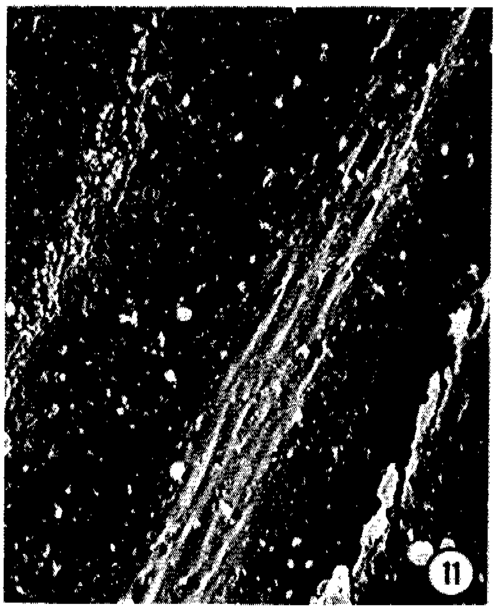
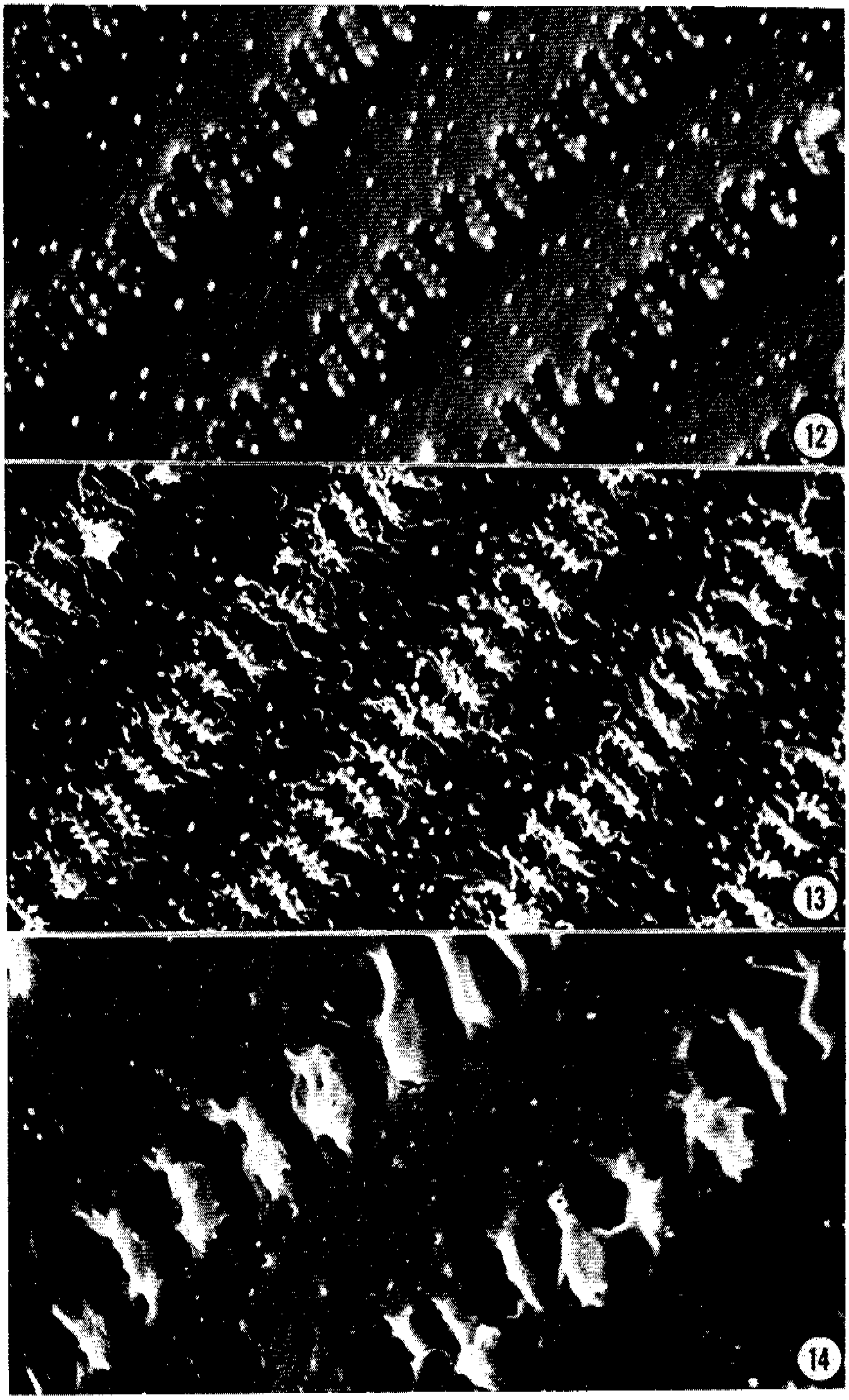
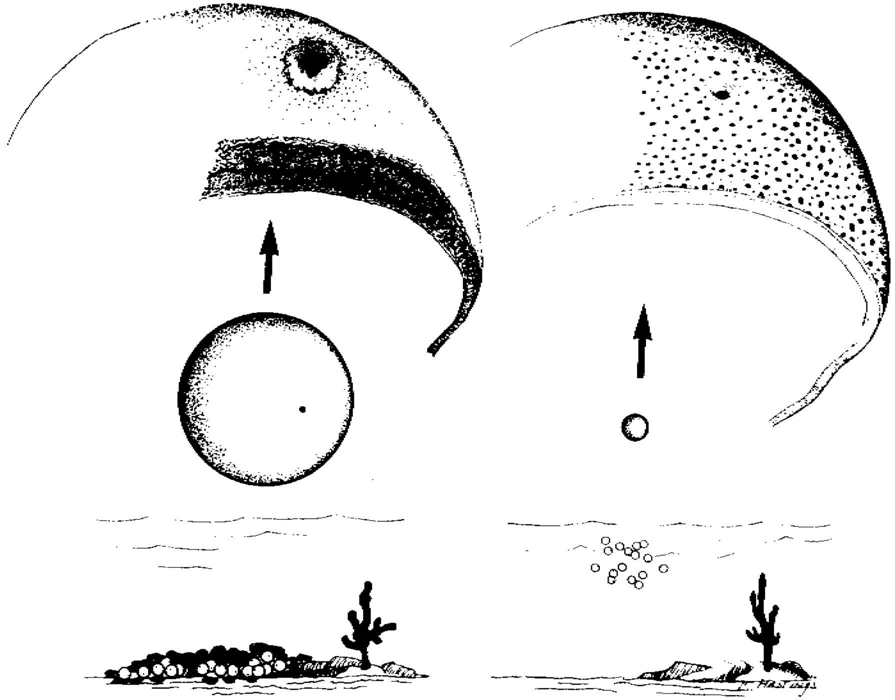


Figure 11. Opaque region of cataractous lens. There is such extensive degradation of the fiber cells that their borders are nearly indistinguishable (2,000 X).



Figures 12-14. Effects of hydration on lens filament surface with scanning electron microscopy.

12. Micrograph of a normal lens for comparison (2,400 X).
13. Lens hydrated in distilled water. Osmotic swelling of the fibers is followed by shrinkage and wrinkling during processing (2,400 X).
14. Lens hydrated in distilled water with loss of structure in the lateral projections (4,800 X).



	Egg diameter (mm)	Zona radiata thickness (μm)	Micropyle opening diameter (μm)	Pore canal opening diameter (μm)	Spacing between pore canal openings (μm)
Starry flounder (*Platichthys stellatus*)	0.9	2.0-5.0	8-10	0.6-0.7	1.0-2.0
Pink salmon (*Oncorhynchus gorbuscha*)	7.0	55-70	15-16	0.7-0.8	1.0-2.0

Fig. ⑮ Comparison of pink salmon (on the left) and starry flounder (on the right) egg membrane and associated structures.

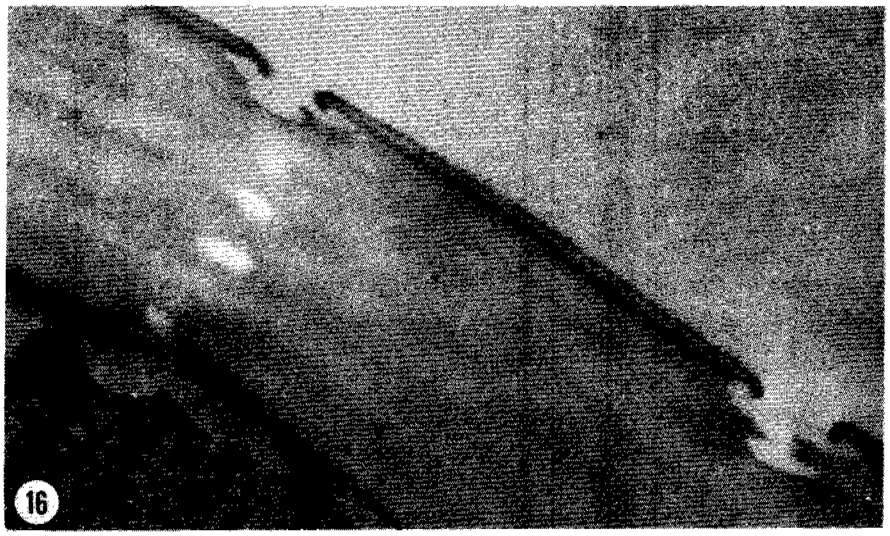


Figure 16. Transmission electron micrograph (TEM) of a starry flounder egg membrane. Pore openings and portions of a canal penetrate the six lamellae (30,000 X).

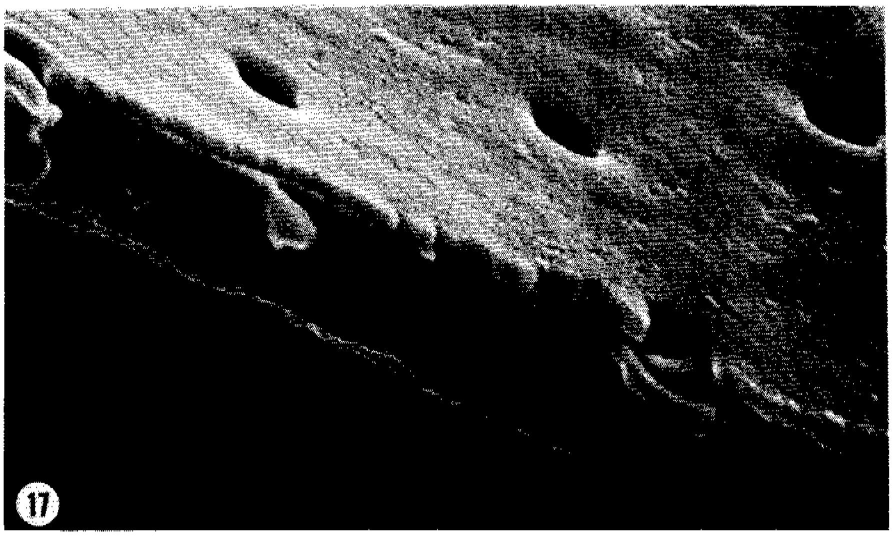


Figure 17. Scanning electron micrograph (SEM) of a starry flounder egg membrane broken edge. The fine structure of the lamellae are not distinguishable with SEM (15,000 X).

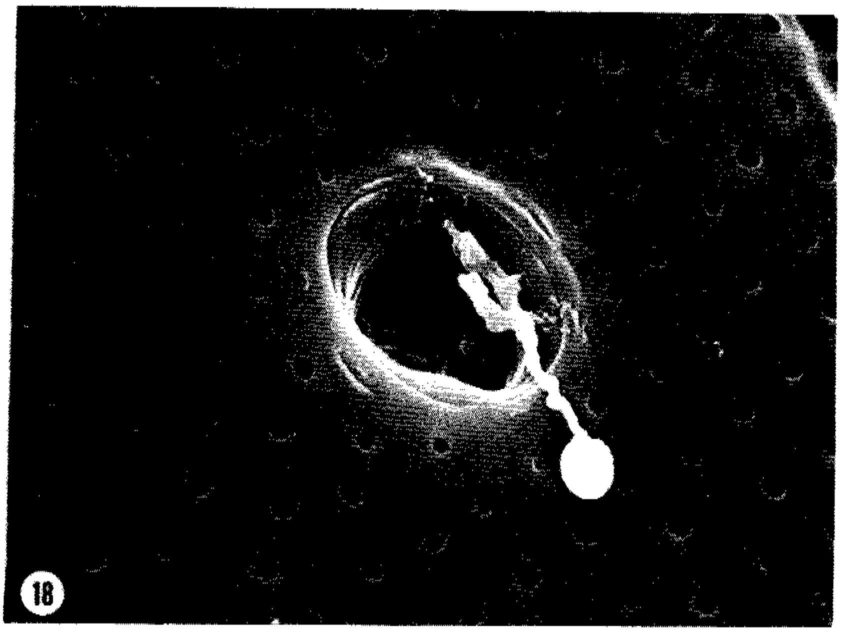


Figure 18. Micropyle of a starry flounder egg (SEM) 2 minutes after sperm was added to the eggs. A sperm lies beside the micropyle. The sperm head diameter is 2.0 μm. Material in the micropyle canal may be debris or a plug formed as a result of fertilization changes in the membrane (4,500 X).

Figure 19. The terminal aperture of the starry flounder micropyle (SEM). The internal face of the membrane is relatively smooth, correlating with the homogenous structure of the lamellae forming this surface (2,400 X).

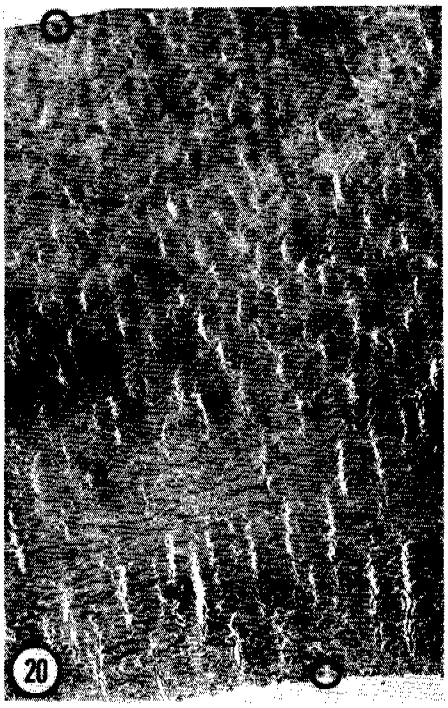


Figure 20. Pink salmon egg membrane (TEM) (1,300 X).

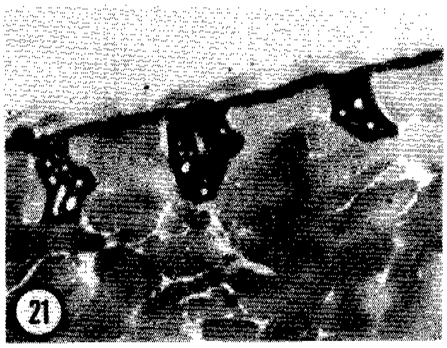


Figure 21. Pink salmon membrane surface, enlarged from top circle of Figure 6 (TEM). Electron dense inclusions or invaginations of the border form at the opening to the pore canals (12,000 X).

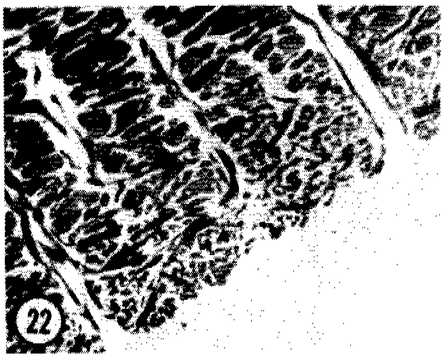


Figure 22. Lamellar structure at the internal face of the membrane, enlarged from bottom circle of Figure 6 (TEM). Microvilli are still present in this area of the pore canals (4,700 X).

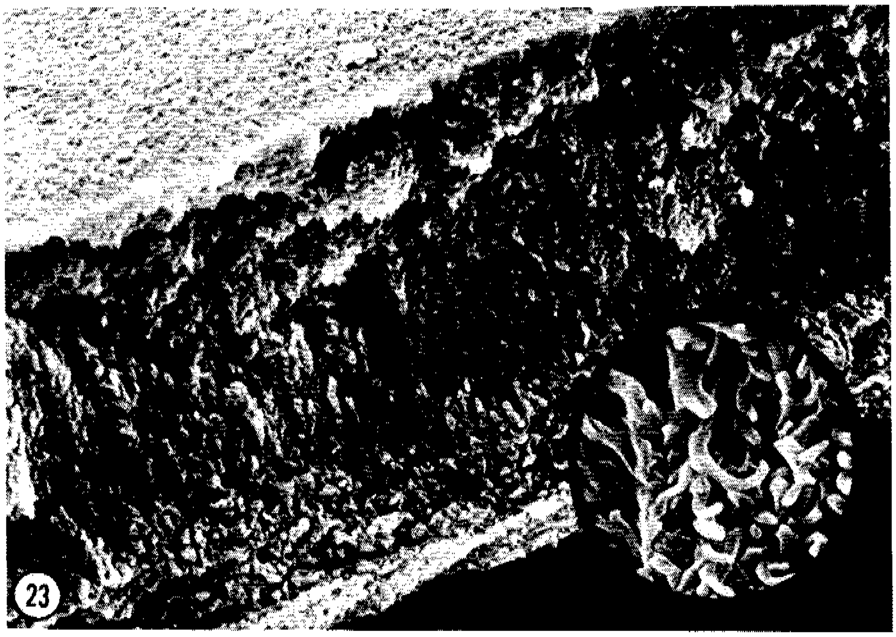


Figure 23. Cross section of a pink salmon membrane (SEM). Different densities of lamellae form three zones (a, b, and c) (1,000 X).

Figure 24. (Insert) High magnification (SEM) of a short discontinuous lamellae. Spaces aligned perpendicular to the lamellar structures are pore canals (4,200 X).

Figure 25. Pink salmon egg surface (SEM). Except for the micropyle area, the irregular coating (on the left) contains no protrusions. A gap in the coating reveals pore canal openings containing an unknown structure, perhaps remnants of microvilli or extrusions that may form the coating. Sperm lying on the surface average 2 μm in diameter (4,600 X).

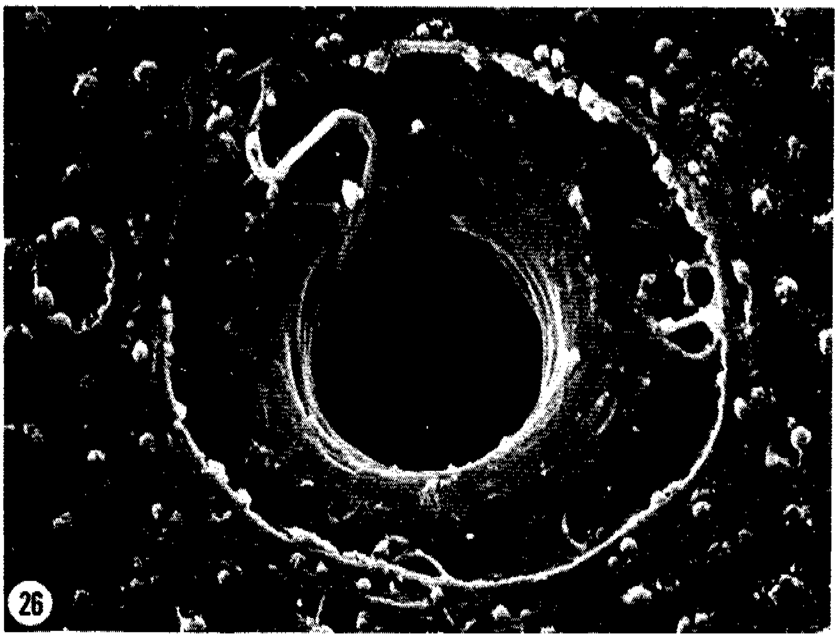


Figure 26. Pink salmon micropyle (SEM) 45 seconds after sperm was added to the eggs. A single sperm occupies the micropyle canal. Protusions surround the micropyle, and a secondary opening occurs on the left (5,000 X).

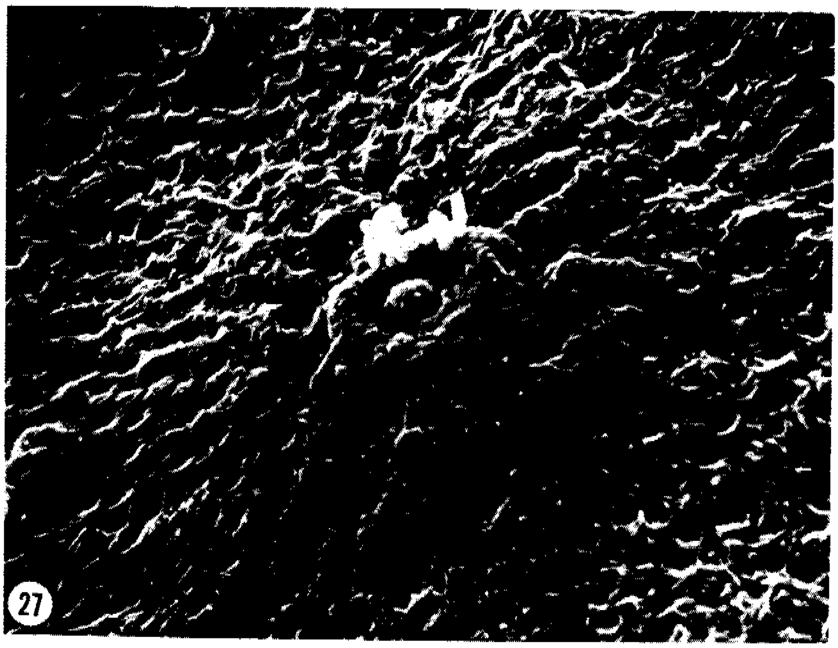


Figure 27. Terminal aperture of the pink slamon micropyle (SEM). The lamellar structure and pore canals form the filamentous and porous appearance of the internal membrane face. Extraneous bacteria lie to the side (5,000 X).

RESEARCH TO DETERMINE THE ACCUMULATION OF ORGANIC CONSTITUENTS AND HEAVY METALS FROM PETROLEUM-IMPACTED SEDIMENTS BY MARINE DETRITIVORES OF THE ALASKAN OUTER CONTINENTAL SHELF

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CONTENTS

List of Tables . . . .

List of Figures . . . .

Abstract . . . .

Introduction . . . .

Oil Weathering Study . . . .

Uptake of Trace Metals from Clean and Oil-Contaminated Detritus . . .

Condition Index and Free Amino Acid Level of *Protothaca staminea* Exposed to Oil-Contaminated Sediment . . . .

Distribution of Polyaromatic Hydrocarbons and Degradation Products in a Sediment Exposure System . . . .

Analysis of GPC Purified Extracts by Reverse-Phase Liquid Chromatography . . . .

Effects of Prudhoe Bay Crude Oil Contamination on Sediment Working Rates of *Abarenicola pacifica* . . . .

Literature Cited . . . .

LIST OF TABLES

Table 1. Parameters measured during the course of the weathering experiment.

Table 2. Concentrations of saturate hydrocarbons in Prudhoe Bay crude oil (PBC) and in 24 day weathered oil samples. Concentrations in mg/gram oil.

Table 3. Concentration of aromatic hydrocarbons in Prudhoe Bay crude oil (PBC) and in 24 day weathered oil samples. Concentrations in mg/gram oil.

Table 4. Significance in the relationships between the concentrations of various saturate and aromatic hydrocarbons and hydrocarbon types and the type of exposure. Confidence limits are measured at the 95% level.

Table 5. Co content of filtered sea water ($\mu g \times 10^{-5}/ml$).

Table 6. Detritus (mg/g d.w.) ingested by <u>Macoma inquinata</u>

Table 7. Metals (µg/g d.w.) incorporated into <u>Macoma inquinata</u> exposed to oiled and non-oiled detritus.

Table 8. Condition indices of initial control, field control, and exposed <u>Protothaca staminea</u>.

Table 9. Free amino acid concentration in gills, mantle, and adductor muscle of Protothaca staminea (µmoles/g).

Table 10. Recovery of ^{14}C-aromatic hydrocarbons from clam tissue.

Table 11. Separation of aromatic hydrocarbons and possible metabolic products by gel permeation chromatography.

Table 12. ^{14}C-phenanthrene, chrysene and benzo(a)pyrene interstitial water-sediment distributions. % water in experimental sediments = 15.7 ± 1.2, n = 43.

Table 13. ^{14}C-phenanthrene, chrysene, benzo(a)pyrene <u>Macoma</u> tissue-sediment-interstitial water distribution. Dry weight of tissue = 16.9% of wet weight.

Table 14. Percent recovery of ^{14}C radioactivity from tissue and sediment extracts chromatographed on GPC and reverse phase liquid chromatographic systems.

Table 15. Adsorption characteristics of ^{14}C-phenanthrene and ^{14}C activity from 30 day phenanthrene interstitial water sample on XAD-2 resin.

Table 16. Hydrocarbon content of sediment after 11 days in the exposure system (ppm).

Table 17. Effects of PBC on survival and behavior of *Abarenicola pacifica*.

Table 18. Effects of PBC on sediment working rate of *Abarenicola pacifica*.

LIST OF FIGURES

Figure 1. Gas capillary chromatograms of (A) saturate hydrocarbon fraction from original Prudhoe Bay crude oil and (B) saturate hydrocarbon fraction from 24 day weathered oil sample from Tank #1.

Figure 2. Gas capillary chromatograms of (A) aromatic hydrocarbon fraction from original Prudhoe Bay crude oil and (B) aromatic hydrocarbon fraction from 24 day weathered oil sample from Tank #1. C denotes monoaromatic hydrocarbon region.

Figure 3. Detritus (mg/g) ingested by *Macoma inquinata*.

Figure 4. Incorporation of radio-labelled zinc into *Macoma* tissue.

Figure 5. Incorporation of radio-labelled cobalt into *Macoma* tissue.

Figure 6. *Macoma* sediment exposure apparatus.

Figure 7. Scheme for the extraction and analysis of ^{14}C radioactivity from clam tissue, sediment and interstitial water.

Figure 8. ^{14}C radioactivity in tissue and sediments from phenanthrene exposure (n = 3).

Figure 9. ^{14}C radioactivity in tissue and sediments from chrysene exposure (n = 3).

Figure 10. ^{14}C radioactivity in tissue and sediments from benzo (a)-pyrene exposure (n = 3).

Figure 11. Effect of exposure to crude oil impacted sediment on regression of weight-specific fecal weight on body weight *Abarenicola pacifica*.

ABSTRACT

Prudhoe Bay crude oil was weathered 24 days under different conditions of light and agitation. The weathering resulted in the complete disappearance of light saturate (C_8 to C_{10}) compounds and of most monoaromatics under all conditions. Severe agitation and exposure to light caused the disappearance of 72% or more of the heavier saturates (up to C_{26}) and of 49% or more of the diaromatics. A relative enrichment of triaromatics was observed. Gentler agitation and protection from light had qualitatively similar effects but to a lesser degree.

Macoma inquinata were exposed to detritus, containing neutron activated native metals, in the presence and absence of 1000 ppm Prudhoe Bay crude oil. Oil did not enhance the net uptake of Fe, Zn, Co, or Cr, but did reduce the feeding rate of the clams in comparison with the controls.

Protothaca staminea were exposed to 1200 ppm Prudhoe Bay crude oil in the field for 54 days. Eighty-five percent of the group survived, compared to 17% of a similar group of Macoma. The average condition index of the surviving Protothaca were reduced by 6% and their average taurine content by 58%, while their average glycine content did not differ significantly from non-oiled controls. In a group of Macoma exposed at an earlier time under milder conditions the condition index was reduced by 16% and the glycine level by 38%. It was concluded that the suspension feeder Protothaca suffers less stress as a result of exposure to oiled sediment than the detritus feeder Macoma.

Macoma inquinata were exposed for sixty days to a coarse sand sediment contaminated with ^{14}C labelled phenanthrene, chrysene, or benzo(a)pyrene. Ninety percent of the phenanthrene disappeared from the sediment during the exposure. The phenanthrene level in the clams rose during the first three days and dropped steadily thereafter. The level of ^{14}C in the interstitial water, which was carried on a polar metabolite rather than on parent phenanthrene, rose for two weeks and then dropped. By contrast, over 70% of the

added chrysene and benzo(a)pyrene remained in the sediment. The amount of radioactivity associated with these compounds rose steadily in the clams and interstitial water through the exposure period. Less chrysene and benzo(a)pyrene than phenanthrene was present in the interstitial water at any time, but about thirty times as large a proportion of the originally added 4- and 5-ring compounds as of the 3-ring compound remained in the clams after 60 days. There was no evidence that any of the polyaromatic hydrocarbons were metabolized by *Macoma*.

Lugworms (*Abarenicola pacifica*) were exposed to sediment containing 250 to 1000 ppm Prudhoe Bay crude oil. At concentrations of 500 and 1000 ppm, the rate of feeding, as measured by fecal production, was reduced by 70%. In control animals a marked negative regression of weight-specific feeding rate on body size was found. Exposure to oil at high levels abolished this regression by depressing the rate more in smaller individuals.

INTRODUCTION

Increasing concern has been expressed in recent years about the entry of petroleum hydrocarbons into the marine environment resulting from the production and transportation of oil. An effort has been initiated to investigate the components or products of oil that are available to benthic intertidal organisms and the effects of such components on the organisms. As part of this effort we have used a variety of approaches to study shifts in hydrocarbon composition resulting from physico-chemical and biological actions, the accumulation of petroleum hydrocarbon fractions and metals in representative organisms, and several effects on the physiology and behavior of these organisms.

Two species of bivalves and a sedentary polychaete have been utilized: the detritivorous clam Macoma inquinata, the suspension feeder Protothaca staminea, and the detritivorous worm Abarenicola pacifica. Exposures utilized coarse sand and fine mud, both in the laboratory and in the field, as well as detritus from natural sources. Several analytical techniques were employed to quantify hydrocarbons in animal tissue and sediment: gas capillary chromatography, infrared spectrophotometry, high pressure liquid chromatography, and liquid scintillation spectrometry. Trace metals were analyzed by neutron-activation analysis. Effects on organisms were studied by gravimetric methods and chromatographic amino acid analysis.

To date we have conducted experiments to examine the following: (1) changes in hydrocarbon composition of Prudhoe Bay crude oil resulting from exposure to air, water, and sunlight; (2) the effect, or lack thereof, of petroleum hydrocarbons on the bioavailability of metals in detritus; (3) condition index and free amino acid content of oil exposed suspension feeding clams; (4) long-term uptake, distribution, and metabolism of specific aromatic compounds from sediment; and (5) effect of crude oil on behavior of benthic infauna. Prudhoe Bay crude oil was the test oil in all experiments.

OIL WEATHERING STUDY

Materials and Methods

Three large volume tanks measuring 1.6 m in diameter and 0.9 m deep (2 m^2 area and 1,830 ℓ volume) were layered with 20 ℓ of Prudhoe Bay crude oil. Each tank received flowing seawater that was maintained at a constant level by an external standpipe.

Each tank simulated a different weathering condition:

Tank #1: To simulate weathering under violent weathering conditions inflow water was injected through holes in pipes (about 12 cm) above the surface of the oil (without a sun shield).

Tank #2: To simulate weathering under calm conditions in the presence of sunlight, a slow flow of seawater was both injected and removed from below the oil slick.

Tank #3: To reduce the effects of sunlight (photo-oxidation of hydrocarbons), a system similar to tank #2 was prepared but with a sun shield over the oil.

Three replicate 25 ml samples were taken from each tank at days 1, 2, 4, 8, 16, and 24. These samples were placed in small vials that were completely filled with oil and then wrapped with foil to exclude light and sealed with a teflon lined cap and refrigerated. Each sample vial was washed in CCl_4 and N_2 dried before use.

At termination (24 days) additional samples were taken for future analysis. These samples consisted of a 1 liter sample from each tank that was packaged and immediately shipped to Alaska and a 1 gallon sample taken for use by other investigators. These samples were taken and prepared similarly to the routine samples described above.

Due to some unforeseeable circumstance, the 1 gallon termination samples from tanks #2 and #3 exploded and all the samples were lost. Therefore, a second gallon was taken from tanks #2 and #3 two days later to replace the lost ones. These samples were only filled 2/3 full, and the lids left slightly loosened to allow the pressure to be relieved. Approximately 2 ℓ of each oil has been placed in PVC tubes (with caps) and frozen at -70°C until needed.

Samples of the original and weathered oil were shipped frozen to the Battelle, Pacific Northwest Laboratories, for hydrocarbon analyses. 6-100 mg samples of oil were chromatographed according to the method of Warner (1976) with the following modifications: Fifteen grams of silica gel (Grace Davison

Chemical Company, 100-200 mesh) was used to separate the oil into saturate (eluted with 40 ml in hexane) and aromatic (eluted with 86 ml of 20% CH_2Cl_2 in hexane) fractions. The fractions, collected in 40 ml conical tubes, were concentrated under a stream of nitrogen without the aid of external heat, transferred to 5 ml conical vials and concentrated to 1 ml. An internal standard (2, 6, 10-trimethyldodecane for saturate fraction, hexamethylbenzene for aromatic fraction) was added to each sample, and the samples were analyzed by capillary gas chromatography. Individual hydrocarbons were separated and quantitated on a Hewlett Packard 5840 A gas chromatograph employing 30 meter OV-101 glass capillary columns operating at 65°C with an initial 4 minute hold and then programmed at 4°/min to 250°C. Data reported in Tables 2 and 3 were corrected based on the recovery data of aliphatic and aromatic hydrocarbon standards. Typical recoveries were 82-111% for saturate hydrocarbons (C_{12} to C_{24}) and 84-89% for aromatic hydrocarbons (naphthalene to dimethylphenanthrenes).

Results and Discussion

Flow rates in each tank as well as several other weathering parameters were monitored daily during the course of the experiment. These data are summarized in Table 1.

Average relative decreases of saturate hydrocarbons (between C_{12} and C_{26}) in tanks #2 and #3 after 24 days of exposure ranged between 45% and 49% (Table 2). These results are in marked contrast to tank #1 where an average relative decrease of 83% was observed. The saturate hydrocarbons C_8 - C_{10}, although present in the original oil, were not detectable in any of the 24 day weathered oil samples (Figure 1).

Relative decreases in the concentrations of aromatic hydrocarbons were different from those observed for the saturate hydrocarbons in the three exposure systems. Decreases in aromatic hydrocarbons (naphthalene - 3, 6-dimethylphenanthrene) were 37% for tanks #1 and #2 and 9% for tank #3. The tricyclic aromatic hydrocarbons (phenanthrene - 3, 6-dimethylphenanthrene) appeared to have the greatest persistence, with relative enrichments occurring in tank #1 (Table 3). 3, 6-dimethylphenanthrene showed relative enrichment in all three exposure systems. Also reported in Table 3 are concentrations for a variety of mono-aromatic hydrocarbons (toluene - 1, 2, 3, 5-tetramethylbenzene). The concentration values reported for these compounds in the

Table 1. Parameters measured during the course of the weathering experiment.

	X ± S.D.	N	Range Maximum	 Minimum
Air temperature by stem thermometer in °C. Randomly taken during day	12.20 ± 1.65	16	15.5	10.0
Water temperature by stem thermometer in °C taken at outfall of tank #3 randomly during day	9.88 ± 0.51	16	10.6	9.0
Salinity by refractometer in ppt taken at outfall of tank #3 randomly during day	30.19 ± 0.36	16	31.0	30.0
Light by meter in (Lux) ca over tanks @ 0800 hrs	$9.3X10^4$ ± $5.1X10^4$	15	$1.75X10^5$	$2.2X10^4$
Light by meter in (Lux) ca over tanks @ 1200 hrs	$2.54X10^5$ ± $9.0X10^4$	10	$3.5X10^5$	$1.31X10^5$
Light by meter in (Lux) ca over tanks @ 1600 hrs	$1.52X10^5$ ± $6.9X10^4$	7	$2.7X10^5$	$6.6X10^4$
Flow rate in tank #1 in ℓ/min randomly during day	26.66 ± 4.37	16	30.0	15.0
Flow rate in tank #2 in ℓ/min randomly during day	8.95 ± 0.34	16	10.0	8.5
Flow rate in tank #3 in ℓ/min randomly during day	8.58 ± 1.93	16	15.0	5.0

Table 2. Concentrations of Saturate Hydrocarbons in Prudhoe Bay Crude Oil (PBC) and in 24 Day Weathered Oil Samples. Concentrations in mg/gram oil.

Compound	Concentration in Original Oil[1]	Concentration in Weathered Oil[2]			Relative Decrease in Concentration (%)[3]		
		Tank No. 1	Tank No. 2	Tank No. 3	Tank No. 1	Tank No. 2	Tank No. 3
C_8	4.20 ± 0.12	*	*	*	100	100	100
C_9	4.42 ± 0.10	*	*	*	100	100	100
C_{10}	4.44 ± 0.35	*	*	*	100	100	100
C_{11}	4.68 ± 0.08	0.15 ± 0.02	0.22 ± 0.01	1.68 ± 0.32	96.8	95.3	64.1
C_{12}	4.62 ± 0.15	0.54 ± 0.01	0.97 ± 0.02	2.19 ± 0.40	88.3	79.0	52.6
C_{13}	4.46 ± 0.26	0.63 ± 0.02	1.64 ± 0.05	2.38 ± 0.15	85.9	63.2	46.6
C_{14}	4.16 ± 0.05	0.69 ± 0.01	1.93 ± 0.06	2.26 ± 0.20	83.4	53.6	45.7
C_{15}	3.99 ± 0.22	0.70 ± 0.01	1.99 ± 0.05	2.15 ± 0.24	82.5	50.1	46.1
C_{16}	3.74 ± 0.24	0.64 ± 0.02	1.85 ± 0.05	1.99 ± 0.29	82.9	50.5	46.8
C_{17}	3.39 ± 0.42	0.58 ± 0.03	1.75 ± 0.04	1.85 ± 0.26	82.9	48.4	45.4
Pristane	2.07 ± 0.38	0.33 ± 0.02	1.04 ± 0.02	1.12 ± 0.12	84.1	49.8	45.9
C_{18}	2.50 ± 0.24	0.48 ± 0.05	1.38 ± 0.04	1.30 ± 0.23	80.8	44.8	48.0
Phytane	1.05 ± 0.24	0.22 ± 0.01	0.57 ± 0.03	0.58 ± 0.04	79.0	45.7	44.8
C_{19}	3.04 ± 0.76	0.46 ± 0.01	2.07 ± 0.24	1.73 ± 0.10	84.9	31.9	43.1
C_{20}	1.93 ± 0.24	0.38 ± 0.02	1.08 ± 0.04	0.99 ± 0.17	79.8	44.0	48.7
C_{21}	1.58 ± 0.20	0.33 ± 0.03	1.05 ± 0.27	0.85 ± 0.19	79.1	33.5	46.2
C_{22}	1.86 ± 0.30	0.31 ± 0.03	1.18 ± 0.01	1.24 ± 0.30	83.3	36.6	33.3
C_{23}	1.65 ± 0.29	0.30 ± 0.03	1.20 ± 0.12	1.26 ± 0.31	81.8	27.3	23.6
C_{24}	1.27 ± 0.26	0.30 ± 0.04	1.11 ± 0.19	1.00 ± 0.24	76.4	12.6	21.3
C_{25}	1.02 ± 0.55	0.24 ± 0.03	0.79 ± 0.16	0.71 ± 0.13	76.5	22.5	30.4
C_{26}	0.76 ± 0.23	0.21 ± 0.02	0.60 ± 0.15	0.53 ± 0.07	72.4	21.1	30.3
Total (C_{12}- C_{26})	43.39 ± 4.27	7.30 ± 0.10	21.98 ± 0.61	23.98 ± 4.27	Avg% 83.1	49.3	44.7

[1] Compounds C_8- C_{11} were corrected for recovery on the basis of the recovery of C_{12} hydrocarbon and, therefore, more than likely are low.

[2] * indicates compound not detected at the sensitivity level that analyses were conducted.

[3] $$\frac{\text{concentration in original oil - concentration in weathered oil}}{\text{concentration in original oil}} \times 100$$

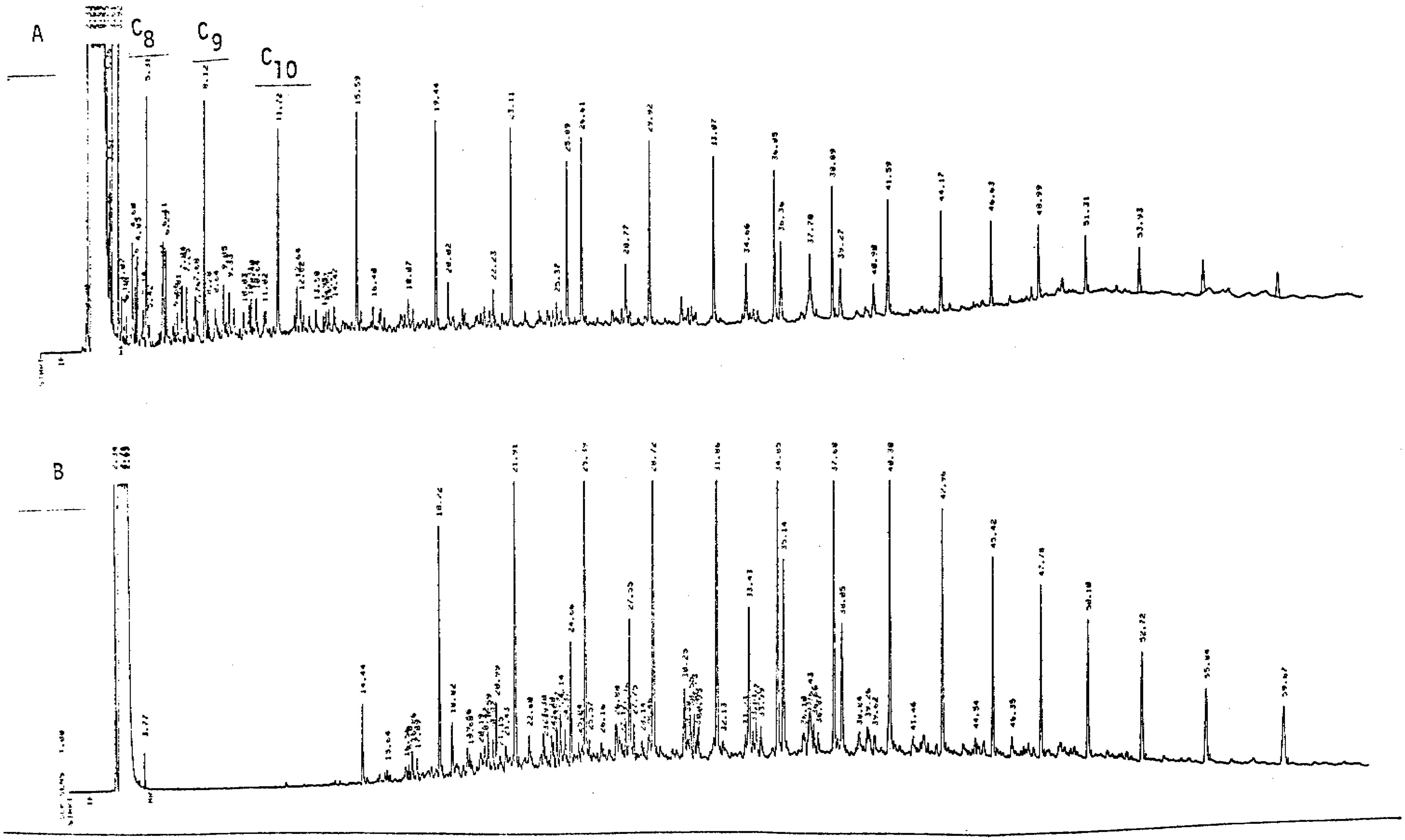

Figure 1. Gas Capillary Chromatograms of (A) Saturate Hydrocarbon Fraction from Original Prudhoe Bay Crude Oil and (B) Saturate Hydrocarbon Fraction from 24 Day Weathered Oil Sample from Tank #1.

Table 3. Concentrations of Aromatic Hydrocarbons in Prudhoe Bay Crude Oil (PBC) and in 24 Day Weathered Oil Samples. Concentrations in mg/gram oil.

Compound	Concentration in Original Oil[1]	Concentration in Weathered Oil[2] Tank No. 1	Tank No. 2	Tank No. 3	Relative Decrease in Concentration %[3] Tank No. 1	Tank No. 2	Tank No. 3
toluene	0.82 ± 0.08	*	*	*	100	100	100
ethylbenzene	0.56 ± 0.01	*	*	*	100	100	100
m+p-xylene	2.05 ± 0.04	*	*	*	100	100	100
o-xylene	0.79 ± 0.01	*	*	*	100	100	100
isopropylbenzene	0.16 ± 0.00	*	*	*	100	100	100
1-ethyl+4-methylbenzene	0.29 ± 0.00	*	*	*	100	100	100
1,3,5-trimethylbenzene	0.41 ± 0.00	*	*	*	100	100	100
1,2,4-trimethylbenzene	1.14 ± 0.01	*	*	*	100	100	100
secbutylbenzene	0.14 ± 0.00	*	*	*	100	100	100
methyl-4-isopropylbenzene	0.12 ± 0.00	*	*	*	100	100	100
indane	0.67 ± 0.00	*	*	*	100	100	100
1,3-dimethyl-5-ethylbenzene	0.27 ± 0.00	*	*	*	100	100	100
1,2-diethylbenzene	0.24 ± 0.02	*	*	*	100	100	100
1,2-dimethyl-4-ethylbenzene	0.24 ± 0.01	*	*	*	100	100	100
1,2,4,5-tetramethylbenzene	0.38 ± 0.00	0.03 ± 0.00	*	0.25 ± 0.03	**	100	**
1,2,3,5-tetramethylbenzene	0.27 ± 0.00	0.03 ± 0.00	*	0.18 ± 0.02	**	100	**
napthalene	0.92 ± 0.01	0.06 ± 0.01	0.16 ± 0.01	0.51 ± 0.08	93.5	82.6	44.6
2-methylnapthalene	1.63 ± 0.02	0.53 ± 0.07	0.76 ± 0.08	1.34 ± 0.18	67.5	53.4	17.8
1-methylnapthalene	1.29 ± 0.02	0.48 ± 0.06	0.69 ± 0.06	1.20 ± 0.16	62.8	46.5	7.0
1-ethyl+2-ethylnapthalene	0.48 ± 0.00	0.27 ± 0.03	0.43 ± 0.08	0.51 ± 0.06	43.8	10.4	-6.3
2,6+2,7-dimethylnapthalene	0.69 ± 0.01	0.52 ± 0.06	0.83 ± 0.13	0.94 ± 0.12	24.6	-20.3	-36.2
1,3+1,6-dimethylnapthalene	0.99 ± 0.01	0.51 ± 0.06	0.70 ± 0.05	0.91 ± 0.12	48.5	29.3	8.1
1,7-dimethylnapthalene	1.10 ± 0.01	0.51 ± 0.04	0.77 ± 0.06	0.94 ± 0.12	53.6	30.0	14.5
1,4+2,3+1,5-dimethylnapthalene	0.80 ± 0.01	0.52 ± 0.06	0.35 ± 0.11	0.90 ± 0.12	35.0	56.3	-12.5
1,2-dimethylnapthalene	0.40 ± 0.00	0.23 ± 0.03	0.21 ± 0.01	0.37 ± 0.04	42.5	47.5	7.5
2,3,6-trimethylnapthalene	0.51 ± 0.07	0.26 ± 0.03	0.39 ± 0.12	0.43 ± 0.04	49.0	23.5	15.7
phenanthrene	0.38 ± 0.05	0.61 ± 0.06	0.34 ± 0.05	0.22 ± 0.00	-60.5	10.5	42.1
1-methylphenanthrene	0.33 ± 0.02	0.77 ± 0.15	0.24 ± 0.02	0.31 ± 0.04	-133.3	27.3	6.7
2-methylphenanthrene	0.21 ± 0.01	0.53 ± 0.04	0.19 ± 0.01	0.22 ± 0.02	-152.4	9.5	-4.8
3,6-dimethylphenanthrene	0.11 ± 0.00	0.53 ± 0.04	0.24 ± 0.05	0.20 ± 0.04	-381.8	-118.2	-81.8
Total (napthalene - 3,6-dimethylphenanthrene)	9.91 ± 0.15	6.21 ± 0.42	6.27 ± 0.41	9.03 ± 1.05			

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[1] Monoaromatic hydrocarbons have not been corrected for recovery.

[2] *compound not detected at the sensitivity level that analyses were conducted

[3] $\frac{\text{Concentration in original oil - concentration in weathered oil}}{\text{concentration in original oil}}$ X 100; minus sign indicates higher concentration of compound found in weathered oil on weathered oil basis as compared to original oil.

**Relative decrease in concentration % was not calculated because recovery data was not obtained on monoaromatic hydrocarbons.

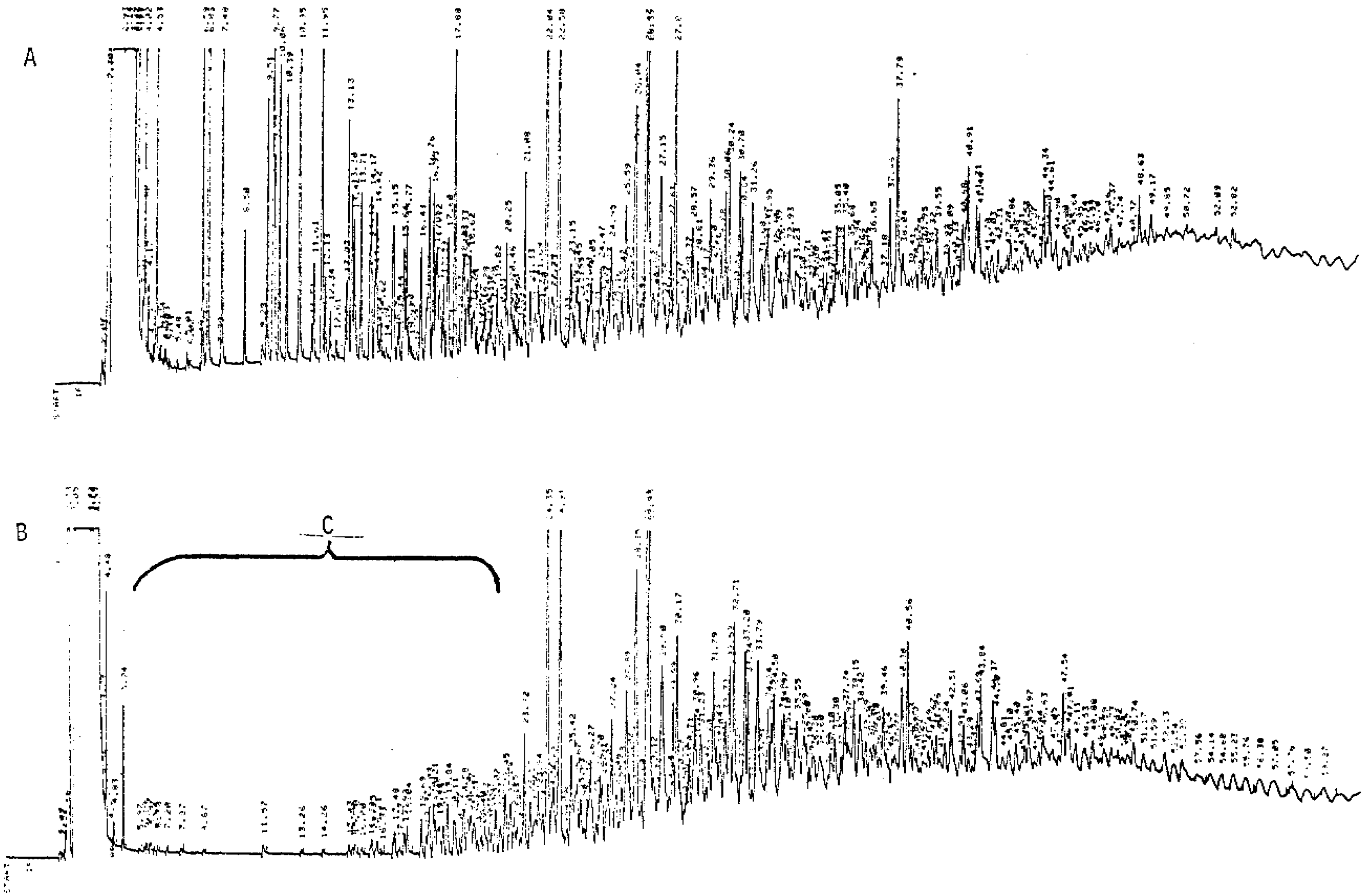

Figure 2. Gas Capillary Chromatograms of (A) Aromatic Hydrocarbon Fraction from Original Prudhoe Bay Crude Oil and (B) Aromatic Hydrocarbon Fraction from 24 Day Weathered Oil Sample from Tank #1. C denotes monoaromatic hydrocarbon region.

Table 4. Significance in the Relationships Between the Concentrations of Various Saturate and Aromatic Hydrocarbons and Hydrocarbon Types and the Type of Exposure. Confidence Limits are Measured at the 95% Level.

Hydrocarbon or Hydrocarbon Type	Concentration in mg/gram Oil Tank #1	 Tank #2	 Tank #3
		S.D.[1]	
$(C_{12} - C_{26})$ + Pristane + Phytane	7.30 ± 0.10	21.98 ± 0.61	23.98 ± 4.27
	S.D.		N.S.D.[2]
		S.D.	
Napthalene	0.06 ± 0.01	0.16 ± 0.01	0.52 ± 0.08
	N.S.D.		S.D.
		S.D.	
Methylnapthalenes	1.01 ± 0.12	1.43 ± 0.14	2.54 ± 0.34
	N.S.D.		S.D.
		S.D.	
Dimethylnapthalenes	2.29 ± 0.22	2.83 ± 0.27	4.12 ± 0.54
	N.S.D.		N.S.D.
		S.D.	
2,3,6-Trimethylnapthalene	0.26 ± 0.03	0.39 ± 0.12	0.43 ± 0.04
	N.S.D.		N.S.D.
		S.D.	
Phenanthrene	0.61 ± 0.06	0.34 ± 0.05	0.22 ± 0.01
	S.D.		S.D.
		S.D.	
Methylphenanthrenes	1.19 ± 0.06	0.43 ± 0.03	0.52 ± 0.05
	S.D.		N.S.D.

Table 4 (cont.)

Hydrocarbon or Hydrocarbon Type	Concentration in mg/gram Oil				
	Tank #1		Tank #2		Tank #3
			S.D.		
3,6-Dimethylphenanthrene	0.53 ± 0.04		0.26 ± 0.03		0.20 ± 0.04
		S.D.		N.S.D.	
			S.D.		
Total Aromatics (Napthalene - 3,6-dimethylphenanthrene)	6.21 ± 0.42		6.27 ± 0.41		9.03 ± 1.05
		N.S.D.		N.S.D.	

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[1] S.D. = significantly different

[2] N.S.D. = not significantly different

original oil were not corrected for recovery and were not a part of the original research. Nevertheless, they are reported because, with the exception of the tetramethylbenzenes, none of these compounds were detected in the 24 day weathered oil samples from any of the three exposure systems. These results are more graphically depicted in Figure 2 where the gas capillary chromatogram of the aromatics fraction of the original crude oil is compared to the aromatics fraction derived from the 24 day weathered oil sample of tank #1.

Confidence limits were determined for establishing the significance of differences observed between various saturate and aromatic hydrocarbons and hydrocarbon types in the three exposure systems. These results are compiled in Table 4. Variability associated with the sum of all saturate hydrocarbons C_{12} - C_{26} including pristane and phytane indicated differences between tank #1 vs. tanks #2 and #3 to be significant; however, total differences between tanks #2 and #3 were not significant. Significant differences were also found for the concentrations of all aromatic hydrocarbons and hydrocarbon types between tanks #1 and #3. Significant trends in the differences in concentrations of the aromatic components of tank #1 vs. tank #2 and tank #2 vs. tank #3 are more subtle. No significant differences in the concentrations of diaromatic hydrocarbons and hydrocarbon types are observed between tanks #1 and #2; however, significant differences are observed for the triaromatics. Although significant differences in the concentrations of naphthalene, methylnaphthalene, and phenanthrene were observed, no trends were observed for the aromatic components of tanks #2 vs. tank #3.

Conclusions

The combination of light and water exposure parameters of tank #1 produced the largest relative decreases in volatile saturate (C_{12} to C_{26}) and most aromatic (naphthalene -2, 3, 6-trimethylnaphthalene) hydrocarbons relative to the original oil of the three exposure systems. Detectable amounts of monoaromatic hydrocarbons were absent in all three weathered oils as were the saturate hydrocarbons from C_8 to C_{10}. The different exposure parameters of tank #1 and #3 produced the greatest differences in the volatile hydrocarbon content of these oils following 24 days of weathering. The decreases in the content of most aromatic compounds were less for oil protected from light, water agitation, and somewhat from air circulation (tank #3). The only components shown to increase somewhat in tank 3 in proportion to the original oil was the heaviest compound, 3, 6-dimethylphenanthrene. This component was enriched to a greater extent in tank 2 and in tank 1 its contribution to the total was nearly four times as great. There was an increasing degree of enrichment in the weathered (mousse) oil in tank 1 as molecular weight increased from phenanthrene to the 3, 6-dimethylphenanthrene. These data may well indicate that higher molecular weight compounds of 4 and 5 rings (polynuclear aromatics) are also enriched in weathered oil and perhaps relative to their molecular weight. The significance of this possibility is rather large since possible tainting and/or effects from carcinogenic or mutagenic compounds in this class could be enhanced. The polynuclear aromatics are less water soluble than those identified in Table 3, so it is not likely that water column species would be affected. However, the mixing of weathered oil with sediments may produce an environment more hazardous to benthic species than contamination from fresh oil.

The results of this preliminary experiment on oil weathering have produced very interesting results regarding aromatic compounds up to dimethylphenanthrene. Other analytical methods should be used to characterize the alterations in polynuclear aromatics to determine the relative hazard of weathered oil compared to fresh oil. As the most dramatic effects from enrichment of polynuclear aromatics would be on benthic organisms, particularly detritivores, weathered oil should be used in laboratory and field exposures. Results of these tests could then be compared to our findings on effects from fresh oil to evaluate the potential hazard.

UPTAKE OF TRACE METALS FROM CLEAN AND OIL-CONTAMINATED DETRITUS

Methods

Previous experiments have indicated that the presence of oil has little or no effect on the availability of trace metals from sediment. A final experiment has been conducted, using longer periods of exposure and depuration and examination of a larger number of isotopes. Detritus was collected from the laboratory seawater system head tanks, dried, subjected to neutron activation for two hours at a neutron flux of approximately 1×10^{13} n cm^{-2} sec^{-1}, and aged for three months to reduce its activity. Six g dry weight of neutron activated detritus was added to 100 g wet weight of "cold" detritus and 1 liter sea water, which was then shaken by hand for 1 minute. The resulting slurry was aerated and held in a water table five days, then filtered onto #42 Whatman paper and divided into two portions. One received 100 ml sea water and 1 ml ether containing enough Prudhoe Bay crude oil to produce a concentration of 1000 ppm oil in the sediment. The other received only sea water and ether. The detritus was shaken 4 minutes and filtered again, and a sample of oiled detritus was removed for gamma counting.

Two liters of sea water were placed in each side of two two-sided aquaria which were surrounded by a water bath at 13°C. Oiled or non-oiled detritus was placed in one side of each aquarium and allowed to settle to the bottom and thirty *Macoma inquinata* were placed in each of the four compartments. Water was pumped out of the detritus-containing sides, passed through a 100 μ mesh nylon screen and transferred to the other side, from which it returned by flowing over the dividing barrier. This system allowed for the aeration of both sides without agitating the detritus enough to suspend it in the water column. Thus only metals dissolved in water or on particles less than 100 μ in diameter could reach the animals on the filtered side of the aquarium. When necessary small amounts of detritus which had accumulated on the bottom of the filtered side were removed by gentle suction and returned to the detritus side.

Groups of five clams were removed from each compartment after 2, 4, 8, and 15 days of exposure and shucked, and the meat and shells were rinsed in fresh sea water. Shells were scrubbed if needed, to remove adhering detritus. The meat and shells of each group was dried to constant weight at 80°C. One-hundred ml samples of filtered sea water were taken after 2, 8, and 15 days and evaporated to dryness for counting. Samples of oiled and non-oiled detritus were removed and dried on the 15th day of exposure, for gamma counting.

After 15 days of exposure the remaining clams were transferred to depuration tanks with clean water and detritus, which was replaced after two and four days. Groups of five clams were removed after 2 and 8 days of depuration and prepared for counting. The gamma activity of samples of detritus, meat, shells, and residue from evaporated sea water was measured on a Ge(Li)diode.

Results

The numbers of net counts at energy levels corresponding to ^{51}Cr, ^{152}Eu, ^{46}Sc, ^{59}Fe, ^{65}Zn, and ^{60}Co were calculated and corrected for the rates of decay of each isotope to determine the count rate/g d.w./1000 minutes at the time each sample was removed from the experiment. The relation between the corrected isotope count and the actual amount of metal present was established by reference to the known metal content of the dtritus. These values had been established in this laboratory for K, Ca, Ti, V, Cr, Mn, Fe, Cu, Zn, Se, Pb, and As, and for all these there was good agreement with the trace metal concentrations in shale as reported by Krauskopf (Introduction to Geochemistry, pp. 639-640, McGraw-Hill, New York, 1967; taken from Vinogradov, Geokhimiya, Vol. 1962, pp. 560-561). Therefore, it seemed quite probable that the elemental composition of the collected detritus was similar to that of shale and the levels of Eu, Sc, and Co in shale were accepted as those present in the detritus.

It was thus possible to determine for each sample the amount of metal present per g or per ml sea water. However, since the clams were not depurated to purge their intestinal tracts before they were shucked and dried, it was necessary to determine how much of their total sample isotope content was incorporated into their tissue and how much was only in transit through their guts. Since scandium is known to be associated only with detritus and not incorporated into tissue, its concentration was used to calculate the amount of detritus present per g d.w. of the total *Macoma* samples. This amount was multiplied by the known detrital or shale concentration of each of the other metals present, and the products were subtracted from the total amounts. The differences corresponded to the tissue concentration of each metal.

One example of this treatment of the data is given here:

Metal	Concentration in shale	Concentration in detritus	Corrected Counts /1000 mins/g d. w. detritus	Corrected Counts /1000 mins/ g d.w. *Macoma* (non-oiled, 4 days)
Sc	10 μg/g		287,907	4086
Zn	80 μg/g	88 μg/g	3,493	90

$\frac{3493}{88} = \frac{90}{x}$ $x = 2.27$ μg Zn/g d.w. total *Macoma* sample.

$\frac{287,907}{10} = \frac{4086}{y}$ $y = .142$ μg Sc/g d.w. total *Macoma* sample.

$\frac{10}{10^6} = \frac{.142}{z}$ $z = 14,200$ μg = 14.2 mg detritus/g d.w. total *Macoma* sample.

$\frac{14.2 \times 88}{1000} = 1.25$ μg Zn/g d.w. sample, associated with detritus.

$2.27 - 1.25 = 1.02$ μg Zn/g d.w. sample, incorporated into tissue.

The only metal which appeared consistently at detectable levels in sea water was cobalt. As shown in Table 5, the amount of Co given up by oiled and non-oiled sediment did not differ.

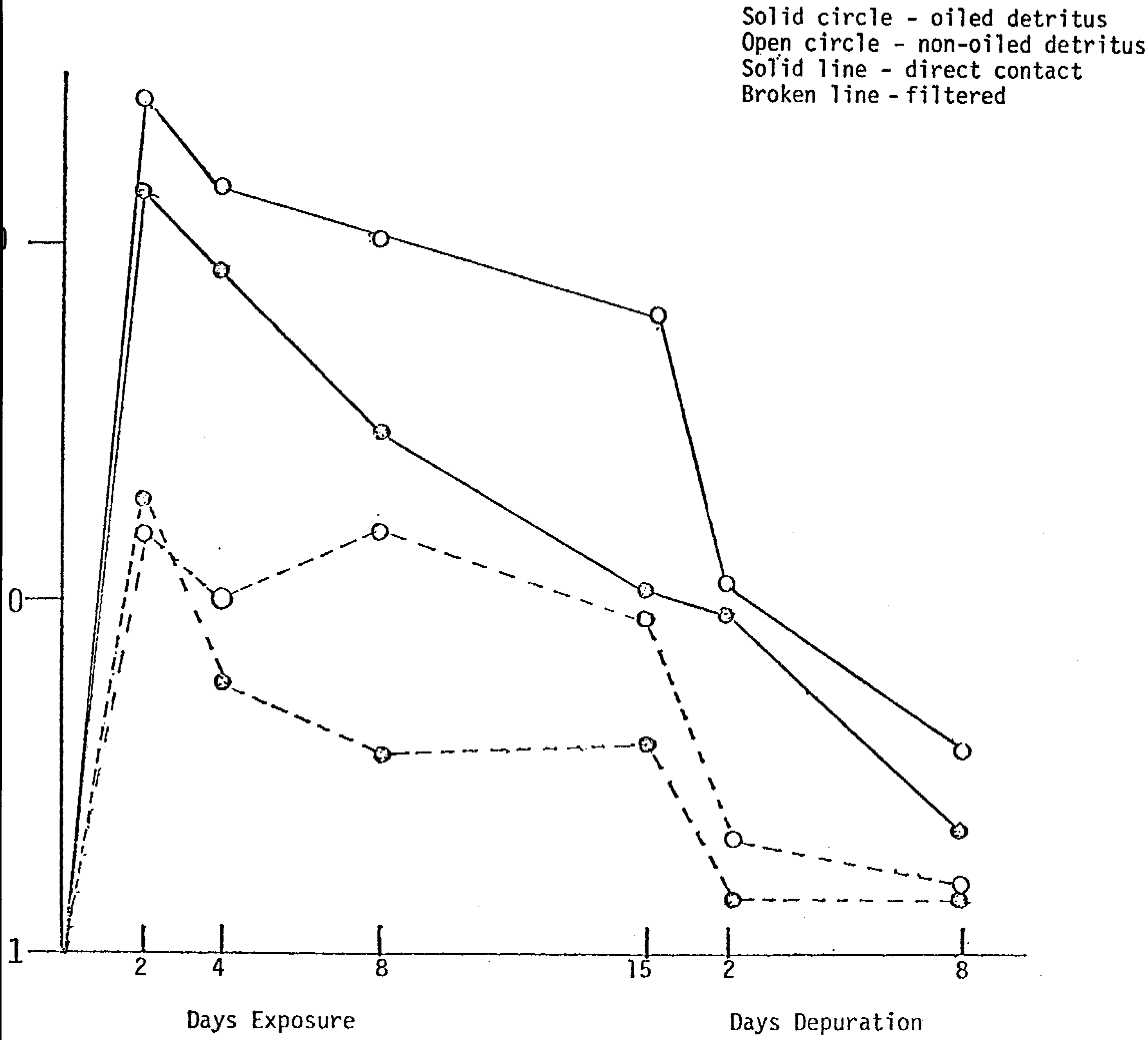
Table 5. Co content of filtered sea water (μg x 10^{-5}/ml).

Days Exposure	Oiled	Non-oiled
2	5.1	4.5
8	4.15	no sample
15	6.0	5.5

Cr, Eu, and Sc appeared sporadically in sea water and Fe and Zn did not appear.

The detrital contents, calculated from the scandium levels of the samples, indicated that the clams fed in the first two days of direct exposure to detritus, and the net amount of food in their digestive tracts declined thereafter. Initially about 2½% of the body dry weight was composed of detritus in the absence of oil. In the presence of oil only one half as much food was taken in initially, and it was lost at a greater rate. On the filtered side of the aquaria, less than one tenth as much non-oiled

Figure 3. Detritus (mg/g) ingested by <u>Macoma inquinata</u>.



detritus was taken up initially, as compared to the side containing the bulk of the detritus. This level changed less during the course of exposure. Clams receiving filtered water from oiled detritus took in about as much as the non-oiled controls. Table 6 and Figure 3 illustrate these results.

Table 6. Detritus (mg/g d.w.) ingested by Macoma inquinata.

Days Exposure	Non-oiled	Oiled	Non-oiled (filtered)	Oiled (filtered)
2	25.7	13.5	1.53	1.99
4	14.2	8.31	.96	.57
8	10	2.97	1.52	.37
15	6.2	1.07	.88	.38
Days Depuration				
2	1.1	.88	.22	.14
8	.37	.24	.15	.14

Table 7 shows the amounts of metal per g d.w. incorporated into Macoma tissue. Evidence for the incorporation of metals from detritus into tissue was found only for Co and Zn. Cr was detected in only three clam samples, though it was present in the detritus. Eu was accumulated at barely detectable levels, and no labelled Fe remained in the tissue longer than eight days.

Figures 4 and 5 show the amounts of Co and Zn incorporated into Macoma tissues during two weeks exposure to labelled detritus and one week depuration. Those organisms which received their metal through the water column or on very fine particles incorporated nearly identical amounts whether oil was present or absent. Those which had direct access to detritus incorporated the same amounts early in the exposure period, but later the oiled animals took in less. This difference is probably due to the fact that less oiled than non-oiled detritus was ingested and, therefore, a smaller amount of labelled metal was available for absorption across the walls of the intestinal tract.

The labelled-metal contents after two days exposure of two groups of shells has been determined. They ranged between 2 and 10% of the concentration of the corresponding metals in the clam flesh.

Figure 4. Incorporation of radio-labelled zinc into Macoma tissue.

Solid circle - oiled detritus
Open circle - non-oiled detritus
Solid line - direct contact
Broken line - filtered

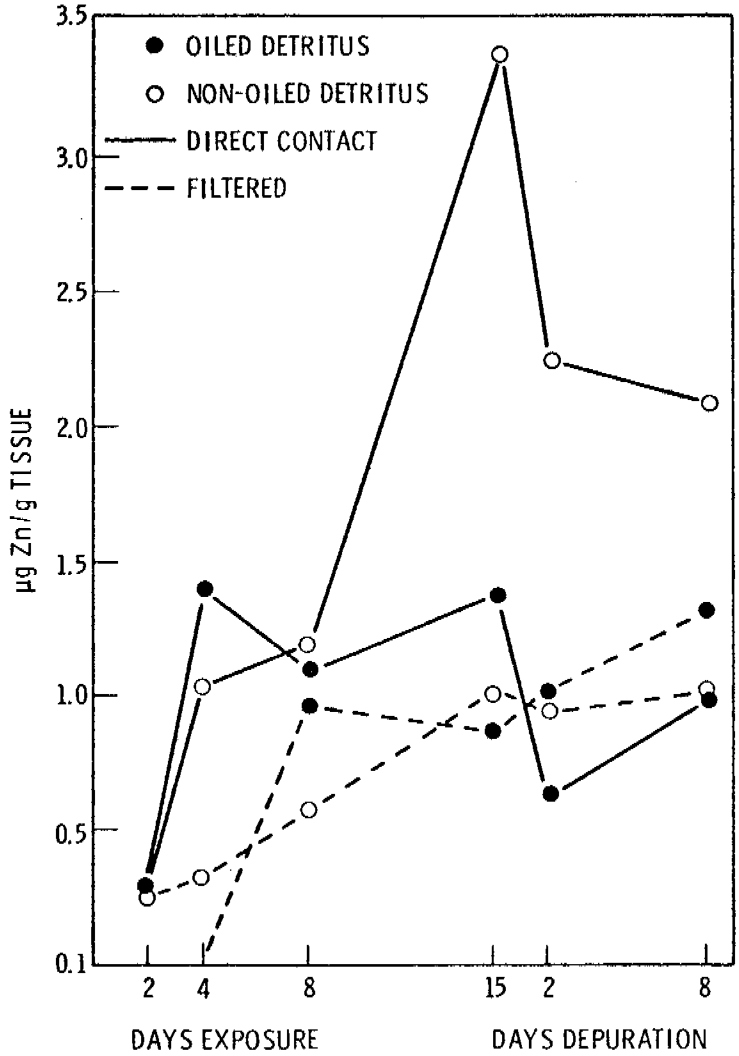
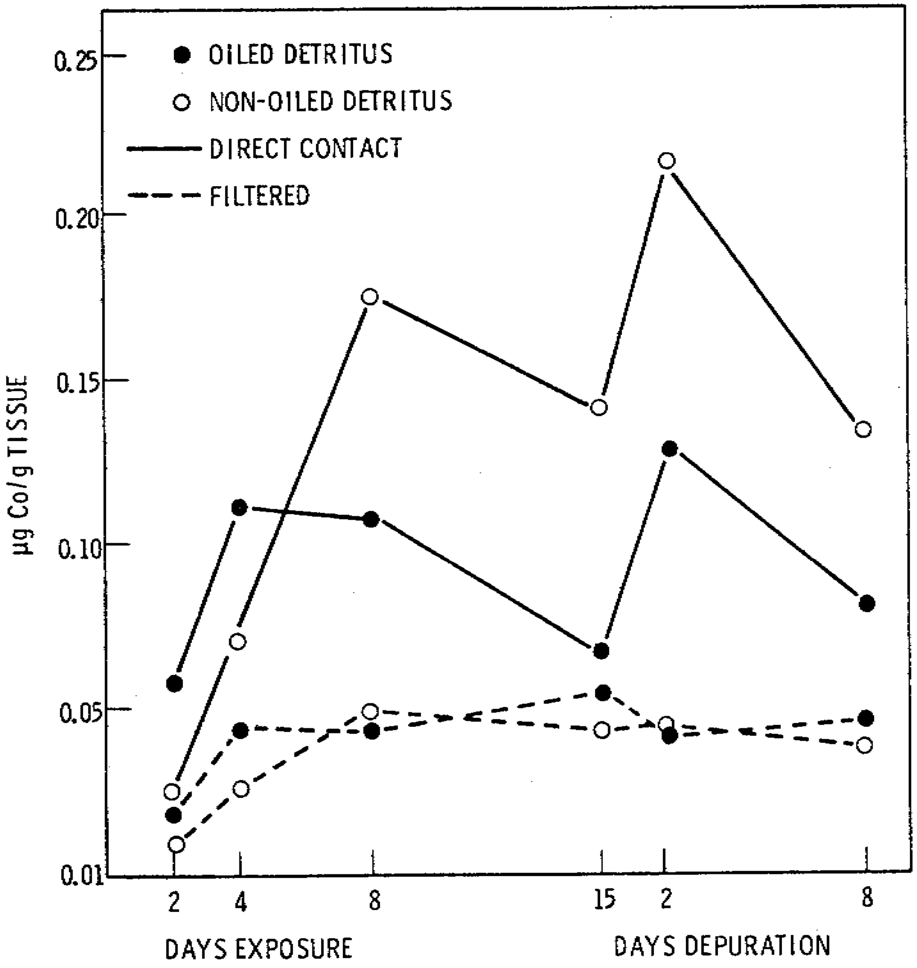


Figure 5. Incorporation of radio-labelled cobalt into *Macoma* tissue.



Solid circle - oiled detritus
Open circle - non-oiled detritus
Solid line - direct contact
Broken line - filtered

Table 7. Metals (μg/g d.w.) incorporated into <u>Macoma inquinata</u> exposed to oiled and non-oiled detritus.

	Eu				Fe			
Days Exposure	NO	O	NOF	OF	NO	O	NOF	OF
2	0	.013	0	-	0	130	16.8	13
4	.001	.0083	.0001	-	131	22	0	-
8	.004	.0083	.0002	-	85	16	11	-
15	.001	.00107	.0003	-	0	-	0	-
Days Depuration								
2	.001	.00089	.0004	-	0	0	-	-
8	0	.00084	.0003	-	-	-	-	-

	Zn				Co			
Days Exposure	NO	O	NOF	OF	NO	O	NOF	OF
2	.24	.288	.257	-	.024	.059	.009	.019
4	1.02	1.38	.318	-	.070	.112	.025	.043
8	1.18	1.09	.572	.952	.175	.108	.049	.043
15	3.41	1.38	1.054	.873	.140	.067	.042	.054
Days Depuration								
2	2.23	.626	.937	1.01	.216	.130	.043	.041
8	2.10	.99	1.095	1.32	.133	.080	.037	.0455

O = oiled

NO = not oiled

F = filtered

0 = no net incorporation into tissue

\- = no metal present in sample

Discussion

The detritus on which the clams fed in this experiment was the same material they ingest in nature. There is, therefore, no reason to believe that the concentrations of metals in their food were any higher during than before the experiment or to expect a net increase in metal concentration in the control animals exposed to non-oiled detritus. The fact that lebelled Zn and Co appeared in the controls indicates that a more or less rapid exchange takes place between the metals in the tissue and in the environment.

The tissue zinc concentration of Macoma is about 200 ppm. The cobalt concentration is not known, but probably resembles that of other bivalves from unpolluted waters, which is on the order of 0.5 ppm. Thus, the amount of labelled zinc and cobalt taken in by control Macoma in two weeks, presumably replacing metals lost to the environment, amounts to about 1% and 30%, respectively, of their normal metal pool. If hydrocarbons enhanced the rate of uptake of metal from normal environmental concentrations, then oil-exposed animals would be expected to accumulate metals from the environment at a faster rate than that at which they lost them to the environment and so to exhibit a greater increase in radioactivity than is found in the controls. This is not the case, since the net amount of radioactivity incorporated into the tissues of oil-exposed animals over time was less than that in the controls.

This reduction, however, does not imply that PHC's reduce the ability of Macoma to absorb metals from detritus. In fact, comparison of the zinc and cobalt concentration of the gut contents after two and fifteen days exposure shows a 92 and 94% decline, respectively, between the initial and final sample. In control animals the concentration goes down by 78% over the same period. This difference can also be attributed to the maintenance of a higher feeding rate by control clams, which would bring in larger quantities of labelled metal.

There seem to be no grounds for believing that exposure to 1000 ppm PBC either increases or decreases the rate at which Macoma absorbs metals, except through a reduction in the rate of food intake. This conclusion is supported by the fact that on the filtered side of the aquarium, where the absolute differences between food intakes of oiled and non-oiled animals were less and where more of the metals may have been taken in via the water column, the amounts incorporated by the two groups were quite similar.

CONDITION INDEX AND FREE AMINO ACID LEVEL OF *PROTOTHACA STAMINEA* EXPOSED TO OIL-CONTAMINATED SEDIMENT

Roesijadi and Anderson (1979) exposed *Macoma inquinata* to sediment contaminated with 1100 ppm Prudhoe Bay crude oil for 38 days, beginning in June 1977. They observed a 16% reduction, significant at the .001 level, in condition index and a 27% reduction, significant at the .01 level, in the free amino acid concentration of the gills, mantle, and adductor muscle in exposed *Macoma*, compared to control animals. Two-thirds of the decrease in FAA was due to a 38% decrease in glycine. A similar experiment was carried out on a larger scale, beginning in January 1978, in which two detritivores, the clam *Macoma*, and the sipunculid worm *Phascolosoma agassizi*, and one suspension feeder, the clam *Protothaca staminea*, were exposed for 54 days.

Methods

Ninety-eight mls PBC was emulsified in a blender with two 500 ml volumes of sea water. The oil and one liter sea water were added to 42 kilograms of coarse, sandy sediment and mixed for one hour in a cement mixer. The oiled sediment was flushed three times with sea water and left in a sea table overnight. Cores for IR analysis of total hydrocarbon content were then taken. One hundred and ninety *Protothaca*, sixty *Macoma*, and seventy *Phascolosoma* were collected from the intertidal region of Travis Spit, near the Battelle Laboratory on Sequim Bay, Washington State, U.S.A. Initial control groups of the two clams were taken for condition index and free amino acid determination by the methods of Roesijadi and Anderson (1979), and a group of sipunculids were taken for free amino acid determination. The remaining animals were distributed in mesh-bottomed trays, containing oiled or clean control sediment, which were replaced in the Travis Spit intertidal on January 11, 1978.

On March 6, 1978 the trays were removed. The five surviving oil-exposed *Macoma*, five exposed *Protothaca*, and five controls of both species were taken for hydrocarbon analysis. Condition indices and FAA contents of exposed and control *Protothaca* were determined by the methods of Roesijadi and Anderson (1979). Condition indices were calculated by the formula:

$$\text{C.I.} = \frac{\text{g ash-free dry weight}}{\text{cm shell length}^3} \times 1000$$

FAA determinations of control *Macoma* and *Phascolosoma* and HC analysis of the clams have not been completed.

Results

At the start of the experiment the oiled sediment contained 1237 ± 112 ppm hydrocarbon, measured by IR analysis, and the control sediment 10 ± 11 ppm. After 54 days the HC level in oiled sediment had fallen to 850 ± 17 ppm.

In the control trays, 82 out of 90 *Protothaca* (91%), 20 out of 20 *Macoma* (100%), and 11 out of 30 Phascolosoma (37%) were alive and present. In the trays containing contaminated sediment 77 out of 90 *Protothaca* (85%), but only 5 out of 30 *Macoma* (17%) and none out of 30 *Phascolosoma* remained. The more mobile sipunculid worms may have migrated from the oiled environment, but the missing *Macoma* presumably died. The data on condition index are summarized in Table 8.

Table 8. Condition indices of initial control, field control, and exposed *Protothaca staminea*.

	$\bar{x}$ ± s.e.	n
Initial Control	19.3 ± .36	10
Field Control - 54 days in clean trays	18.2 ± .20 n.s.	59
Exposed - 54 days in contaminated trays	17.1 ± .17 **	64

n.s. Not significantly different at .10 level from initial control.
** Significantly different from field control at .01 level means compared by student's *t* test.

The concentration of free amino acids in the mantle, gills, and adductor muscle of *Protothaca staminea* is shown in Table 9.

Discussion

The condition index of *Macoma inquinata*, exposed to oil contaminated sediment for 38 days in June 1977, was 16% lower than that of control animals. Fifty-nine percent of the exposed animals survived, compared to 92% of the controls. When exposed for 54 days, beginning in January 1978, only 17% of the *Macoma* survived. By contrast, 85% of the *Protothaca* exposed to oiled sediment in January 1978 survived for 54 days, and the condition index of the

Table 9. Free amino acid concentration in gills, mantle, and adductor muscle of *Protothaca staminea* (μmoles/g).

	Initial Control	Field Control	Field Exposed
Alanine	9.47 ± 1.48	6.47 ± 2.23††	4.01 ± 2.3*
Arginine	2.84 ± .56	2.75 ± .85	1.92 ± 1.31
Aspartic Acid	1.30 ± .65	1.15 ± .47	.56 ± .50*
Glutamic Acid	3.89 ± 1.57	3.26 ± .88	1.99 ± 1.32*
Glycine	26.7 ± 6.5	21.9 ± 7.8	18.33 ±12.6
Histidine	.21 ± .06	.11 ± .03 ††	.34 ± .70
Isoleucine	.27 ± .05	.24 ± .10	.15 ± .10
Leucine	.43 ± .10	.24 ± .11 ††	.31 ± .16
Lysine	.34 ± .12	.37 ± .11	.21 ± .11**
Methionine	.08 ± .02	0	0
Phenylalanine	.31 ± .08	.22 ± .07 †	.22 ± .17
Proline	.26 ± .08	.16 ± .10 †	.10 ± .09
Serine[1]	1.17 ± .30	.91 ± .18 †	.93 ± .67
Threonine	.36 ± .13	.28 ± .08	.21 ± .13
Tyrosine	.28 ± .06	.25 ± .08	.21 ± .22
Valine	.37 ± .07	.33 ± .10	.23 ± .15
Taurine	33.6 ±10.6	43.3 ±17.1	18.36 ±13.05**
Total	79.94 ±17.96	85.56 ±26	47 ±24.5 **
Taurine:Glycine	1.23 ± .28	2.04 ± .54	1.38 ± .78

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† significantly different from initial control at .05 level; student's *t* test

†† significantly different from initial control at .01 level; student's *t* test

* significantly different from field control at .05 level; student's *t* test

** significantly different from field control at .01 level; student's *t* test

[1] serine, glutamine, and asparagine co-chromatograph

survivors was only 6% less than that of the controls. The contrasting survival pattern of the two species in the same experiment clearly shows that *Protothaca* is under less stress than *Macoma* under these conditions.

The difference in percent decrease in condition index may also be significant, although it must be viewed more cautiously since the measurements on *Macoma* and *Protothaca* were made at different seasons. Since it is not likely that the shell lengths of any individual animal changed significantly during the course of the experiment, the condition indices are directly proportional to the ash free dry weights. These declined by only one third as large a percentage, compared to the controls, in exposed *Protothaca* as in exposed *Macoma*, indicating that the former were not forced to draw on their stored reserves for nutrition to as great an extent as the latter. This also points to a lesser degree of stress suffered by the suspension feeders than by the deposit feeders.

The changes found in free amino acid levels in the tissues of *Protothaca* differ from those reported in other bivalve species under stress. Roesijadi and Anderson (1979) found a pattern in *Macoma* resembling the stress syndrome described by Bayne *et al*. (1976) in *Mytilus edulis*. In their exposed animals the average level of glycine was reduced to 62% of that in the controls, while the taurine level stayed constant, leading to an increase in the taurine: glycine ratio. Jeffries (1972) reported a drop in glycine level in stressed *Mercenaria mercenaria* accompanied by an increase in taurine levels, again leading to an elevated taurine:glycine ratio.

In *Protothaca* the situation was reversed. The mean glycine level of exposed clams did not differ significantly from that of controls, but the mean level of taurine was reduced by 58%, leading to a decline in the taurine: glycine ratio. The significance of this decline is not clear at this time, since the only known role of taurine in the metabolism of marine invertebrates is to function in osmoregulation. There is no reason to suspect any difference between the salinity level of the water surrounding the oil-exposed and the control groups. However, there is some evidence to indicate that the taurine levels of *Protothaca* tissue may fluctuate as a result of conditions not related to stress or osmoregulation. Roesijadi (1979) reported that holding *Protothaca* in the laboratory for 26 days under constant temperature and salinity resulted in a significant decrease in the taurine level of the gills while the glycine levels remained constant. Stress, in the form of addition of up to 155 μg/l of Na hypochlorite led to a significant decrease in the concentration of glycine but not of taurine.

In view of these data, which indicate that taurine levels may change in this species for unknown reasons, it may be more useful to consider the changes in other free amino acids, especially glycine, as indicators of stress. There is only a slight, statistically insignificant, decrease in the glycine levels in the oil-exposed *Protothaca*. This response, together with the smaller decrease in condition index and the higher rate of survival, all support the conclusion that the suspension feeder *Protothaca* is less vulnerable to oil-contaminated sediment than the deposit feeder *Macoma*.

DISTRIBUTION OF POLYAROMATIC HYDROCARBONS AND DEGRADATION PRODUCTS IN A SEDIMENT EXPOSURE SYSTEM

One set of experiments has been conducted and another is in progress to determine the fate of representative three, four, and five ring polyaromatic hydrocarbons in several types of oil-impacted sediments. The distribution of the compounds among sediment particles, interstitial water, and detritivorous macro-organisms, as well as their alteration into polar metabolites was and is being examined. The first set of experiments was carried out with a fairly coarse sand and a bivalve mollusc, *Macoma inquinata*. In the second, a fine grained muddy sediment and a polychaete worm, *Abarenicola pacifica*, are being used.

Methods

Exposure systems

The compounds tested were 9-^{14}C phenanthrene, 5, 6, (11, 12)-^{14}C chrysene, and 7, 10-^{14}C benzo(a)pyrene, purchased from Amersham-Searle Co., Arlington Heights, Illinois. Impurities associated with benzo(a)pyrene degradation have been characterized by reverse phase high pressure liquid chromatography (Clarke, 1976). We have recently used this technique to determine the radiopurity of all three substrates used in these studies. Phenanthrene and chrysene undergo no significant chemical degradation under prolonged storage. Benzo(a)-pyrene however, showed the presence of about 10% impurities and, therefore, was purified by silica gel chromatography immediately before exposure to assure that no degradative chemical artifacts were introduced to invalidate the radioactivity analyses. The purification procedure was: benzo(a)pyrene (60.7 mCi/mmol, 200 µCi in 1 ml benzene) was chromatographed over 10 grams of silica gel (Grace Davison Chemical Co., 100/200 mesh-heated overnight at 120°C) using benzene as the eluent. Ten milliliter fractions were collected and pure benzo-(a)pyrene eluted from the column in the second 10 ml fraction. The column and collection tubes were wrapped in aluminum foil to minimize the exposure of the benzo(a)pyrene to light. The benzene was removed under a stream of purified nitrogen and the crystalline benzo(a)pyrene was stored at -20° until use the next day.

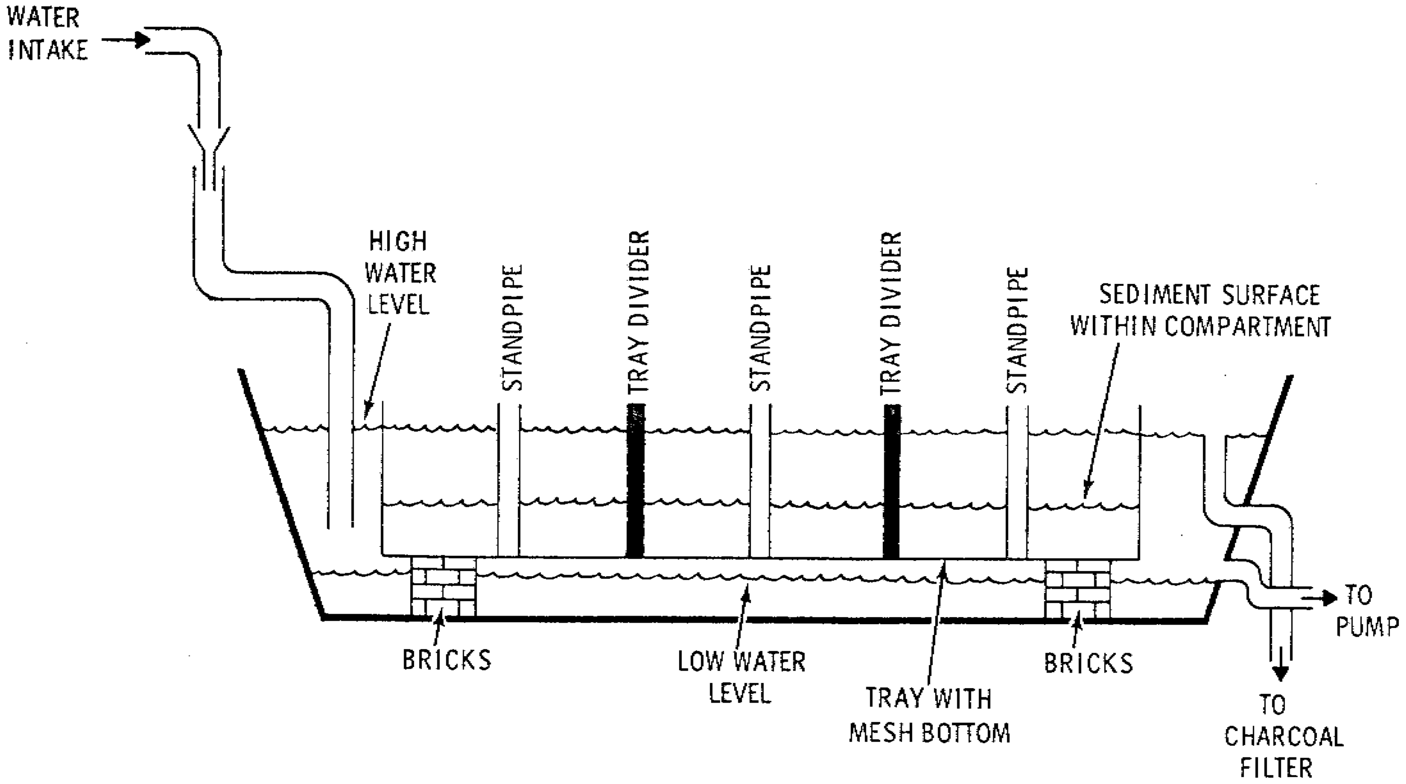
Previously, 190 M. inquinata and 100 kg sediment were collected from the low intertidal zone in an area of coarse sand mixed with fine gravel subject to moderate wave action. The sediment was passed through a 6 mm mesh sieve, and it and the clams were stored in the laboratory under flowing sea water at approximately 10°C and 30°/₀₀ salinity. Detritus was collected from the laboratory seawater head tanks, filtered onto #42 Whatman filter paper, and refrigerated.

The labelled hydrocarbon compounds were individually dissolved in solvent together with Prudhoe Bay crude oil, mixed with detritus, and incorporated into sieved sediment in a fiberglass-lined cement mixer. The final mixtures contained approximately 80 g detritus, 40 ppm PBC, and between 4.5 and 6.8 μCi labelled compound per kg. Final concentration of chrysene was 232 μg/kg, of phenanthrene 79 μg/kg, and of benzo(a)pyrene 18 μg/kg. These mixtures were poured to a depth of 8 cm into mesh-bottomed trays divided into three compartments each. The trays were placed on cement blocks in fiberglass tanks at a depth which permitted 5 cm of water to stand above the sediment surface but which did not permit water to rise above the edge of the trays. At 12 hour intervals, water was pumped out of the fiberglass tanks for one hour, allowing the water in the trays to drain out through the mesh bottom and to be replaced by fresh volumes of water after the pumping stopped. (Figure 6).

After two flushings, a sediment core was taken from each compartment and replaced by a 12 mm standpipe to facilitate future drainage. At this time, ten M. inquinata were placed in each compartment. The cores from the center compartment of each tray were divided into upper, middle, and lower section. The radioactivity in replicate samples from each section was measured, and the results indicated that the labelled compounds were evenly distributed throughout the sediment. Eighty percent of the calculated radioactivity added was recovered in the chrysene and benzo(a)pyrene exposures and 67% in the phenanthrene.

At intervals of one, three, seven, fifteen, thirty, and sixty days after the clams were initially exposed, a sample of the surface water overlying the sediment was removed from one compartment and passed through a 0.45 μ Millipore filter. The water level was then lowered, the clams were removed

Figure 6. *Macoma* sediment exposure apparatus.



and placed in a mesh basket in clean running sea water for 24 hours depuration, after which they were rinsed with distilled water and frozen. Part of the sediment was also frozen immediately. The remaining sediment was placed in a Wildco CR^{TM} Core Squeezer, in 100 cc batches, and the interstitial water was forced out with compressed air at 50 psi, passing through several layers of Whatman #42 filter paper within the squeezer. This filtrate was then passed through a syringe fitted with a Swinnex-47 Filter Holder (Millipore Corporation) containing a pre-filter and a 0.45 μ filter. Glassware containing benzo(a)pyrene in water was protected from light by aluminum foil wrappings. All water was kept in ice and protected from evaporation wherever possible.

Chemical Analyses

Tissue samples were analyzed by a method described in the previous annual report, designed to monitor the uptake and fate of ^{14}C-aromatic hydrocarbons in marine organisms. The method has been expanded to include the analysis of the sediments and interstitial waters containing the ^{14}C species to which the clams were exposed. Stress has been placed on using the expanded scheme to account for the formation of degradation products other than CO_2 as a result of microbial activity or metabolism within the clams. The expanded scheme is shown in Figure 7. Conventional tissue digestion techniques such as that described by Warner (1976) cannot be used because of the potential chemical destruction of degradation products that might be formed during the experiments. Therefore, Macoma tissue samples were initially homogenized in 2:1 ethyl acetate/ acetone. This extraction technique has previously been applied to a study of the metabolism of 7, 12-dimethylbenz(a)anthracene in mouse skin homogenates (DiGiovanni et al., 1977), and it produced very high recoveries of original substrate and metabolites. A modification of the technique has been used in a study of benzo(a)pyrene phenols formed by the metabolism of benzo(a)pyrene by rat liver microsomes (Selkirk et al., 1974, 1976). The specific procedures for the recovery and analysis of tissue and sediment extract containing ^{14}C radioactivity are described in the appendix.

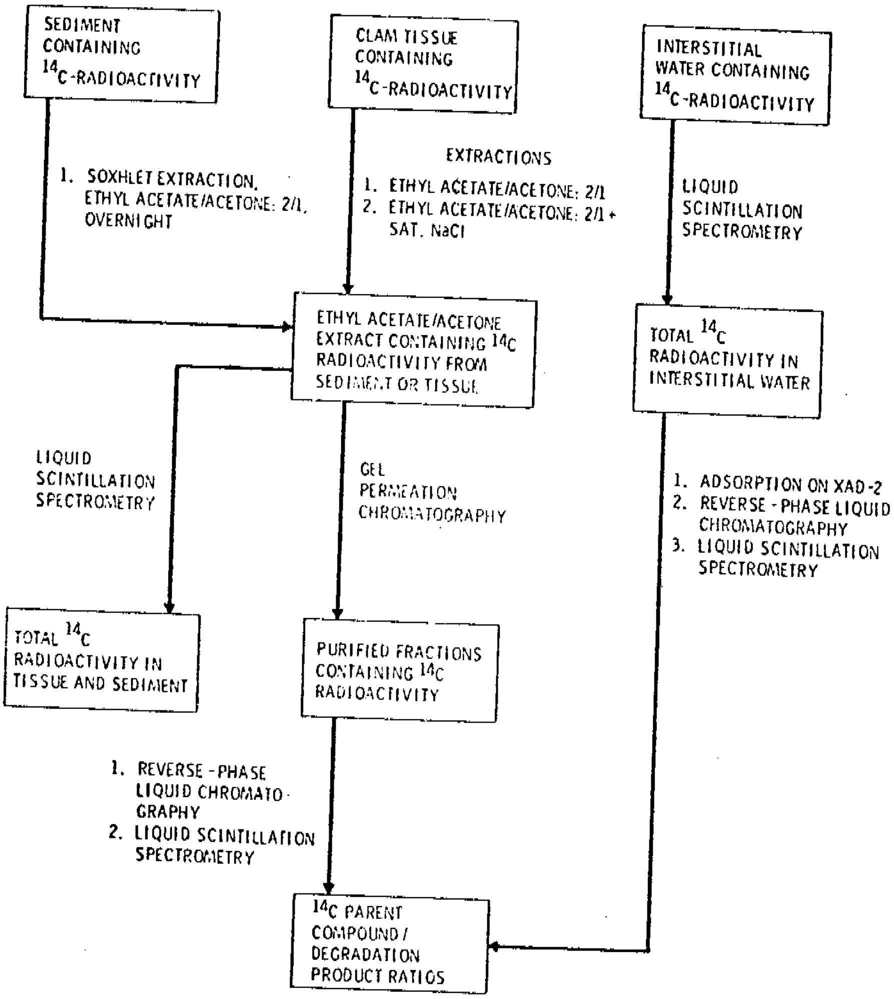
To test the efficiency of recovery employing these techniques, tissue samples were spiked with known amounts of ^{14}C-phenanthrene, ^{14}C-chrysene, and ^{14}C-benzo(a)pyrene and extracted according to procedures described in the appendix. The results of the recovery experiment are shown in Table 10. Recovery of all three hydrocarbons was greater than 90%. Only about 80% of the radioactivity could be recovered in the first extraction of hydrocarbon, but the second extraction was satisfactory. Similar results were obtained for the recovery of ^{14}C radioactivity from experimental sediment. In no case was ^{14}C radioactivity detected in experimental sediment after Soxhlet extraction overnight.

Table 10. Recovery of ^{14}C-aromatic hydrocarbons from clam tissue.

Compound	DPM Added	DPM Recovered	% Recovered
Phenanthrene	32,185	30,419 ± 1272	94.5 ± 3.9
Chrysene	21,898	21,081 ± 853	96.3 ± 3.9
Benzo(a)pyrene	34,586	31,703 ± 1854	91.7 ± 5.3

The next step in the isolation sequence involved the use of high-pressure gel permeation chromatography (GPC) to remove high molecular weight components, which have the potential for interfering with the final detailed analysis of individual ^{14}C-labelled degradation products during analysis by reverse phase high-pressure liquid chromatography (RPLC). Initial attempts to use a modified version of a method described by Kuehl et al. (1978) failed, and therefore, a GPC technique was developed using three series coupled μ-styragel columns with pore sizes of 1000, 500 and 100 Angstroms, respectively. To test the separation capability of the GPC system, model compounds with structural types equal to or similar to the compounds of interest were analyzed on the system using UV detection at 254 nm. The results are shown in Table 11. Compounds with structural types equal or similar to those of the substrates used in the uptake studies (benzene, naphthalene, phenanthrene and chrysene) were tested for their retention volumes. The retention volume of chrysene differed from the other three compounds by 0.2 ml. 1-Naphthol, which simulates compound types that might be formed as a result of degradation of the parent compounds has a larger retention volume compared to the non-polar compounds previously described. This is not the case for the 7, 8-dihydrodiol of benzo(a)pyrene. Therefore, in some instances recognition of degradation products may be observed by this method. Components extracted from the tissue with molecular weight greater than 1000 are also easily separated from these compounds as shown by the

Figure 7. Scheme for the extraction and analysis of ^{14}C radioactivity from clam tissue, sediment and interstitial water.



retention volumes for polystyrene (MW 2,900 and 15,000). Therefore, recognition of the formation of conjugates is also possible. Samples of tissue extract containing ^{14}C-phenanthrene when subjected to the above separation produced a ^{14}C-phenanthrene fraction almost completely devoid of extraneous tissue components as determined by mass balance. This GPC technique, therefore, provides a means of reducing separation interferences and minimizing quenching effects resulting from the presence of biogenic high molecular weight components in the tissue and sediment extracts. It can provide initial information on the presence of low molecular weight polar degradation products or higher molecular weight conjugates produced by organism metabolism or other degradative processes associated with the experimental system.

Table 11. Separation of aromatic hydrocarbons and possible metabolic products by gel permeation chromatography.

Compound	Molecular Weight	Log Molecular Weight	Retention Volume (ml)
Benzene	78	1.89	31.7
Naphthalene	128	2.11	31.7
Phenanthrene	178	2.25	31.7
Chrysene	228	2.36	31.9
Benzo(a)pyrene	252	2.40	32.00
Benzo(a)pyrene Trans-7, 8-dihydrodiol	286	2.40	32.00
1-Naphthol	144	2.16	35.7
Polystyrene	2,900	3.46	20.6
Polystyrene	15,000	4.18	17.4

Appendix

Preparation of Tissue Extracts for GPC Analysis

Tissues[1] from individually shucked clams containing ^{14}C hydrocarbons were patted dry and weighed into 25 ml corex centrifuge tubes. To each tube was added a solution of ethyl acetate/acetone, 2/1 (3 ml/2.5 g tissue, wet weight). The samples were homogenized using a Tekmar Tissumizer and then centrifuged at 5000 rpm for 10 minutes. The organic layer (top) from each sample was transferred to calibrated 15 ml glass stoppered centrifuge tubes with pasteur pipettes. The extraction sequence was repeated using

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[1] Wet weight of tissue of individual clams used in these experiments was 4.37 ± 1.16 grams.

ethyl acetate/acetone 2/1 (2 ml/2.5 g of tissue) and saturated sodium chloride (1.0 ml/2.5 g of tissue). The organic extracts (two from each tissue sample) were combined and the volume recorded. An aliquot of the samples were analyzed for total ^{14}C radioactivity by liquid scintillation spectrometry. The remaining portion of each sample was concentrated to 1.0 ml under a stream of nitrogen and injected onto the μ-Styragel columns.

Preparation of Sediment Extracts for GPC Analysis

Samples of sediment from cores (~ 15 to 30 grams, wet weight) containing ^{14}C-radioactivity were Soxhlet extracted with 50 ml of ethyl acetate/acetone 2/1 overnight. The Soxhlets were cooled in such a manner as to retain as much of the solvent as possible in the Soxhlet cup. The concentrated organic extract from each sample was transferred to calibrated glass stoppered centrifuge tubes and the volume recorded. An aliquot of each sample was analyzed for total ^{14}C-radioactivity. The remaining portions of the samples were concentrated to 1.0 ml under a stream of nitrogen and injected onto a μ-Styragel column. The extracted sediments were dried at 110° and their dry weight determined.

Analysis and Simplification of Tissue and Sediment Extracts by Gel Permeation Chromatography (GPC)

The concentrated tissue and sediment extracts were chromatographed on three series coupled μ-Styragel columns with the following pore sizes: 1000Å, 500 Å, and 100Å. The dimensions of each column were 7.9 mm x 30.0 cm. The following liquid chromatographic parameters were used.

Mobile Phase: Methylene Chloride

Flow Rate: 2.0 ml/min

Pressure: ~400 psi

UV at 254 nm, Attenuation, 0.04 to 2.10 Absorbance Units

The column system was calibrated using polystyrene standards and compounds of interest in our experiment. Retention volumes for these compounds are listed in Table 11.

It should be noted that, due to limitation on manufacturer quality control, retention volumes for a similar set of columns could be slightly different.

Aliquots of 2.0 ml fractions collected were analyzed for total ^{14}C-radioactivity. Those containing ^{14}C-radioactivity were appropriately combined, concentrated, and analyzed in more detail by reverse-phase high pressure liquid chromatography.

ANALYSIS OF GPC PURIFIED EXTRACTS BY REVERSE-PHASE LIQUID CHROMATOGRAPHY

One milliliter methylene clhoride tissue and sediment extracts containing radioactive compounds were solvent exchanged by the addition of 1ml of acetonitrile. The tissue and sediment extracts were chromatographed in two series coupled μ-Bondapak C-18 columns (7.9 mm x 30.0 cm each) using the following liquid chromatographic parameters:

Mobile Phase:	Acetonitrile/water
Solvent Program:	Acetonitrile/water: 60/40 80/20, 20 min.
Flow Rate:	2.0 ml/min
UV:	254 nm

Aliquots of 2.0 ml fractions collected were analyzed for total ^{14}C-radioactivity.

Results

The distribution of radioactivity associated with phenanthrene and/or its products in tissue, sediment and interstitial water, followed a different pattern from that seen with chrysene and benzo(a)pyrene (Figures 8-10 and Tables 12 and 13). Fifteen days after the exposure began 50% of the phenanthrene initially present in the sediment had been removed, and after 60 days only 8% of the original amount remained. By contrast 70 and 80%, respectively, of the originally added chrysene and benzo(a)pyrene remained in the sediment after 60 days. Complementing its more rapid depletion from the sediment, phenanthrene or its metabolites appeared in the interstitial water in concentrations two orders of magnitude higher than chrysene or benzo(a)pyrene, so that after 60 days almost 3% of the activity remaining in the phenanthrene exposure system was found in the water.

The incorporation of radioactivity from phenanthrene into the tissues of Macoma also differed from that of the heavier compounds. The concentrations of chrysene and benzo(a)pyrene in the clams rose steadily over the 60 day period, while the sediment level fell. The tissue magnification factor therefore also increased continually reaching 54 for chrysene and 25.5 for benzo(a)pyrene, on a dry weight to dry weight basis. Phenanthrene, on the other hand, was taken up in larger amounts than chrysene or benzo(a)pyrene in the first three days of exposure, but its concentration fell thereafter. Since the sediment concentration of phenanthrene fell rapidly the tissue magnification factor continued to increase for two weeks, but is also declined towards the end of the exposure period. Put another way, the tissue content of chrysene and benzo(a)pyrene after 60 days exposure was 9.5 and 7.5 times as high as on day 1, respectively, while the tissue concentration of phenanthrene was only 1/8 as high on the last day of exposure as on the first (Table 13).

The tissue magnification factors with respect to interstitial water concentration differed in several ways from that with respect to sediment concentration. As a corollary to their extremely low solubility in water chrysene and benzo(a)pyrene displayed extremely high tissue magnification factors of several thousand fold, while the phenanthrene magnification factor over water was closer to the sediment magnification factor.

As the amount of chrysene and benzo(a)pyrene, or their metabolites in the water, increased in the latter part of the exposure period the tissue concentration of the parent compounds also increased, but at lower rates, so that the water magnification factor declined. The interpretation of these findings may be clearer when the analysis of the radioactive species in interstitial water has been completed.

It is possible to roughly estimate the proportion of those hydrocarbon compounds leaving the sediment over 60 days which appeared in the clams at the end of this period by assuming that the total weight of the sediment in each compartment was approximately 6.6 kg and the total weight of the ten Macoma in each was 43 g. These are reasonable assumptions, based on the volumes of the compartments, the density of the sediment and the average size of individuals of the populations of animals. Calculations based on these assumptions indicate that 14.5% to 14.7%, respectively, of the radioactivity of chrysene and benzo(a)pyrene which left the sediment can be accounted for by its presence in the clams, while only 0.15% of the corresponding phenanthrene remained in the organisms. Therefore, of the hydrocarbons present in the sediment when the clams were originally exposed, approximately 4.2% of the chrysene, 3% of the benzo(a)pyrene and 0.12% of the phenanthrene was present in their tissues after 60 days. Since these figures are not based on actual measurements of the animals' weight, they should be taken only as order of magnitude estimates.

The search concerning degradation or metabolic products in the tissue of Macoma inquinata and in the associated sediment for all three ^{14}C species showed that: (1) separation of tissue and sediment extracts by gel permeation chromatography and by reverse phase high pressure liquid chromatography resulted in the generation, in each case, of one radioactive peak which had a retention time identical to that of the parent compound; and (2) recoveries of substrate radioactivity in tissue and sediment extracts from the GPC and reverse phase chromatography steps were high, indicating no loss of activity on the column systems which could be ascribed to polar compounds (Table 14).

The possibility that the ^{14}C-radioactivity associated with the interstitial water was due, in part, to degradation products was next explored. Phenanthrene has the greatest potential for microbial degradation (McKenna and Heath, 1976) and in these experiments produced the highest levels of activity in the interstitial water. Therefore, eighty-eight milliliters of the 30-day phenanthrene interstitial water was passed through two series coupled stainless steel columns (22 cm X 1 cm O.D.) containing XAD-2 macroreticular resin. These resins are

Table 12. ^{14}C-phenanthrene, chrysene and benzo(a)pyrene interstitial water-sediment distributions. % water in experimental sediments = 15.7 ± 1.2, n = 43.

Compound	Day	^{14}C activity (DPM) in water from 1 gram sediment (wet wt.)	^{14}C activity (DPM) in equivalent volume of surface H_2O	^{14}C activity in sediment DPM/gram wet wt.	% distribution[2] of ^{14}C activity in interstitial water from 1 gram of sediment (wet wt.)
Phenanthrene	1	36	12	7,740	$\overset{\sim}{<}0.42$
	3	28	4	7,036	$\overset{\sim}{<}0.37$
	7	53	30	7,132	$\overset{\sim}{<}0.85$
	15	83	31	3,896	$\overset{\sim}{<}1.97$
	30	24	4.4	1,959	$\overset{\sim}{<}1.22$
	59	19	1.3	609	$\overset{\sim}{<}2.80$
Chrysene	1	2.8	0.5	10,711	$\overset{\sim}{<}0.03$
	3	2.3	-	10,975	$\overset{\sim}{<}0.02$
	7	1.5	1.5	10,318	$\overset{\sim}{<}0.02$
	15	1.1	0.8	10,816	$\overset{\sim}{<}0.01$
	30	5	2	8,106	$\overset{\sim}{<}0.07$
	59	6.7	3.6	7,548	$\overset{\sim}{<}0.07$
Benzo(a)pyrene	1	0.49	0.09	8,072	$\overset{\sim}{<}0.01$
	3	0.76	0.03	7,095	$\overset{\sim}{<}0.02$
	11	0.9	-	7,215	$\overset{\sim}{<}0.03$
	20	0.9	0.19	8,353	$\overset{\sim}{<}0.03$
	35	1.1	0.33	6,601	$\overset{\sim}{<}0.04$
	60	2.2	0.37	6,340	$\overset{\sim}{<}0.08$

[1] Calculation of distribution ratio assumes that the trace levels of ^{14}C activity in the interstitial water samples is present as parent substrate.

[2]

$$\% \ ^{14}C \text{ Activity} = \frac{^{14}C \text{ Activity in Water}}{^{14}C \text{ Activity in sediment} - {}^{14}C \text{ Activity in water}} \times 100$$

Table 13. ^{14}C-phenanthrene, chrysene, benzo(a)pyrene *Macoma* tissue-sediment-interstitial water distribution. Dry weight of tissue = 16.9% of wet weight.

Compound	Day	^{14}C activity (DPM) in 1 g *Macoma* (wet wt.)	^{14}C activity in 1 g sediment (d wt.)	% of initial ^{14}C activity in sediment	^{14}C activity (DPM) in 1 ml interstitial water	DPM/g d wt. *Macoma* / DPM/g d wt. sediment	DPM/g wet wt. *Macoma* / DPM/ml interstitial water
Phenanthrene		$\bar{x}$ ± s.d.					
	0		9229 ± 533				
	1	15,639 ± 4384	-		210	9.99	74
	3	47,238 ± 8011	9181 ± 606	99	165	30.4	286
	7	41,129 ± 17,943	8346 ± 1209	90	388	29	106
	15	30,813 ± 17,388	4622 ± 1915	50	490	39.4	63
	30	10,942 ± 5552	2324 ± 1079	25	141	27.8	78
	59	1964 ± 465	721 ± 117	8	108	13.9	18
Chrysene	1	8576 ± 1125	12,705 ± 1064		18	4.0	476
	3	19,235 ± 1144	13,018 ± 2681	102	14.5	8.7	1326
	7	25,168 ± 10,326	12,239 ± 1185	96	9.5	12.2	2649
	15	53,569 ± 25,616	12,829 ± 1524	101	7	24.7	7653
	30	69,644 ± 9289	8734 ± 1277	69	32	47.1	2176
	58	81,710 ± 8981	8953 ± 4834	70	43	54	1900
Benzo(a)pyrene	0		8967 ± 383				
	1	4366 ± 1193	9575 ± 29	107	3.1	2.72	1408
	3	9306 ± 1780	8416 ± 690	94	4.8	6.56	1938
	11	14,515 ± 681	8559 ± 1168	95	5.7	10.05	2483
	20	23,892 ± 5423	8353 ± 145	93	5.7	16.9	4192
	35	24,605 ± 2401	7830 ± 1965	87	7	18.6	3515
	60	32,450 ± 11,737	7521 ± 838	84	14	25.5	2317

Table 14. Percent recovery of ^{14}C radioactivity from tissue and sediment extracts chromatographed on GPC and reverse phase liquid chromatographic systems.

Chromatography	Compound	Tissue[1]	Sediment[1]
GPC	Phenanthrene	101.5	97.6
	Chrysene	114.6	99.3
	Benzo(a)pyrene	102.1	102.6
Reverse-Phase	Phenanthrene	96.9	85.6[2]
	Chrysene	103.8	101.4
	Benzo(a)pyrene	87.3[2]	89.9[2]

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[1] % recovery of activity injected on column system.

[2] Due to the low count levels in these samples, the lower recovery values can be accounted for by the greater counting error, which ranged from 10-30% for these samples.

Table 15. Adsorption characteristics of ^{14}C-phenanthrene and ^{14}C activity from 30 day phenanthrene interstitial water sample on XAD-2 resin.

Sample	% Activity on Top Column	% Activity on Bottom Column	% Activity In Aqueous Column Effluent
^{14}C-phenanthrene[1]	99.9	0.1	0.1
^{14}C Activity from ^{14}C-phenanthrene Interstitial Water Sample[2]	2.0	0.2	97.9

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[1] 93% of the total activity recovered.

[2] 96% of the total activity recovered.

Figure 8. ^{14}C radioactivity in tissue and sediments from phenanthrene exposure (n = 3).

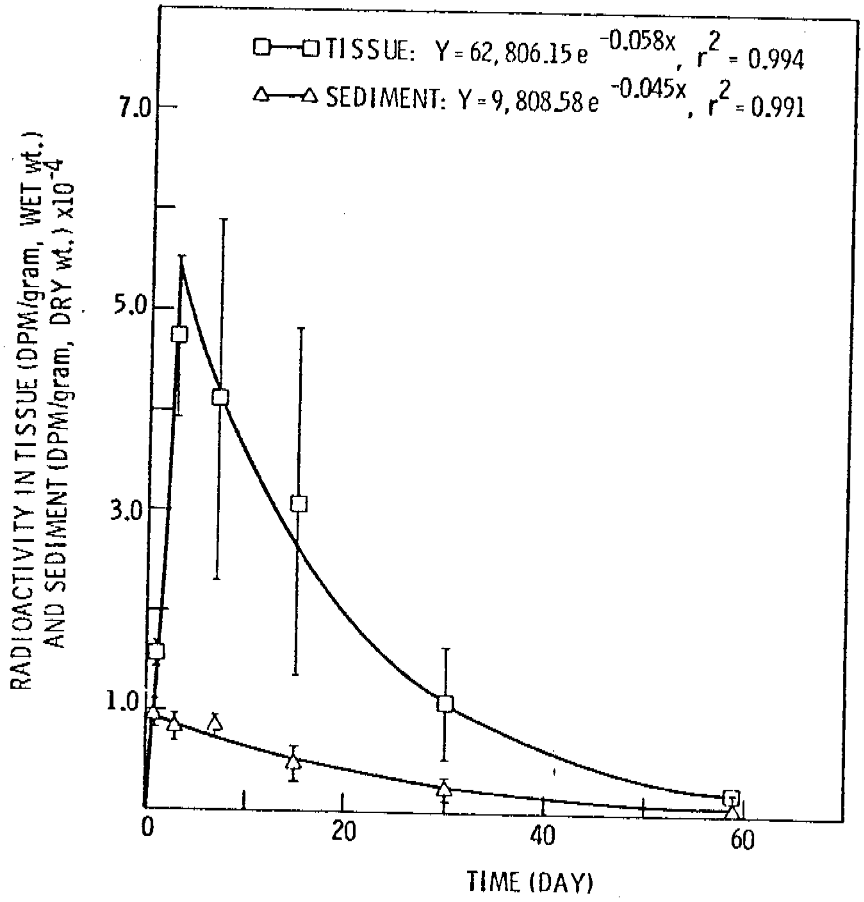


Figure 9. ^{14}C radioactivity in tissue and sediments from chrysene exposure (n = 3).

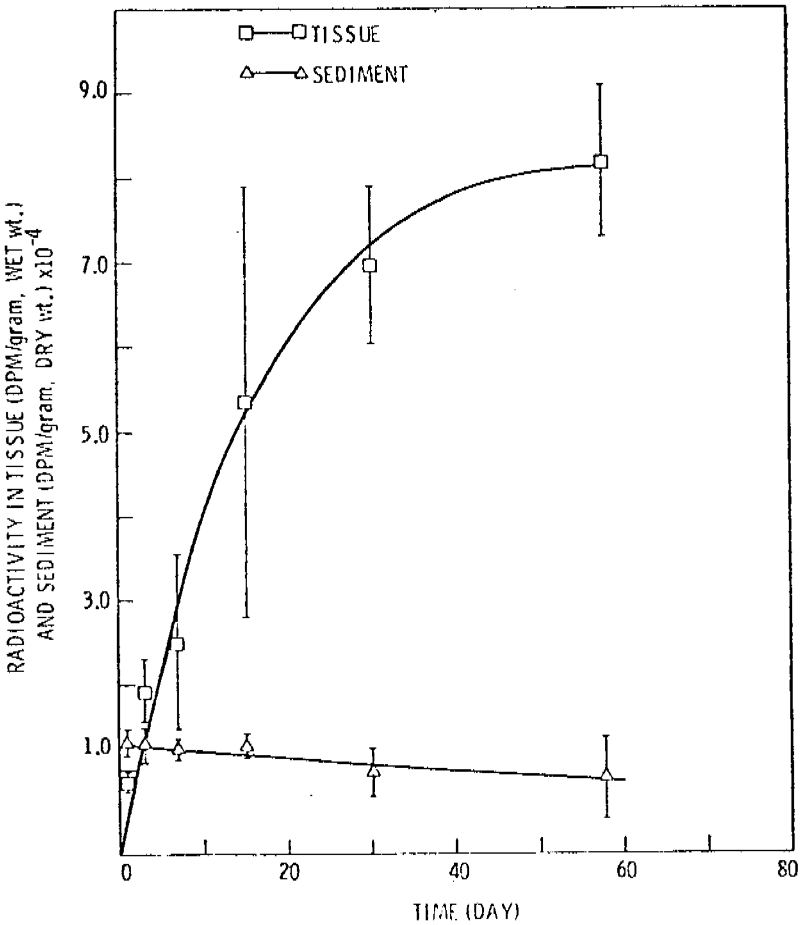
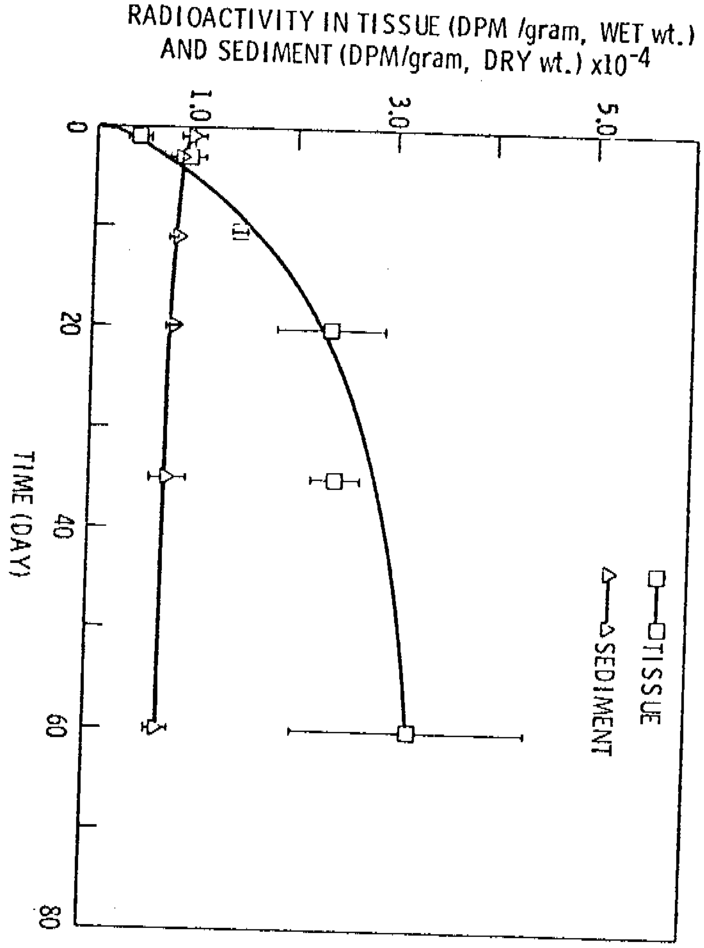


Figure 10. ^{14}C radioactivity in tissue and sediments from benzo(a)pyrene exposure (n = 3).



known for their ability to adsorb aromatic hydrocarbons efficiently (Junk et al., 1974). The second column was present in case the capacity of the first column for phenanthrene was exceeded. Results showed that 97.9% of the recovered ^{14}C activity in the initial sample was not retained by the XAD-2 resin. This was in marked contrast to the adsorption characteristics of ^{14}C-phenanthrene on this column system where 99.9% of the total recovered activity was retained by the first column. These results (Table 15) support preliminary studies in which it was found that the majority of ^{14}C activity from interstitial water samples (phenanthrene exposure) could not be extracted by use of hexane, benzene or chloroform as extraction solvents.

Discussion

The differences between the fate of phenanthrene on the one hand and chrysene and benzo(a)pyrene on the other may be accounted for on the basis of the greater - by three orders of magnitude (May, Warik and Freeman, 1978) - solubility in water of the former and by the tendency of water-insoluble hydrocarbons to remain sequestered in animals' lipids. According to this model, half the added phenanthrene leaves the oil coats surrounding the sediment particles within two weeks of exposure to dissolve in the water, while most of the two heavier compounds remain with the particles. This water-borne phenanthrene enters the clam tissue, producing the observed early peak of radioactivity there. Within the clam relatively more phananthrene enters the aqueous compartment in exchange with that in the lipid compartments and is eliminated by subsequent exchange with the surrounding water. Parent phenanthrene was found in the tissues at early time intervals. Later when microbial metabolism acting in the exposure system altered the hydrocarbons in the interstitial water, there was no evidence of uptake of these products by the clams. Later in the exposure period this metabolism may have acted more rapidly, converting phenanthrene into soluble products which were then eliminated from the exposure system by the daily flushing. As the sediment became depleted of phenanthrene, the interstitial water level of all radioactive compounds fell, allowing the phenanthrene level in the clam to fall by exchange with the now less heavily polluted water.

Chrysene and benzo(a)pyrene by contrast enter the water phase more slowly, but once they are picked up by *Macoma* they apparently remain longer in their lipid depots.

Conclusions

The purpose of these experiments was to determine the fate of ^{14}C-phenanthrene, chrysene and benzo(a)pyrene in oil-impacted sediments, in terms of their distribution in association with sediment particles, in interstitial and surface water, and in detritivorous organisms, as well as their chemical alteration as a result of degradation processes within the experimental system.

Uptake of ^{14}C-phenanthrene, ^{14}C-chrysene, and ^{14}C-benzo(a)pyrene follow the general pattern previously described for these compounds in clams (Roesijadi *et al.*, 1978). Substantial differences were observed in the accumulation of phenanthrene vs. chrysene and benzo(a)pyrene in tissues and the amounts of these components in sediments. The rapid depuration of phenanthrene from clam tissue correlates with the rapid loss of this compound from sediment to interstitial water with subsequent loss from the system due to periodic tidal flux. This chain of events is, in part, a result of the higher solubility and lower lipophilicity of phenanthrene. Similarly, the increased lag time associated with the accumulation of chrysene and benzo(a)pyrene in tissue appears to correlate with the greater persistence of these compounds in sediment. Their greater persistence, in part, is a result of their greater lipophilicity and lower solubility in water. It would appear that *Macoma* would continue to accumulate these latter compounds for as long as they were released from the sediment into the water. While all the compounds are bioavailable, their retention times in the tissues vary and it appears that uptake is primarily via interstitial water rather than ingestion of oiled particles. Within the limits of detection of the analytical techniques employed, we could not find any significant levels of metabolic degradation products associated with the tissue or sediments from these laboratory exposure systems.

EFFECT OF PRUDHOE BAY CRUDE OIL CONTAMINATION ON SEDIMENT WORKING RATES OF *ABARENICOLA PACIFICA*

Introduction

Accidentally spilled petroleum hydrocarbons (PHCs) which impact fine-grained sediments in intertidal zones may remain *in situ* for periods of years (Mayo *et al*., 1978; Teal, Burns, and Farrington, 1978) resulting in long-term effects on local populations (Krebs and Burns, 1977). One factor which may contribute to this persistence is the existence of anoxic conditions at depths of more than 1 cm below the surface of these habitats (Teal and Kanwisher, 1962; Pamatmat, 1968; Hylleberg, 1975). ZoBell (1964) has reported that PHCs are degraded at much slower rates in anaerobic sediments than under aerobic conditions.

The burrowing and feeding activities of certain organisms transport sediment from the lower anoxic areas to the surface, where aerobic microbes can metabolize hydrocarbons more rapidly. One such organism which occurs in high densities in fine-grained sediment along the shores of the North Pacific is the sedentary polychaete worm, *Abarenicola pacifica* Healy & Wells. Hobson (1967) has calculated that a population of *A. pacifica* located in False Bay, San Juan Island, Washington State could move all the sediment in the upper 10 cm of the area they inhabit to the surface in a little more than two years. Their activity could aid in the recovery of intertidal zones from the effects of oil pollution if they can continue to feed in contaminated sediment.

Gordon, Dale and Keizer (1978) reported that exposure in the laboratory to No. 2 fuel oil, Venezuelan Bunker C, South Louisiana Crude, Kuwait Crude oil, or to sediment which had been impacted by an accidental spill led to reductions of 51% to 82% in sediment-working rates of *Arenicola marina L*., a species which is found in sandy beaches around the Atlantic and is closely related to *A. pacifica*. Gordon *et al*., found that direct contact with sediment containing oil at concentrations as low as 153 ppm for as little as 5 days caused some of their worms to surface and some died at concentrations of 275 ppm.

In our laboratory *A. pacifica* has been found to tolerate direct contact with sediment containing 1000 ppm of Prudhoe Bay crude (PBC) oil for more than three weeks. It therefore seemed possible that the mud-dwelling Pacific species is more tolerant of oil contamination than the sand-dwelling Atlantic species. An experiment was designed to learn whether contamination of their habitat with various levels of PBC would reduce the amount of sediment which A. pacifica transports to the surface, making use of the fact that the worm deposits its feces in easily recognizable coils around the entrance to its burrow.

Materials and Methods

Forty specimens of A. pacifica and 12 kg sediment were collected from the high intertidal region of an almost enclosed lagoon adjacent to Sequim Bay, Washington State, U.S.A. The upper 10 cm of the sediment consisted of very fine grained, semi-liquid mud, and a layer of firmer fine-grained sand lay beneath. In the laboratory the worms were kept in sediment under running sea water at 10°C and 30°/₀₀ salinity.

Sediment (2.5 kg) consisting of equal volumes of the mud and sand strata, were placed in each of four cylindrical metal containers of 3 liter capacity. Three different volumes of PBC (.625, 1.25 or 2.5 g) were added to three containers, and the contents of each, including the unoiled control, were stirred 6 minutes with a motor driven impeller. Previous trials with the dispersion of radio-labelled material have shown this time period to be adequate for thorough mixing. The resulting mixtures were injected into 40 pieces of tubing, 40 cm long and 17 mm i.d. The tubes were bent into U-shapes and placed in racks under running sea water for 20 hours to allow the more toxic low molecular weight components of the oil to wash out. Remaining sediment was placed under running sea water as a reserve supply.

One worm was placed in each tube, and plastic trays, 64 mm on a side, were placed around the ends of the tubes. At 24 hour intervals the water levels in the tanks were lowered and the feces produced by each worm were collected from the trays and from the surface of the sediment within the tubes with a stainless steel spatula. At intervals of several days sediment from the appropriate reserve supply was added to the tubes to replace consumed material. The feces were dried in air for 24 hours and weighed. Preliminary studies indicated that this time period was long enough to achieve a constant weight. All calculations of fecal cast production were based on the mean daily dry weight produced by each individual worm.

After 11 days of exposure the sediment and worms were removed from the tubes. The worms were rinsed with sea water, blotted dry, weighed, and frozen. Samples of sediment were taken from tubes at each treatment level, frozen, and later analyzed for total hydrocarbon content by IR spectrophotometry.

Results

The level of PHC in the sediment changed little during the exposure period. The worms' native substrate used in the experiment has a fairly high endogenous content of hydrocarbon measurable by IR spectrophotometry. As Table 16 shows, the content of sediment at the three treatment levels, when corrected for the content of the control sediment, was between 80 and 100% of the amount originally added.

All the control worms survived, but two of them left their tubes and burrowed into detritus at the bottom of the tank, where their feces could not be collected. Mortality was slightly higher in the exposed groups, and some signs of behavioral stress were observed (Table 17). When the feces were collected, at 24 hour intervals, some of the worms exposed to medium and high levels of PBC were seen to extend their posterior segments from the burrows and slowly move them through the water. This behavior, which would obviously be maladaptive under natural conditions, was never observed in the controls or in the field. Feeding behavior was apparently depressed during the first two days of exposure, to a greater extent at the higher concentrations. During the remaining nine days the frequency of defecation, based on 24 hour observation periods, was slightly, but not significantly, lower in the exposed animals. Data on fecal production was, therefore, taken from this nine day period, as being more representative of the long term effect of oil exposure.

A strong negative correlation was found between weight-specific fecal production and wet body weight. The slope of the regression line relating these parameters was steeper in the control and the low level exposure groups than in the two higher level exposure groups (Figure 11). The degree of scatter around the regression lines was less in the exposed groups than in the control. Mean weight-specific fecal production was moderately depressed in low level exposed and severely depressed in the higher level exposed groups.

Table 16. Hydrocarbon content of sediment after 11 days in the exposure system (ppm)

		Exposure Level		
	Control	Low	Medium	High
PBC Added	0	250	500	1000
Total HC Present	98	349	513	905
Net Added HC Recovered		251	415	807

Table 17. Effects of PBC on survival and behavior of _A_. _pacifica_.

		Exposure Level		
	Control	Low	Medium	High
Survival	10/10	9/10	8/10	7/10
Left Tubes	2/10	0	0	0
Tail Extended From Tubes	0	0	6	12
Cast Production* First 2 days	4.5	3.5	2	1
Cast Production* Next 9 days	5	4.9	4.6	4.5

---

* Mean number of casts/day produced by all surviving worms.

The regression of dry fecal weight, unadjusted for body weight, on body weight, was not significant within any treatment group. As Table 3 shows, the mean fecal weight is markedly reduced by exposure to hydrocarbon levels about 400 ppm. Pairwise comparison of the control with each treatment group by the Newman-Keuls test showed no significant difference between it and the low exposure level while the mean production rate at the medium and high exposure levels differed significantly at the .05 level from that of the controls.

Discussion

Exposure to oil reduces the degree of scatter around the regression lines relating weight-specific fecal production to body weight of A. pacifica, and at levels above 400 ppm greatly reduces the slope of the lines (Figure 11). Both of these effects may be attributed to a greater impact of exposure on the smaller and more active animals. Among control worms weighing less than 0.25 g, weight-specific fecal production varied between 0.9 and 2.1 g feces per g worm. Production by worms in this size class ranged from 0.84 to 1.3 g per g worm under exposure to a low level of oil. At the higher oil levels values for the smaller worms fell to between 0.27 and 0.45 g per g worm. By contrast, the maximum production of worms weighing more than 0.6 g was reduced only from 0.2 g per g worm in control animals to .08 g per g worm at the higher exposure levels. Exposure to oil clearly leads to a greater reduction in feeding activity at the lower end of the size range than at the upper end. The individual variability of production is lessened by a greater decrease in the maximum rate achieved by the smaller animals than in the minimum rates.

These data indicate some of the effects of hydrocarbon pollution on the biology of the worms. However, measures of weight-specific fecal production such as these, and those reported by Gordon et al. (1978) are less useful in predicting the effect of the affected worms on sediment turnover, since predictions based on them would require information on the size distribution of the affected population, which might not be available. Fortunately, the effect of the negative regression of fecal production on body weight is cancelled out by the increasing body weight itself, which accounts for the fact that none of the regressions of fecal weight per se on body weight,

Figure 11. Effect of exposure to crude oil impacted sediment on regression of weight-specific fecal weight on body weight - *Abarenicola pacifica*.

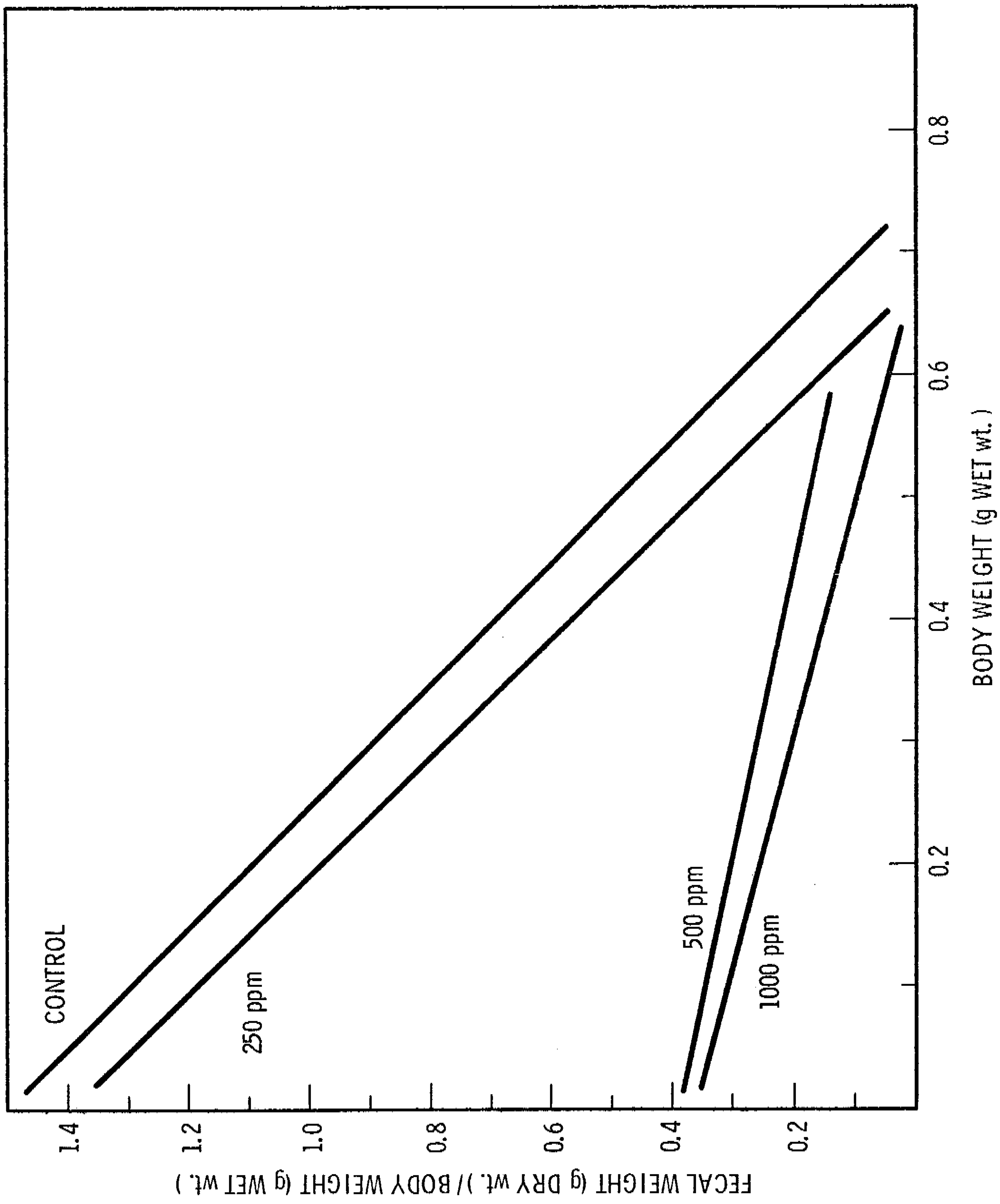


Table 18. Effect of PBC on sediment working rate of *A. pacifica*.

	Exposure Level			
	Control	Low	Medium	High
Mean body weight ± standard error	.32 ± .15 g	.32 ± .14 g	.52 ± .17 g	.52 ± .16 g
Mean fecal dry weight/day	.25 ± .14 g	.16 ± .11 g	.073 ± .06 g	.077 ± .06 g
Mean fecal dry weight/day/ g body weight	.99 ± .30 g	.63 ± .24 g	.18 ± .12 g	.17 ± .12 g
Regression of mean fecal weight on body weight	-.31 n.s.[1]	-.37 n.s.	+.012 n.s.	+.012 n.s.
Regression of mean fecal weight/g body weight on body weight	-2.56[2]	-2.56[3]	-.51[3]	-.50[3]

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[1] Not significant

[2] Significant at .10

[3] Significant at .01

within any treatment group, is significant. The somewhat surprising conclusion is that under uniform conditions and within the weight range examined, the size of the worms has no significant effect on the average dry weight of feces produced per day. Therefore, if suitable control populations were available for comparison the defecation rate of A. pacifica could be used as an indicator of a particular level of environmental stress, even if the size distribution of the worm populations is not known.

The results also suggest that if pollution is not too severe Abarenicola may continue to turn over the equivalent of its own wet body weight per day in sediment. However, high concentrations of oil may reduce the sediment-working rate of surviving worms by as much as 70%. This effect, together with any mortality due to the environmental pollution, would substantially retard the transportation of subsurface sediments to the surface. If these effects were found in the field sufficiently high levels of oil might retard the rate of sediment recovery by reducing the feeding behavior of ecologically significant species.

An extention of the work just described has been begun, in which the effects of sediments contaminated with various levels of PBC on the survival and behavior of Abarenicola pacifica is being studied under field conditions. Sediment into which 0, 200, or 1000 ppm PBC had been stirred was placed in 800 ml beakers, whose bottoms had been replaced with Nitex, one mm mesh. One Abarenicola was placed in each beaker, and 12 unoiled controls, 12 containing 200 and 12 containing 1000 ppm PBC were set into the intertidal mudflat from which the animals and sediment had been taken. They were placed at a depth which kept the surface of the sediment within the beakers level with the mud surface around them. The area contains many worm castings, which indicates that the general environmental conditions are favorable to their survival.

In contrast to the laboratory results in which 70% of the worms exposed to 1000 ppm PBC remained and survived in the contaminated sediment, in the mudflat environment no castings were produced by any worms at this exposure level. After 17 days the beakers were examined and no worms were found. A second set of animals was then placed in these beakers, since it seemed possible that the first set might have been killed or stimulated to migrate from the contaminated area during the first few days of exposure by highly toxic low molecular weight components of the oil, which might later have been washed out. At the same time three worms were placed in sediment with 1000 ppm oil in boxes fitted with lids. This sediment had aged in the field environment for the same time and under the same conditions as that in the beakers. The bottoms of the boxes and the centers of the lids had been replaced with Nitex mesh, to allow circulation of water and passage of the meio- and micro fauna on which A. pacifica feeds, while confining the worms to the contaminated area.

The feces of all animals were collected daily during exposure at low tides, dried in air to constant weight, and weighed. The worms were removed and weighed five weeks after their initial exposure.

Results

The worms confined to the boxes with 1000 ppm oil died within three days. The beakers to which the second set of worms had been added contained no worms at the end of the experiment and no fecal casts were found in them at any time.

The worms in the control beakers and in the beakers containing 200 ppm oil produced feces during the five weeks of the exposure though at less regular intervals and in smaller amounts than the animals in the laboratory. The mean daily fecal production was not correlated with the weights of the individuals. Nevertheless there was wide variation between production by individual worms. This variation obscured any statistical differences between the control group and that exposed to 200 ppm oil. However, based on comparisons of the means alone it appears that the fecal production of the exposed group was reduced by approximately one half during the first week, did not differ from the controls during the next 3 weeks, and was reduced by about 1/3 during the final week.

Discussion

It is clear that oil contamination has a more severe impact on A. pacifica under field conditions than in the lab. The most obvious difference between the two situations is that in the field they are cut off from access to fresh supplied of oxygenated water for about six hours each day, and must either spend additional energy to aerate their burrows by drawing air bubbles into them, or undergo anaerobic conditions. These additional stresses, from which the animals are relieved in the ordinary laboratory tank, may reduce their abilities to cope with the effects of high levels of oil contamination in the sediment.

This suggests that if laboratory investigation of physiological responses of intertidal animals to stress are to be relevant to field populations the investigation should be conducted under conditions which simulate tidal rhythms of immersion and emersion. Apparatus which can produce such simulated rhythms has been designed, and is being used in appropriate experiments in this laboratory.

The results also suggest that these or related organisms can be placed in similar installations in other coastal areas, such as the Alaskan coast line, to provide information on the effects of local environmental changes on their physiology or behavior under field conditions.

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ANNUAL REPORT

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BEAUFORT SEA BARRIER ISLAND-LAGOON ECOLOGICAL PROCESS STUDIES

Section I	Avian Ecology
Section II	Ecology of Fishes
Section III	Ecology of Invertebrates
Section IV	Oceanographic and Geologic Processes

1 April 1979

This Annual Report of the Beaufort Sea Barrier Island-Lagoon Ecological Process Studies Program contains four sections as follows:

(1) Avian Ecology in Simpson Lagoon, Beaufort Sea, Alaska.
- S.R. Johnson

(2) Ecology of Fishes in Simpson Lagoon, Beaufort Sea, Alaska.
- P.C. Craig and L. Haldorson

(3) Ecology of Invertebrates in Simpson Lagoon, Beaufort Sea, Alaska.
- W.B. Griffiths and R. Dillinger

(4) Oceanographic and Geologic Processes Along the Beaufort Coast - A Synthesis of Ecologically Important Information
- J.C. Truett

These are interim presentations of research and are therefore incomplete. Furthermore, because the sections are each part of a major multidisciplinary integrated research program, they are not intended to stand alone. The rationale for the research objectives of each section within the context of this program appears in the Annual Report of this program (RU 467) for 1978.

This report is to be followed within the year by a Final Report for the Barrier Island-Lagoon Program. This Final Report will describe in detail the strategies and findings of the program since its inception in 1976. It will also evaluate the effectiveness of this sort of program for environmental assessment so that future planners and researchers may thereby profit from our experiences.

ACKNOWLEDGEMENTS

An arctic research project of this size invariably draws upon a wide range of support personnel. In addition, the interdisciplinary nature of this project has brought together an even larger number of people who have all, in some way, had an impact on project design and operation. We want to thank everyone who has contributed to this project, and we are concerned that some who have made essential contributions to the project may have been inadvertently excluded from these acknowledgements.

Research Planning: At the modelling workshops at the University of British Columbia, a number of participants have provided ideas and criticism which has influenced the research undertaken. Included in this group are Carl Walters, Ray Hilborn, Sandy Buckingham, Mike Staley, Randall Peterman, Mike Jones, Bob Everitt, Max Dunbar, Grant Gross, John Hobbie, Gary Hufford, Dave Norton and Alan Birdsall.

Field Research: The field team included Howard McElderry, Chip Welling, Bob Baden, Geoff Clarke, Phil Lulman and George Lewbel. Their contributions are greatly appreciated.

Jim Helmericks provided invaluable and reliable air support. Logistic support was provided by Maya Spies and Dan Brooks. We would especially like to thank Kate Persons for her patient and persistent help throughout the field season. John "Jumper" Bitters and others provided essential supplies in a series of air drops to the field camp.

Analysis and Report Preparation: The fish and bird stomach contents and invertebrate samples were analyzed by Wayne Bennett, Tim Byers, Brian Herbert and Dyane Kurylowicz. Rick Dressler, Diane Hollingdale and Kathy Bruce drafted figures for the report. Kathy in particular showed great endurance and tolerance in meeting the unreasonable deadlines given her by the authors. The report was typed by Joan Bjornson, Debbie Whitford, Christine Furlong and Gail Wylie. Eric Tull organized the preparation for the annual report. LGL's data manager, Brian Harvie, contributed a great deal to the data analyses. Laureen Lomas did an excellent job of data checking and coding. Don Pattie performed the bomb calorimetry of invertebrate samples.

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BEAUFORT SEA BARRIER ISLAND-LAGOON ECOLOGICAL PROCESS STUDIES

AVIAN ECOLOGY IN SIMPSON LAGOON BEAUFORT SEA, ALASKA

S.R. Johnson
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10110 - 124th Street
Edmonton, Alberta, Canada

1 April 1979

TABLE OF CONTENTS

Page

SUMMARY........ viii

  Migration Studies........ viii

  Nesting Studies........ ix

  Molting and Staging Studies........ ix

  Feeding Studies........ x

  Disturbance Studies........ xi

  Conclusions........ xi

ACKNOWLEDGEMENTS........ xiv

INTRODUCTION........ 1

  General Nature and Scope of Study........ 1

  Specific Objectives........ 1

  Relevance to Impact Assessment........ 2

CURRENT STATE OF KNOWLEDGE........ 3

STUDY AREA........ 5

METHODS AND RATIONALE OF DATA COLLECTION........ 7

  Migration Studies........ 7

    Spring Migration........ 11

      Radar Monitoring........ 11

      Visual Migration Watches During Spring-1977........ 12

      Visual Migration Watches During Spring-1978........ 13

    Mid-Summer Molt Migration........ 13

    Fall Migration........ 15

  Nesting Studies........ 15

    Survey Methods........ 16

  Molting and Pre-Migratory Staging Studies........ 17

    Aerial Surveys During 1977 and 1978........ 19

    Shoreline Transects........ 23

  Feeding Studies........ 25

    Collections of Birds and Habitat Samples........ 26

      Oldsquaw........ 26

      Phalaropes and Glaucous Gulls........ 28

TABLE OF CONTENTS (cont'd)

Page

Laboratory Techniques.................................... 29

RESULTS.. 32

Migration Studies...................................... 32

Spring Migration..................................... 32

Mid-Summer Molt Migration............................ 37

Fall Migration....................................... 40

Nesting Studies.. 41

Molting: Oldsquaw...................................... 51

Pre-molt Period...................................... 51

Male Molt Period..................................... 53

Female Molt Period................................... 67

Post-molt Period..................................... 67

Pre-migratory Staging.................................. 75

Shorebirds... 75

Arctic Tern.. 83

Glaucous Gull.. 87

Feeding Studies.. 90

Oldsquaw... 90

Phalaropes... 100

Glaucous Gull.. 103

Recommended Further Research........................... 105

Summary of 4th Quarter Operations...................... 105

.ITERATURE CITED.. 106

LIST OF TABLES

Table		Page
1	Sensitivity/Vulnerability Index for Various Avian Species and Habitats in Barrier Island-Lagoon Areas Along the Eastern Beaufort Sea Coast of Alaska.	xii
2	Transect Survey Dates and Aircraft Types Used During Aerial Surveys Conducted in the Study Area During the Period 5 June to 22 September, 1977.	20
3	Transect Survey Dates and Aircraft Types Used During Aerial Surveys Conducted in the Study Area During the Period 23 June to 23 September, 1978.	21
4	Aerial Survey Transect Descriptions, Beaufort Sea, Alaska, 1977-1978.	22
5	List of All Avian Species Recorded During Migration Watches Conducted During Spring 1977 at Oliktok Point and Pingok Island and During Spring 1978 at Milne Point, Alaska.	34
6	Numbers of Oldsquaws, Eiders, Scoters and Unidentified Diving Ducks Sighted Flying in Various Directions Through Simpson Lagoon During the Mid-summer Molt Migration in 1977 and 1978.	38
7	List of Avian Species Recorded During Fall Migration, 1977 and 1978, at Simpson Lagoon, Alaska.	42
8	Active Bird Nests Found During 1977 on the Jones Islands and on Adjacent Spits and Bars in Simpson Lagoon, Alaska.	44
9	A Comparison of Bird Densities on Two Tundra Plots on Pingok Island and on the Total Area of Tundra Surveyed During Nest Searches on the Jones Islands, 1977.	45
10	A Comparison of Bird Nest Densities on a Mainland Tundra Plot and a Barrier Island Tundra Plot in the Simpson Lagoon-Jones Islands Area of Alaska (1977-1978).	46
11	A Comparison of the Numbers of Nests Found on Two Gravel-Covered Barrier Islands in the Jones Islands-Simpson Lagoon area of Alaska, 1977-1978.	47
12	Densities (Birds/km^2) of Oldsquaws Recorded in All Habitats During Aerial Surveys of Five Transects in the Jones Islands-Simpson Lagoon Area, 5 June to 22 September 1977 and 23 June to 23 September 1978.	52
13	Numbers of Oldsquaws Recorded On-transect along Various Sections of the Beaufort Sea coast in Northeastern Alaska, 23 June to 23 September 1978.	55

LIST OF TABLES (cont'd)

Table		Page
14	Estimates of the Total Number of Oldsquaws Present in Simpson Lagoon During Aerial Surveys Conducted in 1977 and 1978.	57
15	Locations of Major Oldsquaw Concentrations Recorded During the Period of Summer Molt in Simpson Lagoon, Alaska, 1977 and 1978.	61
16	Locations of Major Oldsquaw Concentrations Recorded During the Period of Summer Molt at Barrier Island-Lagoon Locations Along the Beaufort Sea Coast of NE Alaska, 1978.	62
17	The Change in Adult Oldsquaw Wing Length, Weight and Subcutaneous Fat Thickness During the Premolt, Molt and Postmolt Periods at Simpson Lagoon, Alaska (1977-1978).	64
18	Statistical Comparisons of the Change in Adult Male Oldsquaw Weights and Subcutaneous Fat Thickness Throughout the Summers of 1977 and 1978.	66
19	Locations of Major Oldsquaw Concentrations Recorded During the Postmolt Period (15 August to 23 September 1978) at Barrier Island-Lagoon Locations Along the NE Coast of Alaska.	73
20	Numbers of Red and Northern Phalaropes Observed on Beach Transects in the Simpson Lagoon-Jones Islands Area During August, 1977 and 1978.	77
21	Average Linear Densities (Birds/km of Shoreline) of all Shorebirds Recorded on Three Beach Types Surveyed During 1977 and 1978.	78
22	Estimated Numbers of Shorebirds and Gulls/Terns Present Along the Oceanside and the Lagoonside Beaches of the Jones Islands from Spy to Cottle Island, and Along the Mainland Beach of Simpson Lagoon From Oliktok Point to Beechey Point, 1977 and 1978.	79
23	Changes in Subcutaneous Fatness and Sex Ratios of Red and Northern Phalaropes in Simpson Lagoon During August, 1977 and 1978.	81
24	Average Linear Densities (Birds/km of Shoreline) of Gulls and Terns Recorded on Three Beach Types Surveyed During 1977 and 1978.	85
25	Total Numbers of Terns Recorded During Aerial Surveys of Five Transects in the Jones Islands-Simpson Lagoon Area, June to September, 1977 and 1978.	86

LIST OF TABLES (Cont'd)

Table		Page
26	Total Numbers of Glaucous Gulls Recorded in All Habitats During Aerial Surveys of Five Transects in the Jones Islands-Simpson Lagoon Area, 5 June to 22 September 1977 and 23 June to 23 September 1978.	88
27	A Comparison of Food Organisms Consumed by Oldsquaws Throughout the Season at Simpson Lagoon, Alaska, During 1977 and 1978.	92
28	A Comparison of Oldsquaw Total Season Diet and the Composition of Oldsquaw Epibenthic Feeding Habitat Samples in the Jones Islands-Simpson Lagoon Area of Alaska During 1977 and 1978.	94
29	The Diet of Oldsquaws in Simpson Lagoon During 1978 as Determined by Estimated Relative Volume, Abundance, Wet Weight Biomass, Dry Weight Biomass and Energy Content.	99
30	A Comparison of Phalarope Total Season Diet and the Composition of Phalarope Feeding Habitat Samples in the Jones Islands-Simpson Lagoon Area of Alaska During 1977 and 1978.	101
31	A Comparison of the Organisms Found in the Stomachs and in the Feeding Habitat Samples of Glaucous Gulls in the Simpson Lagoon Area of Alaska, 16 July to 19 September 1977.	104

LIST OF FIGURES

Figure		Page
1	Jones Islands-Simpson Lagoon Study Area, Beaufort Sea, Alaska.	6
2	Locations of Aerial Survey Transects in Areas West and East of the Jones Islands-Simpson Lagoon Study Area.	8
3	A Comparison of the Unweighted Mean Densities of Oldsquaws in Barrier Island-Lagoon Habitats to the East, West and In Simpson Lagoon, Alaska, June-September 1978.	54
4	The Change in the Weighted Mean Density of Oldsquaws Throughout the Seasons of 1977 and 1978 in Simpson Lagoon, Alaska.	60
5	A Comparison of the Changes in Wing Length, Body Weight and Subcutaneous Fat Thickness of Male and Female Oldsquaws During Five Collection Periods in Simpson Lagoon During 1977 and 1978.	65
6	The Relationship Between the Density of Invertebrates in Oldsquaw Feeding Habitats and the Amount of Invertebrates Consumed by Oldsquaws in Simpson Lagoon, Alaska.	97
7	A Comparison of the Distributions of Sizes of the Three Most Important Invertebrate Prey Species Consumed by Oldsquaws and Found in Oldsquaw Feeding Habitats.	98

LIST OF APPENDICES

Table		Page
1	Numbers of Charadriiformes Sighted on a Frequently Surveyed Shoreline Transect on Pingok Island, Alaska, During 1977 and 1978.	110
2	Methods of Estimating the Total Number of Oldsquaws Present in Simpson Lagoon, Beaufort Sea, Alaska, During 1977 and 1978.	111

SUMMARY

In 1976, LGL Limited-U.S., Inc. initiated an interdisciplinary, process-oriented study of a barrier island-lagoon ecosystem on Alaska's Beaufort Sea coast. The general scope of the ornithological components of this study, which was sited primarily in the Simpson Lagoon area, was to characterize the use of nearshore habitats by birds and to clarify those critical feeding and habitat dependencies that development is likely to affect either directly, or indirectly via alteration of ecosystem processes.

The research program addresses four ecosystem uses/dependencies of birds--for migration, breeding, feeding and staging-molting. These uses are evaluated as they relate to barrier island-lagoon habitats and predicted development alterations of habitats.

Migration Studies

Spring migration during 1977 and 1978 (late May to mid-June) was eastward over a broad front; major bird groups involved were loons, glaucous gulls, jaegers, pintails, oldsquaws, eider and black brant.

The westward molt migration by male seaducks consisted of two peaks--movement of oldsquaws during late June and early July, prior to breakup in the lagoon or in the sea, and movement of common and king eiders through the study area during the third and fourth weeks of July, after the lagoon and sea ice had retreated. Oldsquaws made moderate use of shoreleads in lagoons and light use of leads in the ice in mid-lagoon during the course of their molt migration; eiders made light use of lagoon habitats during the westward molt migration.

The fall migration by birds out of the Simpson Lagoon area was protracted and much less intense than either the spring or molt migration. Most oldsquaws and glaucous gulls had not begun their

fall migration out of the study area when the field season was terminated on 25 September 1977 and 1978. A westward movement of adult and juvenile arctic terns occurred along the barrier islands during the third and fourth weeks of August, at which time they congregated at gaps between the islands and along the spits and sandbars where food was more readily available to this species. A major movement of black brant occurred along the mainland coast in the last days of August and the early days of September during 1977 and in the second and third weeks of August during 1978. A westward movement of loons through the lagoon occurred in late August and early September of 1977 and 1978.

Nesting Studies

During 1977, arctic foxes preyed heavily on eggs of birds which nested on the barrier islands, and (presumably because of the predation) densities of successful nests were relatively low. Indications were that in the absence of arctic foxes on gravel islands, the nesting potential for traditionally island-nesting species was high.

During 1978, arctic foxes were absent from the barrier islands. Although the density of tundra nesting birds remained low, those species associated with the gravel islands were more productive than during the preceding year when foxes were present.

Molting and Staging Studies

An estimated 30,000 to 51,000 male oldsquaws may concentrate in the lagoon between mid-July and mid-August to molt. Few molting oldsquaws occur seaward of the barrier islands. An estimated 33,000 to 106,000 oldsquaws, primarily females and juveniles, may occur in the Simpson Lagoon study area during late September.

Juvenile northern and red phalaropes arrived to feed along the shorelines of the barrier islands and mainland both in 1977 and 1978 during August; thousands of individuals concentrated along the beaches of the barrier island during the mid and late parts of August.

Glaucous gulls in the study area were most intensively studied during 1977; they were associated with shorelines and their distribution appeard to be related to the availability of food. During September 1977 and 1978 the number of glaucous gulls increased dramatically in the area; during 1977 they were most abundant along the seaward beaches of the barrier islands, where food (hyperiid amphipods) was concentrated along sections of the shoreline.

Feeding Studies

During both 1977 and 1978 oldsquaws ate primarily mysids and amphipods, and to a lesser extent, bivalves. They ate largely the kinds of foods that were most available; during 1977 their diet was very similar to that of the arctic cisco, the most common coregonid fish in the lagoon.

During both 1977 and 1978 oldsquaws were fattest from mid-July to mid-August, the period of molt. Their fat reserves declined thereafter, which suggests that subcutaneous fat may play an important role during the molt period (e.g., for insulation and/or to satisfy maintenance energy requirements) and that this fat may be utilized after the molt to help meet the energy demands associated with feather replacment. Throughout the summer of both 1977 and 1978 the standing stocks of epibenthos used as food by oldsquaws remained at least one order of magnitude greater than the estimated per-day food requirement of the birds.

During 1977, glaucous gulls in the study area fed exclusively along shorelines and ate mainly isopods, amphipods, small fish and small birds. The relative proportions of these same organisms they consumed bore little resemblance to the proportions of these same organisms at the locations where glaucous gulls were collected. Feeding overlap studies indicated that the diet of glaucous gulls was most similar to that of the four-horned sculpin. The highest densities of glaucous gulls were recorded along the beaches of the barrier islands during the third week of September in both 1977 and 1978. At this time during 1977, glaucous gulls were feeding on hyperiid amphipods that were concentrated along sections of the seaward shorelines of the barrier islands.

Both northern and red phalaropes are specialized shoreline feeders. Phalaropes concentrating on coastal shorelines in August of 1977 and 1978 ate primarily copepods, small amphipods and small mysids. The proportions of these organisms in the diet of phalaropes were similar to the proportions of these taxa found in their feeding habitats along shorelines. During 1978, phalaropes selectively preyed on small amphipods which in shoreline feeding habitats were much less abundant than mysids and slightly less abundant than copepods. During 1977 and 1978, the diets of red and northern phalaropes were very similar to each other. During 1977, the diets of phalaropes collectively were similar to diets of arctic char and least cisco.

Disturbance Studies

Data from other studies coupled with observations made during the course of this study showed that the vulnerability of birds to disturbance varies among species, habitats, and type of bird activity.

Table 1 gives a sensitivity/vulnerability matrix of important avian species, their habitats and the periods when each species is most vulnerable to development-related environmental activities.

Conclusions

General conclusions were that

1. Bird utilization of nearshore lagoon areas was minimal while these areas remained frozen in spring and early summer; potential impacts of development are, therefore, probably low at this time except for those activities that would create open water attractive to birds.

Table 1. Sensitivity/Vulnerability† Index for Various Avian Species and Habitats in Barrier Island-Lagoon Areas Along the Eastern Beaufort Sea Coast of Alaska. (Based on 1977 and 1978 data and the literature.)

	HABITATS								
	Barrier Islands				Lagoon		Mainland Shoreline		Offshore Marine
Species	Tundra	Gravel	Oceanside Shorelines	Lagoonside Shorelines	Shallow Lagoon	Deep Lagoon	Entire Shoreline	Points of Land	
Oldsquaw				loafing* (25 July-30 Aug)	loaf+feed (25 July-30 Aug)	Feeding*** (open water season)		Shelter or* feeding	
Eider		nesting*** (1 June-30 July)			loaf -feed (1-30 Aug)				migration*** (1 May-5 June and 15 July-10 Sept)
Brant		nesting** (1 June-30 July)					migration* (25 Aug-5 Sept)		
Loon									feeding** (open water season)
Phalarope			during high density staging*** (10-30 Aug)	during high density staging** (10-30 Aug)			during high density staging* (10-30 August)		
Glaucous Gull		nesting* (1 June-30 July)	during staging* (15-30 Sept)	feeding/staging* (30 Aug-30 Sept)	feeding* (25 July-30 Aug)				
Arctic Tern		nesting*** (1 June-30 July)		feeding/staging* (15-30 Aug)	feeding* (15-30 Aug)				

* Sensitive/vulnerable.

** Very sensitive/very vulnerable.

***Critically sensitive/critically vulnerable.

† The term sensitive refers primarily to habitats and the term vulnerable refers primarily to species.

2. Shoreleads were used moderately by birds before the nearshore area became ice-free.

3. The density of typical barrier island nesting birds was higher on the gravel/sand islands than on the tundra-covered barrier islands. If development activities are restricted to tundra sites on the barrier islands, then disturbance to these species should be minimal.

4. Shorebirds (primarily phalaropes) that stage in barrier island-lagoon habitats during August are most heavily concentrated along the seaward shoreline of the barrier islands.

5. Molting and post-molting oldsquaws are abundant and are highly concentrated at several barrier island-lagoon sites in and to the east of Simpson Lagoon. In general, the shallow and/or turbid waters directly under the influences of the Colville River, west of Simpson Lagoon, supported a depauperate avifauna.

6. Feeding studies indicated that oldsquaws preyed most heavily on larger individuals of the three major taxa of invertebrates most abundant in lagoon epibenthic habitats, and that oldsquaws preyed most effectively in areas where densities of invertebrates were highest.

7. Heaviest use of nearshore barrier island-lagoon areas by birds occurred during the open-water season--late July through August and September. Primary use of the area at this time was by molting and migrating oldsquaws and staging shorebirds. Feeding activity in the area was intensive by all these birds. Potential impacts of development, therefore, would be most serious during this open-water season.

ACKNOWLEDGEMENTS

Special thanks go to Chip Welling, Jim Helmericks and John Richardson. Chip enthusiastically and competently carried out much of the field work in my absence. Jim also helped with the field studies and provided invaluable advice and logistic support. John analyzed most of the migration data, helped in overall program design and gave editorial assistance. Doug Schamel, Bob Baden and Bill Adams also provided excellent field assistance.

INTRODUCTION

The Alaskan Beaufort Sea, especially its coastal lagoons and barrier islands, is an important area to many species of water-associated birds. During a portion of the year, significant fractions of the total North American populations of a number of species are present in the nearshore waters of the Beaufort Sea (Johnson *et al.* 1975). These include the following: yellow-billed loon, brant, oldsquaw, common and king eiders; glaucous, Sabine's and Ross' gulls; arctic terns; and red and northern phalaropes. Some of these birds occur in the coastal Beaufort Sea area only during migration, but others also nest, molt, feed and accumulate fat reserves there (Johnson *et al.* 1975).

General Nature and Scope of Study

In 1976, LGL Limited-U.S., Inc. initiated an interdisciplinary process-oriented study of a barrier island-lagoon ecosystem on Alaska's Beaufort Sea coast. The general scope of the ornithological portion of this study, which was sited in the Simpson Lagoon area, was to

1. assess the importance to birds of barrier island-lagoon habitats in the Beaufort Sea,
2. determine the degree and nature of dependencies by birds on these habitats, and
3. clarify those critical feeding and habitat dependencies that development is likely to affect either directly or indirectly via alterations of ecosystem processes.

Specific Objectives

The research program addresses each of four ecosystem uses or dependencies of birds--migration, breeding, feeding and staging-molting. These uses are evaluated as they relate to barrier island-lagoon habitats and predicted development alterations of habitats with these objectives:

1. Determine the timing, routes, numbers and major species involved in the spring migration, molt migration and fall migration of birds through a barrier island-lagoon system.

2. Identify the economically or aesthetically important (key) species of birds in the major habitat types present in the barrier island-lagoon system, obtain quantitative estimates of their seasonal abundance in each habitat type, and determine the nature of their utilization of these habitats.

3. Obtain quantitative estimates of the density, nesting success, and major predators of breeding birds in the typical barrier island-lagoon habitats.

4. Determine the major food organisms consumed by the key bird species during periods of their peak abundance in a barrier island-lagoon system.

5. Determine the relationships between feeding birds and their habitats: e.g., Do key bird species select particular food organisms or do they simply eat in accordance with the relative availability of the food organisms? Does cropping by birds have a significant effect on food availability? Do different species of birds (and fish) depend on the same food organisms?

Relevance to Impact Assessment

Plans for the development of petroleum resources in the coastal area of the Alaskan Beaufort Sea are proceeding rapidly. Activities affecting the coastal barrier islands and accompanying lagoon systems play a prominent role in the various development scenarios presented by the petroleum industry (Weller *et al.* 1978). Federal and state authorities have expressed the desire that development proceed with minimum disturbance to bird populations that are of concern to society because of their aesthetic, sport or subsistence value.

Industrial activity following petroleum leasing of nearshore waters may potentially affect birds in two major ways:

1. By imposing direct mortality or stress (e.g., oiling of birds, disturbance caused by human activities such as aircraft overflights, destruction of nesting habitat, or introduction or attraction of predators).

2. By interrupting key physical and biological processes (e.g., coastal erosion, water circulation, nutrient and invertebrate production and cycling, etc.) that currently enable birds to successfully use the area during migration and for breeding, feeding, staging and/or molting.

These two types of effects are not completely separable, since interruptions of key physical and biological processes (2) may affect the degree of mortality or stress mentioned in (1).

CURRENT STATE OF KNOWLEDGE

In general, prior to the initiation of the present barrier island-lagoon studies, little information was available regarding the spatial and temporal patterns of abundance and distribution of birds in the various barrier island-lagoon habitats. No information existed regarding the feeding ecology of key bird species in relation to invertebrate prey species in barrier island-lagoon habitats, nor regarding the effects of predation by foxes on birds nesting on barrier islands. Prior to this study little quantitative information existed regarding the densities on barrier islands of tundra-nesting birds, relative to densities of birds that typically nest on gravel/sand substrates.

Knowledge, as of 1975, of birds found in the Beaufort Sea area was reviewed by Johnson *et al.* (1975). Searing *et al.* (1975) and Richardson *et al.* (1975) present results of aerial surveys of seabirds conducted in the Canadian Beaufort Sea in 1972 and 1974, 1975, respectively. Barry (1976) has presented a brief summary of all available information on seabirds found in the Canadian Beaufort Sea. Richardson *et al.* (1975) and Johnson *et al.* (1975) presented detailed information on the spring migration of birds along a portion of the Beaufort Sea coastline in the Yukon Territory and eastern Alaska. Gavin (1976) and Bergman *et al.* (1977) recently published the results of long-term studies of the avifauna of the Beaufort Sea coast of Alaska. The work by Bergman *et al.* (1977) was restricted to tundra locations on the mainland, whereas the observations by Gavin (1976) included the coastal barrier islands and lagoons.

Several published accounts describe the birds in the immediate vicinity of the Jones Islands-Simpson Lagoon area. Hall (1974, and unpublished data 1972) has provided an annotated list of the birds seen near Oliktok Point and in Simpson Lagoon from 12 June to 23 August 1971 and intermittently from 11 May to 27 November 1972. Gavin (1976) reported on water bird production along most of the barrier islands in the vicinity of Prudhoe Bay, including the Jones Islands, for the 6-year period 1970 through 1975. Divoky (1979) conducted ground and aerial surveys of nesting birds along all of the barrier islands in the Alaskan Beaufort Sea during 1976, including the Jones Islands; he also conducted two aerial surveys of the Simpson Lagoon area during 1976. During 1977, Divoky (1978) conducted opportunistic shipboard surveys of birds in Simpson Lagoon and at this location collected a small sample of oldsquaws for stomach analyses. Schamel (1974) described some aspects of the spring migration, the molt migration of seaducks, and (1978) described the densities of shorebirds, gulls, terns, jaegers and seaducks in a portion of Gwydyr Bay near Egg Island, approximately 15 km east of Simpson Lagoon. Bergman *et al.* (1977) report the results of a five-year study of waterbirds and wetland resources on the mainland coastal tundra near Storkersen Point, which is approximately 25 km east of the Simpson Lagoon study area. Similarly Norton *et al.* (1975) and Hanson and Eberhardt (1976, 1977) report on the ecological relationships of the inland tundra avifauna near Prudhoe Bay, approximately 40 km east of Simpson Lagoon. Derksen *et al.* (1977) conducted habitat analyses during 1977 and reported on waterbird populations at tundra locations in the western portion of the Naval Petroleum Reserve, west of the Colville River, Alaska. King (1977) has reported on aerial surveys of birds on tundra habitats in the Naval Petroleum Reserve. During July to September 1978, Spindler (1978a, b) conducted surveys of snow geese and other terrestrial birds on the coastal plain of northeastern Alaska and surveys of waterbirds associated with the coastal lagoons adjacent to the Arctic National Wildlife Range, northeastern Alaska.

STUDY AREA

The study area chosen for intensive ornithological investigations was the Jones Islands-Simpson Lagoon system. For comparative purposes, intermittent investigations were also conducted in adjacent areas during 1977. During 1978, systematic and more extensive ornithological investigations were conducted as far west as Atigaru Pt. and as far east as the Alaska-Canada border.

The Jones Islands have been defined as all islands, spits and bars from Spy Island to Cottle Island (6.4 km^2, Fig. 1). During 1978, Thetis Island, a 1.6 km^2 gravel and sand island off the Colville Delta and west of Spy Island, was also included in the study area. The tundra-covered portions of Pingok, Peat, Bertoncini, Bodfish and Cottle Islands occupy an area of approximately 3.8 km^2, and are characterized by poor soils (Everett 1975) and tundra vegetation of low growth form (Spetzman 1959; Wiggins and Thomas 1962; Nieland and Hok 1975; Webber and Walker 1975). The remaining 2.6 km^2 of island habitat on the Jones Islands, located principally on Spy, Leavitt and Cottle islands, consists of unvegetated gravel, sand and silt.

Simpson Lagoon has been defined as that area east of a line from the west end of Spy Island to Oliktok Point, and west of a line from the east end of Cottle Island to Beechey Point (Fig. 1). This area occupies approximately 160 km^2, of which approximately 102 km^2 is 1.82 m (6 ft) deep or deeper. The deepest known point in the lagoon, located immediately off the east end of Spy Island, is 4 m deep. A trough, varying in width from 0.3 km at the east end of the lagoon to 5 km at the west end of the lagoon, and varying in depth from 2 to 3 m, runs the length of Simpson Lagoon. The remaining 58 km^2 of lagoon area is shallower than 1.82 m; almost two-thirds of these shallow waters lie along the south shore of Simpson Lagoon. (Planimetry conducted on U.S. Dept. Commerce, Coast and Geodetic Survey, Chart No. 9471, 4th edition, May, 1973.)

Also included within the study area is a 32 km x 20 m (0.64 km^2) strip of coastline that includes beaches, adjoining spits and adjacent

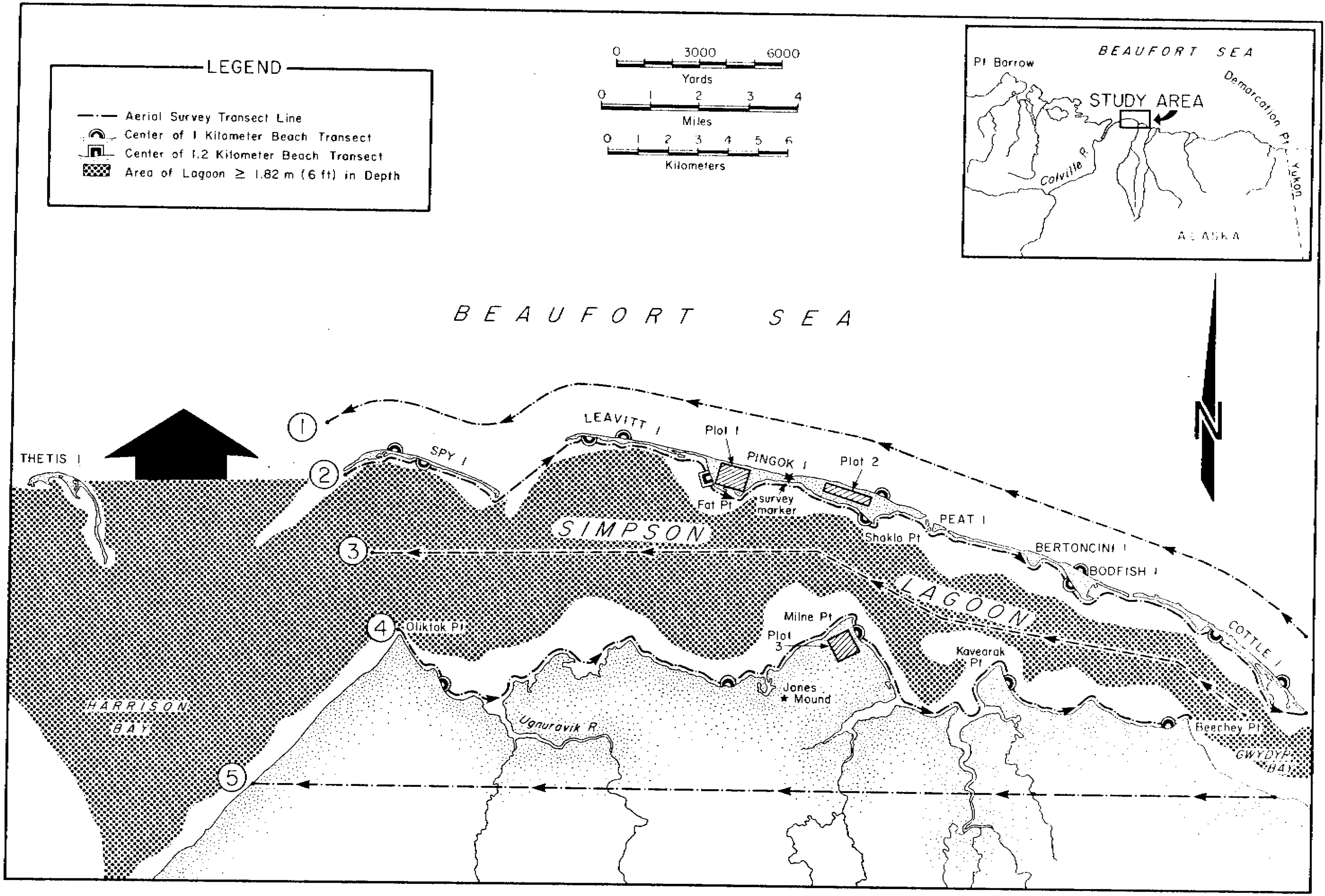


Figure 1. Jones Islands-Simpson Lagoon Study Area, Beaufort Sea, Alaska.

sand bars along the mainland shoreline between Oliktok Point and Beechey Point. This strip includes most of the driftwood and debris along this portion of the Beaufort Sea coast.

In order to compare avian use of the barrier island-lagoon study area with that of immediately adjacent marine and mainland areas, regular surveys were conducted seaward and landward of the intensive study area. The marine area was sampled along a 35 km x 0.4 km transect parallel to and about 2 km seaward from the contiguous Jones Islands (Cottle Island to Spy Island). The mainland area was sampled along a 35 km x 0.4 km transect located about 4 km inland from the shoreline between Oliktok Point and Beechey Point (Fig. 1).

During surveys conducted in 1978, 16 additional transects were established: six were in the shallow waters adjacent to the Colville River delta, west of Simpson Lagoon; ten were along the barrier islands and lagoon systems east of Simpson Lagoon as far as the Alaska-Canada border (Fig. 3).

METHODS AND RATIONALE OF DATA COLLECTION

Migration Studies

Three major migrations of marine-associated birds occur along the coast of the Beaufort Sea: spring migration, mid-summer molt migration and fall migration. During these migrations, birds usually occur in flocks and may be both spatially and temporally concentrated in certain lagoon habitats.

Spring migration occurs during a critical period because at this time there is little open water in normal years. Under certain circumstances, high mortality of marine-associated birds can occur from natural causes (Barry 1968). A previous study in the northern Yukon has shown that spring migration there, is highly concentrated along the Beaufort Sea coast (Johnson *et al.* 1975; Richardson *et al.* 1975). An oil spill at this time into a natural or man-made area of open water might kill large numbers of waterbirds. Hence, we studied spring migration intensively. We monitored migration by radar in 1977 and by visual methods in both 1977 and 1978.

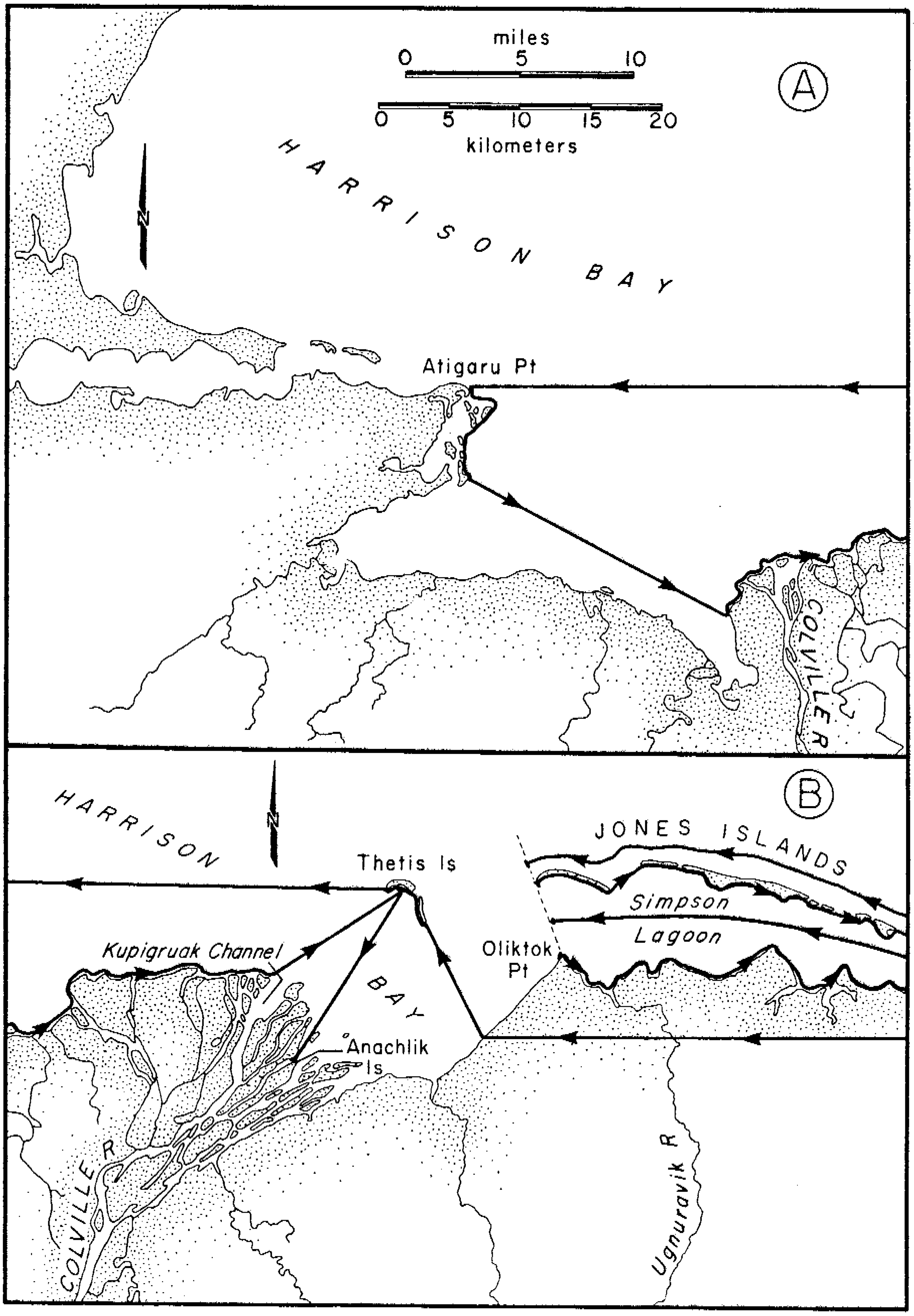
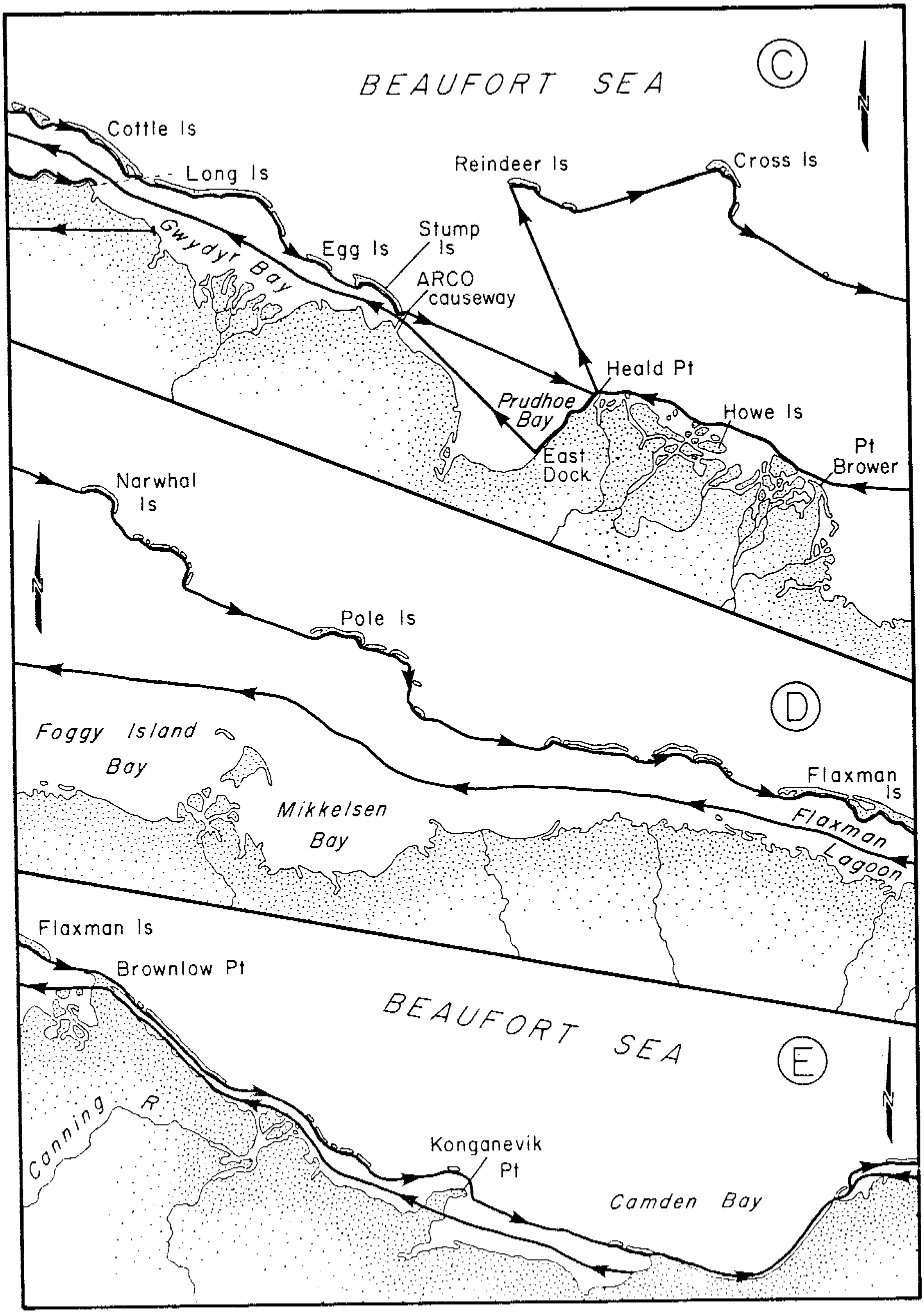


Figure 2. Locations of Aerial Survey Transects in Areas West (maps A and B) and East (maps C through G) of the Jones Islands-Simpson Lagoon Study Area.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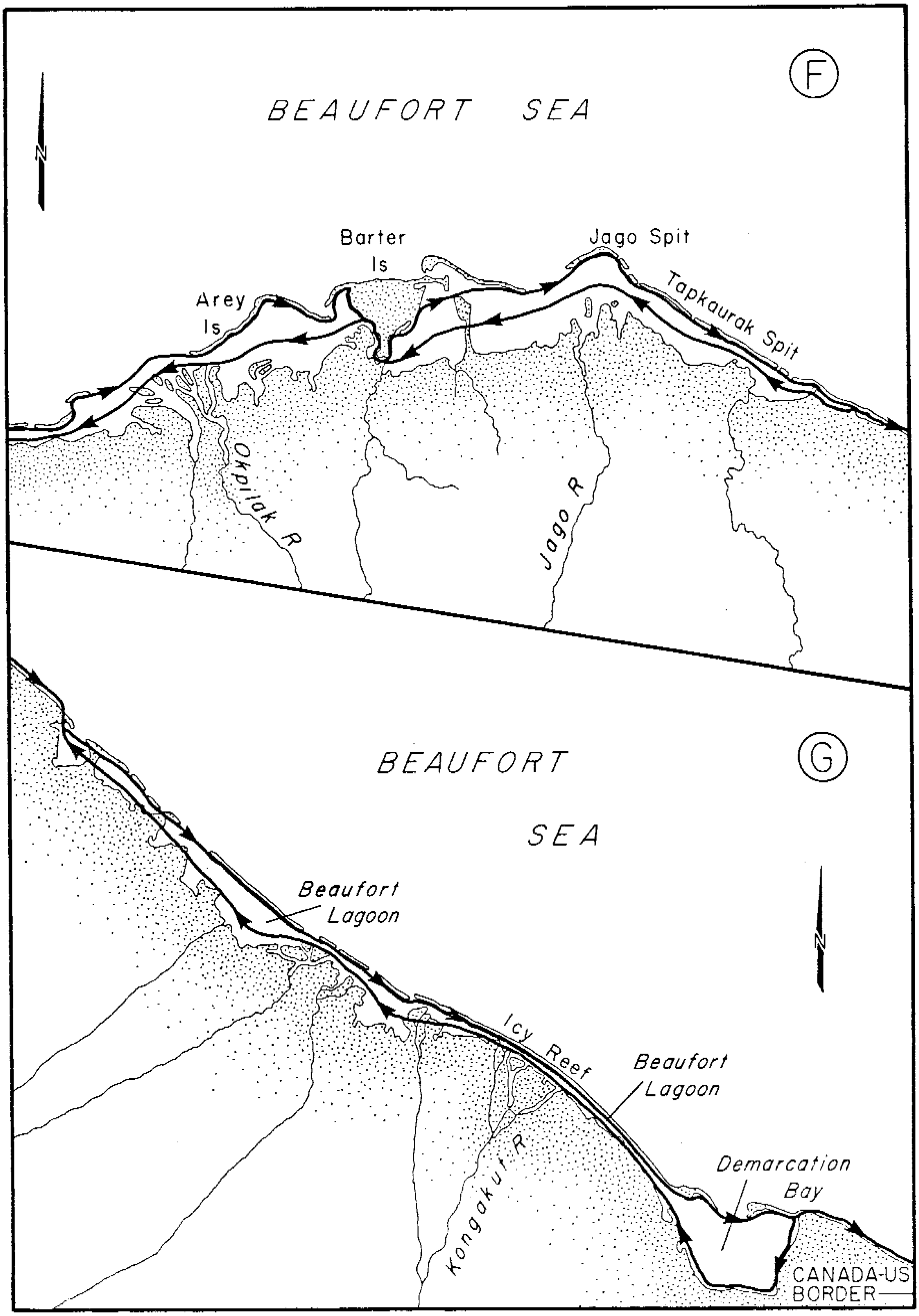
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Icy Reef
Beaufort Lagoon
Kongakut R
Demarcation Bay
CANADA-US BORDER

The westward molt migration by male seaducks generally occurs during July. Fewer species and individuals are involved in this migration than in the spring migration; furthermore, relatively small-scale movements occur in the nearshore waters around barrier islands and lagoons at this time of year. Most coastal lagoon habitats remain predominantly ice-covered until early to mid-July, limiting the number of habitats that these migrating birds may occupy.

The westward fall migration out of the Beaufort Sea generally involves more species than does the molt migration, and movements normally occur on a broader temporal and spatial scale within the coastal Beaufort Sea area than during either the spring or molt migration. All coastal habitats are available to most fall migrants.

This Annual Report presents a summary of the migration watch and radar data obtained in 1977 and 1978. Further analyses of these data will be presented in the Final Report. In this section we describe or document methods used to study migration and in the "Results" we present three tables (Tables 5, 6 and 7) describing important species and events associated with migrations of birds through the study area.

Spring Migration

Radar Monitoring. During spring 1977, radar data were recorded using Oliktok Point, Alaska, DEW surveillance radar (70°30'N, 149° 53'W). Radar data were obtained on a nearly continuous 24-hour basis on 18 May and from 26 May to 17 June 1977. The radar methods used consisted ot time-lapse and still photography of the radar Plan Position Indicator (PPI) display. These methods were virtually identical to those used by Richardson *et al.* (1975) to study spring bird migration along part of the Canadian Beaufort Sea coast. That report describes the radar, filming procedures and methods of quantifying numbers and directions of movement of birds.

Visual Migration Watches During Spring-1977. Daily visual migration watches were conducted from 17 May to 15 June 1977 at Oliktok Point, and from 5 to 14 June at two sites on Pingok Island, both located 12 km NE of Oliktok (Fig. 1). At each site, one observer conducted watches on a regular schedule. Procedures during a migration watch are presented in Johnson *et al.* (1975), and methods of analysis are presented in Richardson *et al.* (1975).

At Oliktok Point, the migration watch was conducted from the top of a fuel storage tank from a level about 7 m above sea level (ASL). This location afforded good visibility on all azimuths except 205°-225° where buildings and radar apparatus 2000 m away partially obstructed visibility. The frozen lagoon surface was smooth. Binoculars (9x or 10x) and spotting telescopes (20-45 x Zoom) were used. On clear days flying birds could often be detected and classified at least to major taxonomic category (i.e., loon, waterfowl, gull, etc.) at distances as great as 7-8 km.

Two migration watch stations on Pingok Island were located at the extreme western end of the tundra-covered portion of the island. One post was situated on the southwest shore and the other about 6 m ASL atop a building located some 40 m south from the north shore (Fig. 1). The observer at the northern post recorded movements seaward of the barrier islands. Rough ice and pressure ridges obstructed visibility of low-flying birds beyond about 3 km seaward. The observer at the southern post recorded movements lagoonward of the island. The southern post was approximately 300 m south of the northern post, and although this post was not elevated, the lagoon surface was smooth and visibility was unobstructed to the mainland coast, approximately 7 km to the south.

Observers at all three posts maintained a daily schedule of three 2-hr watches: one in the morning, usually between 10:00 and 13:00 hrs Alaska Daylight Time (ADT); another during the afternoon, usually between 14:00 and 16:00 hours ADT; and a third in the evening, usually between 20:00 and 22:00 hrs ADT. At all migration watch posts, observations were recorded with a portable tape recorder; this enabled observers to watch continuously. Data were transcribed from magnetic tapes, coded on standard forms and keypunched.

Visual Migration Watches During Spring-1978. A twice-daily schedule of visual migration watches was established during the period 6 to 25 June 1978. The watches were conducted from a platform approximately 6 m ASL atop a building located approximately 1.5 km south of Milne Pt.--midway along the south shore of Simpson Lagoon. Procedures followed during visual watches in spring 1978 were identical to those followed during similar watches conducted in spring 1977.

During both years, for purposes of analysis, definite or probable migrants were separated from local residents on the basis of behavior. Birds in sustained flight and that maintained an eastward (30°-150°) or westward (210° to 330°) course were coded as migrants; those that were sitting, landing or taking off, or engaging in territorial behaviour were later included in an "other" category (with those that flew north or south).

Mid-Summer Molt Migration

Data concerning the mid-summer molt migration of male seaducks (oldsquaws, scoters, common and king eiders) were collected visually from 26 June to 31 July during both 1977 and 1978. Radar was not used.

During 1977, it was not possible to maintain a rigid daily schedule of migration watches. The amount of time devoted to systematic migration watches during 1977 depended on the factors listed below:

1. The prevailing weather conditions; if fog was present throughout the study area, no watches were conducted.
2. The demands of other duties associated with the ornithological program and sometimes judged to be of higher priority than migration watches.
3. The relative volume of bird migration noted during the course of duties (including migration watches) associated with the ornithological program.

During molt migration watches conducted during 1977, one observer used the elevated north post on Pingok Island (as described above).

He recorded all birds seen regardless of whether they flew over the islands, lagoon or sea. Watches were usually conducted between 09:00 and 11:00 ADT and between 21:00 and 23:00 ADT. When weather permitted and the volume of migration dictated, longer and more frequent watches were conducted, as indicated below.

Date	Number of Hours	Time (ADT)
June 26	4	09:00-11:00; 21:00-23:00
July 2	4	15:00-16:00; 17:00-18:00; 19:00-20:00; 21:00-22:00
3	6	09:00-10:00; 11:00-12:00; 13:00-14:00; 15:00-16:00; 18:00-19:00; 21:00-22:00
4	5	09:00-10:00; 11:00-12:00; 13:00-14:00; 15:00-16:00; 18:00-19:00
7	1	09:00-10:00
12	2	21:00-23:00
13	2	09:00-11:00
15	4	09:00-11:00; 21:00-23:00
20	2	21:00-23:00
21	1	09:00-10:00
July 22	2	21:00-23:00
23	4	09:00-11:00; 21:00-23:00
24	4	09:00-11:00; 21:00-23:00
25	2	09:00-11:00

During 1978, the systematic schedule of visual watches established during spring was maintained throughout the mid-summer period except during the peak of the molt migration. During this peak period (2 to 8 July), watches were conducted during fog free periods on alternate hours from 0800 to 2300 ADT.

During the mid-summer period in both 1977 and 1978, all flocks or aggregations of birds seen during other research activities were recorded and included in the analysis of molt migration. Observations during watches were recorded on tape; additional observations were recorded in notebooks and also coded for keypunching. Definite or probable migrants were separated from local residents on the basis of the same behavioral criteria as in spring.

Fall Migration

During 1977, data concerning "fall" migration were collected from 21 August to 22 September. Radar was not used. Watches were conducted by one observer from the elevated north post on Pingok Island using the same procedures as used during molt migration. Migration watches were usually conducted between 08:00 and 12:00 ADT and between 16:00 and 18:00 ADT.

During 1978, data concerning "fall" migration were collected intermittently from 1 August to 15 October. Radar was not used and systematic migration watches were not conducted. All flocks of birds and other apparent migrants observed during the course of other research activities were recorded in notebooks, were coded for keypunching, and were included in the analysis of fall migration.

Nesting Studies

Both Gavin (1976) and Divoky (1978) have presented estimates, based on primarily non-quantitative methods, of the numbers of waterbirds nesting on the Jones Islands. An accurate assessment of numbers of birds nesting on barrier island habitats can only be made by establishing and thoroughly searching plots or by systematically searching all available nesting habitats. Because of the large amount of tundra habitat available on Pingok Island (see "Study Area"), two large plots were established during 1977 on tundra portions of this island. The total area of all the other barrier islands was completely surveyed during 1977. One of these plots on Pingok Island was re-established during 1978 and a comparative plot on the mainland tundra was established. In general, nesting surveys on barrier islands during 1978 were less extensive than during 1977, and were designed to monitor specific barrier island habitats at specific locations.

Survey Methods

On 16-20 June 1977 two tundra plots, one covering 0.63 km^2 (Plot 1) and another covering 0.30 km^2 (Plot 2), were established on Pingok Island (Fig. 1). A compass and 100 m steel tape were used to measure and stake 100 m intervals within the plots. Between 20 June and 20 July 1977, these two island tundra plots were surveyed for nesting birds twice, and all tundra habitats on Peat, Bertoncini, Bodfish and Cottle Islands (total area 0.87 km^2) were surveyed for nesting birds once. During surveys, two or three observers flushed birds from their nests by dragging a 50 m length of rope perpendicular to the direction of their movement across the tundra. Most birds flushed in advance of the oncoming rope, although some did not flush until the rope passed over them.

On 24 to 27 June 1978, Plot 2 (0.30 km^2) on Pingok Island was re-established and an additional comparative plot covering 0.25 km^2 (Plot 3) was established on the mainland tundra near Milne Pt. (Fig. 1). Between 24 June and 12 July 1978, both of these plots were surveyed twice by three observers using a rope drag as described above. Plot 1 on Pingok Island and the tundra portions of the other barrier islands were not surveyed during 1978.

From 21 to 24 June 1977, the locations and numbers of all territorial males (Π♂♂) of all species of birds seen on Plots 1 and 2 on Pingok Island were recorded. Similar data concerning territorial males on Plots 2 and 3 during 1978 were not recorded.

During 1 to 7 July 1977, the 2.6 km^2 of barrier island habitat covered by gravel, sand and silt was surveyed by searching all the driftwood rows and piles of debris where, in the Beaufort Sea area, species such as common eiders, glaucous gulls and arctic terns may nest (Schamel 1974; Divoky 1978). During 1978, such surveys of gravel and sand islands were conducted during 1 to 3 July and were restricted to Spy Island (1.5 km^2) and adjacent Thetis Island (1.6 km^2). Thetis Island was not surveyed in 1977. Birds nesting on

Spy Island traditionally have suffered predation by Arctic foxes (J.W. Helmericks, pers. comm. 1977; Divoky 1978; Johnson 1978). In contrast, Arctic foxes have never been recorded on Thetis Island during the nesting season (J.W. Helmericks, pers. comm. 1977, 1978).

When an active nest (a nest with at least one egg or young) was discovered, its position was mapped and a stake was placed at a given distance and direction from the nest. The stake was labelled, colored flagging tape was attached and the following information was recorded:

1. The presence or absence and behavior of any adult birds near the nest.
2. The number of eggs and/or young present in or near the nest.
3. A description of the substrate, nest material and cover near the nest.
4. Any evidence of predation or recent activity of predators near the nest site.

Nests constructed during previous years, destroyed nests and partially completed nests (including nest scrapes) were also recorded, and their positions mapped.

Molting and Pre-Migratory Staging Studies

Most waterfowl undergo a summer molt during which they simultaneously lose all of their flight feathers. Male seaducks migrate along specific traditional routes to specific locations where they concentrate into large flocks and undergo this molt (Salomonsen 1968). Hall (1974) and Gavin (1976) have previously suggested that Simpson Lagoon may be an important summer molting area for oldsquaws, and Schweinsburg (1974) and Divoky (1978) have suggested that the barrier island-lagoon systems along the entire eastern portion of the Alaskan Beaufort Sea coast are important summer molting areas for seaducks--primarily oldsquaws.

After they leave their tundra rearing areas and before they migrate out of the Beaufort Sea area, immatures of certain species of shorebirds also concentrate into large feeding flocks along the coastline. Connors and Risebrough (1976, 1977, 1978) have indicated that coastal locations in the western portion of the Beaufort Sea are important concentration areas for immature phalaropes. This process of pre-migratory concentration is called "staging". Any species that was not molting and that was concentrated for a significant period of time in the Jones Islands-Simpson Lagoon study area and adjacent barrier island-lagoon system was considered to be staging.

Specific survey programs and methods were designed to efficiently and accurately quantify the abundance and distribution of molting and staging birds in the study area.

Aerial surveys provide a method for rapidly and systematically recording numbers and distributions of medium-sized and large birds, such as oldsquaws, gulls, terns and loons, in a wide area. The aerial method is applicable over land, water and ice.

Shoreline surveys from small boats were used to record numbers and distributions of small shoreline-associated birds such as phalaropes, sandpipers and plovers. Gulls and terns, which also may associate with shorelines, especially when feeding, were also recorded during boat surveys. Hence, species of large shoreline-associated birds such as gulls and terns were surveyed equally well from both aircraft and boats. Those large birds associated with open water areas away from shorelines were surveyed most comprehensively from aircraft.

Aerial Surveys During 1977 and 1978

Aerial surveys were conducted on seven occasions during 1977 (5 June to 22 September; Table 2) and on ten occasions during 1978 (23 June to 23 September; Table 3). Each survey consisted of one flight along each of five to 21 permanent transect strips, each located in a specific type of habitat (Table 4). During 1977, only transects located in the Jones Islands-Simpson Lagoon area (transects 1-5) were surveyed. In order to assess the validity of classifying the Jones Islands-Simpson Lagoon study area as a representative of the extensive barrier island-lagoon systems along the Alaskan Beaufort Sea coast, during 1978 16 additional transects were established at locations both east and west of Simpson Lagoon and were systematically surveyed. In 1978, each single aerial survey consisted of flights along 12 to 21 different transects.

During the survey of the barrier island transect (Transect 2) in 1977, the aircraft was positioned directly over the center of the islands where they were narrower than the 400 m-wide transect strip. Along those portions of the islands that were wider than 400 m, the aircraft was maneuvered to a position 100 m lagoonward (south) of the south shoreline of the island. When surveying the mainland coast the aircraft was positioned 100 m lagoonward (north) of the mainland shoreline (see Appendix 2).

During the surveys of barrier islands and mainland coasts in 1978, the aircraft was positioned 200 m lagoonward of the shorelines. The descriptions of all aerial survey transects are given in Table 4.

Aircraft flight procedures were standarized to the greatest extent possible. However, because it was necessary to use three different types of aircraft during 1977 and two different types during 1978, including both fixed- and rotary-wing aircraft, variations in flight speed, observer visibility and aircraft seating positions were unavoidable.

Table 2. Transect Survey Dates and Aircraft Types Used During Aerial Surveys Conducted in the Study Area During the Period 5 June to 22 September, 1977.

Transect Number	Survey Date and Aircraft Type*						
	5 June	15 June	5 July	28/29 July	15 August	30 August	22 Sept.
1	Bell 205	Bell 205	Bell 206	Bell 206	Not Surveyed	Bell 205	Bell 206
2†	Bell 205	Bell 205	Bell 206	Cessna 206	Cessna 206	Bell 205	Bell 206
3†	Bell 205	Bell 205	Bell 206	Bell 206	Not Surveyed	Bell 205	Bell 206
4†	Bell 205	Bell 205	Bell 206	Cessna 206	Cessna 206	Bell 205	Bell 206
5**	Bell 205	Bell 205	Bell 206	Cessna 206	Cessna 206	Bell 205	Bell 206

*One observer was seated in a front seat and one in a rear seat, on opposite sides of the aircraft. In fixed-wing (Cessna) aircraft, the front observer was seated on the right side; in rotary-winged (Bell) aircraft, the front observer was seated on the left.

†Survey altitude was 30 m and survey ground speed was approximately 160 km/hr (approximately 100 mph).

**Survey altitude was 15 m and survey ground speed was approximately 90 km/hr (approximately 55 mph).

Table 3. Transect Survey Dates and Aircraft Types Used During Aerial Surveys* Conducted in the Study Area During the Period 23 June to 23 September 1978.

Transect Number	Survey Date and Aircraft Type†									
	23 June	5 July	15 July	25 July	5-6 Aug.	15 Aug.	25 Aug.	5-6 Sept.	15 Sept.	23 Sept.
1	Cessna 206	Cessna 206	Bell 206	Cessna 206	Cessna 206	Cessna 206	Cessna 206	Cessna 206	Cessna 206	Cessna 206
2	Cessna 206	Cessna 206	Bell 206	Cessna 206	Cessna 206	Cessna 206	Cessna 206	Cessna 206	Cessna 206	Cessna 206
3	Cessna 206	Cessna 206	Bell 206	Cessna 206	Cessna 206	Cessna 206	Cessna 206	Cessna 206	Cessna 206	Cessna 206
4	Cessna 206	Cessna 206	Bell 206	Cessna 206	Cessna 206	Cessna 206	Cessna 206	Cessna 206	Cessna 206	Cessna 206
5	Cessna 206	Cessna 206	Bell 206	Cessna 206	Cessna 206	Cessna 206	Cessna 206	Cessna 206	Cessna 206	Cessna 206
6	Cessna 206	Cessna 206	Bell 206	Cessna 206	Cessna 206	Cessna 206	Cessna 206	Cessna 206	Cessna 206	Cessna 206
7	Cessna 206	Cessna 206	Bell 206	Cessna 206	Cessna 206	Cessna 206	-	Cessna 206	Cessna 206	Cessna 206
8	-	Cessna 206	-	Cessna 206	Cessna 206	-	-	Cessna 206	-	-
9	-	Cessna 206	-	Cessna 206	Cessna 206	-	-	Cessna 206	-	-
10	-	Cessna 206	-	Cessna 206	Cessna 206	-	-	Cessna 206	-	-
11	-	Cessna 206	-	Cessna 206	Cessna 206	-	-	Cessna 206	-	-
12	Cessna 206	Cessna 206	Bell 206	Cessna 206	Cessna 206	Cessna 206	Cessna 206	Cessna 206	Cessna 206	Cessna 206
13-1	-	Cessna 206	-	Cessna 206	Cessna 206	-	Cessna 206	Cessna 206	-	Cessna 206
13-2	-	Cessna 206	-	Cessna 206	Cessna 206	-	Cessna 206	Cessna 206	-	Cessna 206
14	-	Beaver	-	-	Cessna 206	-	Cessna 206	Cessna 206	-	Cessna 206
15	-	Beaver	-	-	Cessna 206	-	-	Cessna 206	-	-
16	-	-	-	-	Cessna 206	-	-	Cessna 206	-	-
17	-	-	-	-	Cessna 206	-	-	Cessna 206	-	-
18	-	Cessna 206	-	Cessna 206	Cessna 206	-	Cessna 206	Cessna 206	-	Cessna 206
19	-	Cessna 206	-	Cessna 206	Cessna 206	-	Cessna 206	Cessna 206	-	Cessna 206
20	Cessna 206	Cessna 206	Bell 206	Cessna 206	Cessna 206	Cessna 206	Cessna 206	Cessna 206	Cessna 206	Cessna 206
21	Cessna 206	Cessna 206	Bell 206	Cessna 206	Cessna 206	Cessna 206	Cessna 206	Cessna 206	Cessna 206	Cessna 206

*Survey altitude on all transects except Transect 5 was 30 m and survey ground speed was approximately 160 km/hr (100 mph). On Transect 5, the survey altitude was 15 m and survey ground speed was approximately 130 km/hr (80 mph).

†One observer was seated in a front seat and one in a rear seat, on opposite sides of the aircraft. In fixed-wing (Cessna) aircraft, the front observer was seated on the right side; in rotary-winged (Bell) aircraft, the front observer was seated on the left.

Table 4. Aerial Survey Transect Descriptions, Beaufort Sea, Alaska, 1977-1978*.

Transect Number	Transect Length (km)	Habitat Type	Location
1	35.4	Offshore Marine	1.6 km seaward of the Jones Islands, E to W.
2	37.0	Lagoon - south shoreline of Barrier Islands	From W end Spy Is., E to E end Cottle Is.
3	30.6	Mid-lagoon	From Beechey Pt., W to Oliktok Pt.
4	32.2	Lagoon - Mainland Shoreline	From Oliktok Pt., E to Beechey Pt.
5	33.8	Mainland tundra	4 km inland from Simpson Lagoon, E to W.
6	13.8	Mid-lagoon	Harrison Bay from 6 km S of Oliktok Pt., NW to Thetis Is.
7	16.1	Mid-lagoon	Harrison Bay, from Thetis Is., SE to Anachlik Is.
8	56.3	Unprotected Bay	Harrison Bay, from Thetis Is., W to Atigaru Pt.
9	30.3	Unprotected Bay	Harrison Bay, from Atigaru Pt., SE to E side of Colville R. delta.
10	35.1	River Delta	From E side of Colville R. delta to W side of mouth of Kupigruak channel.
11	12.1	Mid-lagoon	From W side of mouth of Kupigruak channel, NE to Thetis Is.
12	34.8	Lagoon - south shoreline of Barrier Islands and Protected Bay	From E end Cottle Is. to E end Stump Is., E across Prudhoe Bay to Heald Pt.
13.1	16.4	Protected Bay	From Heald Pt., NW across Stefansson Sound to Reindeer Is.
13.2	123.9	Lagoon - south shoreline of Barrier Islands	From W end Reindeer Is., ESE to Brownlow Pt.
14	87.7	Lagoon - south shoreline of Barrier Islands	From Brownlow Pt., ENE to W end Arey Is.
15	152.1	Lagoon - south shoreline of Barrier Islands	From W end Arey Is., ENE to E end Demarcation Bay or to US-Canada Border.
16	144.7	Mid-lagoon	From US-Canada Border or E end Demarcation Bay, WNW to W end Arey Is.
17	86.1	Mid-lagoon	From W end Arey Is., WNW to Brownlow Pt.
18	81.3	Mid-lagoon	From Brownlow Pt., W to Pt. Brower.
19	17.4	River Delta	From Pt. Brower, W to Heald Pt.
20	6.4	Mainland Shoreline	From Heald Pt., S to East Dock Prudhoe Bay.
21	37.0	Mid-lagoon	From East Dock Prudhoe Bay, W to Beechey Pt.

*Transects 1-5 lie within the Jones Islands-Simpson Lagoon intensive study area and these transects were surveyed both during 1977 and 1978. The remaining transects lie to the east and west of the intensive study area and were surveyed only during 1978 (see Fig. 2A-G).

Except for the 28-29 July 1977 survey, each survey during 1977 was conducted using a single aircraft on a single day (Table 5). The 28-29 July 1977 survey was conducted over a two-day period and two different types of aircraft were used. A float-equipped aircraft was unavailable on 15 August 1977, so transects over open water were not surveyed on that date. During 1978, a fixed-wing aircraft was used for all aerial surveys except the survey on 15 July when a helicopter was used. During 1978, only the extensive surveys conducted on 5 and 6 August and 5 and 6 September required more than one day for completion (Table 6). On all surveys, both observers recorded into portable tape recorders all birds seen both on-transect (≤200 m from aircraft) and off-transect (>200 m from aircraft). The information recorded was of four types: (1) systematic information about the transect, (2) systematic information about each bird sighting, (3) systematic information about the habitats below the aircraft at two-min intervals, and (4) general remarks. All information except general remarks was numerically coded when transcribed later onto data forms. All transects were divided into 2-min intervals using a timing device. The timer was reset to zero at the start of each transect and it produced a sound at 2-min intervals audible to both observers. The general habitat type found within each 2-min interval was recorded by both observers, and the interval-number in which each bird was seen was recorded.

When counts by both observers were combined, it was possible to calculate an estimate of the density of birds per square kilometer.

Shoreline Transects

Shoreline transects were designed primarily to measure the distribution and abundance of shorebirds, gulls and terns along the three types of beaches common in the study area. During the third week of July 1977 fifteen shoreline transects were established. Five transects were located along seaward shorelines of the barrier islands, five along lagoonward shorelines of the islands, and five along mainland shorelines (see Fig. 1). Each transect was 1.0 km long and 20 m wide (0.02 km^2). The start and end points of each transect were permanently marked by driving 2.5 m pipes approximately 0.5 m into the beach substrate approximately 10 m from the shoreline.

During 1977, each of these shoreline transects was surveyed on 1, 16 and 24 August, and on 1 and 14 September. During 1978, these 15 shoreline transects were surveyed at 5-day intervals from 31 July to 3 September. Another shoreline transect, established along a lagoonward beach on the west end of Pingok Island (Fig. 1), was 1.2 km long by approximately 20 m wide and was surveyed more frequently--18 times from 2 August to 18 September 1977 and 16 times from 2 August to 3 September 1978.

During each survey, all 15 permanent transects were surveyed within one 8-h period with the aid of 10 x 40 binonculars from a boat moving parallel to the transect. The boat was positioned approximately 50 m from the outer edge of the transect, and did not appear to disturb shorebirds along the shoreline. During most surveys, one observer operated the boat while a second systematically recorded into a portable tape recorder the following information about each transect and any birds sighted:

1. The date, transect number, observers, start and end time of the survey, weather and water conditions, and direction of travel.

2. The number of individuals of each bird species present on-transect (within 10 m of the shoreline) or off-transect (greater than 10 m from the shoreline).

3. The estimated distance of each bird or group of birds from the shoreline, and whether the birds were sighted on the beach or in the water.

4. The behavior of each bird or group of birds sighted on-transect or off-transect.

Feeding Studies

Studies of the feeding ecology of marine birds provide a key link in the interpretation of relationships among physical parameters, biological productivity, and distribution and abundance of marine birds in barrier island-lagoon systems. Specific questions regarding the age, sex, stage of molt, physical condition and identity of food organisms consumed by birds during the various stages of bird abundance and lagoon productivity can be answered only by collecting birds.

The primary purpose of the avian feeding ecology studies was to determine which food organisms comprised the important proportions of the diets of those species of birds most widely distributed and most abundant in the study area. During 1977 the key avian species were (1) oldsquaws, (2) red and northern phalaropes (generally treated as a single group), and (3) glaucous gulls. During 1978, only oldsquaws and the phalaropes were treated as key species. We chose a qualitative method (see Hynes 1950 and Griffiths *et al.* 1975) for assessing the relative importance of food taxa found in bird stomachs and in bird feeding habitats during 1977 and 1978 because this method combined the following advantages:

1. It is efficient and relatively accurate in estimating the relative importance of particular food taxa.
2. It is easily used under field conditions and requires no special apparatus for measurement of organisms.
3. It does not give the potentially misleading impression of accuracy given by some other methods that measure stomach contents more precisely but make no better allowance for sampling problems and differential digestion rates.

During both 1977 and 1978, comparisons were made of the diet of oldsquaws as determined by the qualitative Hynes point method and by more quantitative methods of measurement.

Collections of Birds and Habitat Samples

From 17 June to 19 September 1977, 210 specimens of four avian species (oldsquaw, red and northern phalaropes, and glaucous gull) were obtained in the Simpson Lagoon-Jones Islands area. During the last two weeks of June 1977, seven oldsquaws were accidentally caught in gill nets set as part of the aquatic biology investigations; the stomach contents of these birds were retained. The remaining 203 specimens were collected with shotguns during the 11 July to 19 September 1977 period.

Samples of potential food organisms, hereafter referred to as habitat samples, were collected from the precise habitats in which birds were feeding when they were shot. These habitat samples were collected immediately after we collected the birds.

Between 28 June and 23 September 1978, 168 additional specimens of three avian species (oldsquaws and red and northern phalaropes) were collected in the Simpson Lagoon-Jones Islands area (glaucous gulls were not collected during 1978). On 28 June 1978, one oldsquaw was accidentally caught in a gill net; the stomach contents of this bird were retained. The remaining 167 specimens were collected with shotguns during the 10 July to 23 September 1978 period.

Oldsquaw. During 1977, 38 collections of oldsquaws (mean=2.4 birds/collection) were made in Simpson Lagoon during the period 11 July to 14 September. The average depth where 88 of the 90 oldsquaws were collected was 1.5 m ± 0.54 m.* During 1978, 45 collections of oldsquaws (mean=2.4 birds/collection) were made in Simpson Lagoon during the period 10 July to 27 September. The average depth where 108 to the 109 oldsquaws were collected was 1.4 m ± 0.57 m. The general procedures followed for collecting oldsquaws and oldsquaw feeding habitat samples during 1977 were the following:

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*All such values in this report are means ± standard deviations.

1. A flock of oldsquaws was located and watched briefly to determine whether some birds appeared to be feeding (diving). An estimate was made of the size of the flock.

2. Observers then sped into the flock, dropped an anchored buoy as the boat slowed, and collected as many birds as possible.

3. Birds were retrieved and labelled. To mitigate post-mortem digestion of any food items, the gut (proventriculus and ventriculus) and esophogus of each dead bird was injected with absolute isopropyl alcohol. The esophagus of each bird was then plugged with a paper wad.

4. Habitat sampling was initiated after the collecting party returned to the buoy.
   a. For each set of birds collected, two quantitative samples were obtained, one from the surface-water and another from the mid-water portions of the lagoon. This was accomplished by towing both a surface-supported neuston net and a submerged (1 m deep) macroplankton net (see Griffiths and Craig [1978] for more details).
   b. For each set of birds collected, one quantitative sample from the lagoon epibenthos was collected. From a stationary boat in the area of the buoy, a macroplankton net was manually towed across the bottom of the lagoon for a distance of approximately 10 m and at a speeed of approximately 0.5-1.0 m/sec.
   c. Habitat samples were immediately washed from the sampling nets into double-labelled 227-ml (8 oz) bottled and preserved in 10% neutral formalin.

During 1978, the same general procedures as during 1977 were followed for collecting oldsquaws except that, prior to making collections, some flocks of birds were watched more carefully and over a longer period of time than during 1977 to determine whether they appeared to be feeding (diving).

Also during 1978, habitat sampling procedures were different from those followed in 1977. No samples were taken from either the surface water or midwater layers of the lagoon at locations where oldsquaws were collected, but a quantitative method of sampling invertebrates from the epibenthos using a drop net was adopted (see Griffiths and Dillinger [1979] for more details).

Phalaropes and glaucous gull. Visual observations made during shoreline and aerial surveys indicated that during 1977 and 1978 phalaropes and glaucous gulls fed almost exclusively in shallow areas (<1 m deep) along shorelines and in bays. Therefore phalaropes (during 1977 and 1978) and glaucous gulls (during 1977), and associated feeding habitat samples, were collected in these shallow areas.

Phalaropes are very tame birds and large flocks were easily approached on foot as they fed along shorelines. They were collected while they fed and the post-mortem handling procedures were the same as those described for oldsquaws.

The glaucous gulls were initially considered to be a key species; therefore glaucous gulls and their feeding habitats were systematically sampled during 1977--28 glaucous gulls were collected during 1977. However, the 1977 studies indicated that glaucous gulls, by criteria established during the course of the Barrier Island-Lagoon Program, were not key species and that further collections and associated habitat sampling during 1978 were not justified. Glaucous gulls fed either singly or in loose aggregations during 1977; they were not easily approached on foot. We watched from a boat offshore to ascertain whether they appeared to be feeding--if they were, we approached as quickly as possible from a speeding boat. The exact location where the bird was feeding was visually noted as we approached. If a bird was collected, the same procedures described for the post-mortem handling of oldsquaws were applied.

During 1977, a single quantitative habitat sample was collected with a surface-supported neuston net at each shallow location where phalaropes or glaucous gulls were collected. The net was attached by a line to a 3-m pole and was towed manually from shore for approximately 50 m at an approximate speed of 1 to 1.5 m/sec through waters about 1.5 m from shore and that varied in depth from 10 cm to 1 m. During 1978, identical equipment was used to sample phalarope feeding habitats; however, slightly different procedures were followed. Rather than take one sample along a 50 m stretch of shoreline, we took three samples, each of length 10 m, along three stretches of shoreline where the birds were feeding. Habitat samples were treated as described for oldsquaws.

Laboratory Techniques

Within 24 hours of collection all birds were dissected and food items found in the esophagi and guts (proventriculi and ventriculi) were preserved. The following procedures for measurement and dissection of birds were followed:

1. The flattened length of the right wing of each bird was measured (accurate within ± 5 mm) and the weights of each bird (accurate within 1 g) was determined using a Pesola spring balance.

2. The condition of the plumage and the stage of molt were recorded.

3. The amounts of subcutaneous and abdominal mesenteric fat were subjectively classified according to the OCS fat code: 1=none; 2=light; 3=moderate; 4=heavy; 5=excessively heavy. The thickness of subcutaneous fat present at a standard location on the right side of the breast of each bird was measured to the nearest 0.5 mm.

4. The sex organs of each bird were removed, measured and stored in Bouin's fixative solution. In females, the diameter of the largest ovum was measured to the nearest 0.5 mm. In males, the length and width of each testis were measured to the nearest 0.5 mm.

5. The esophagus and gut were removed as a single unit from each bird. During 1978, this unit was slit lengthwise, an arbitrary measure of fullness (Hynes 1950 and Griffiths *et al.* 1975; see below) was assigned to the total unit in the field, and a cursory and tentative description of the contents was recorded. These contents were then washed with

> 10% neutral formalin into a 227-ml double-labelled bottle. During 1977, no measure of fullness was assigned in the field, but all other procedures were the same. Because of the small size of food items consumed by phalaropes and because some food items were difficult to wash from their esophagi and guts, these organs were preserved also.

To assess and compare the importances of various food taxa in the diet of each of the key bird species during both 1977 and 1978, laboratory analysis of the stomach contents of each bird was necessary. During both years the preserved stomach contents and feeding habitat samples were sorted and an estimate was made of the relative volume of each major taxon (e.g., amphipod, mysid, copepod, isopod, etc.) by assigning points (Hynes 1950; Griffiths *et al.* 1975). Our laboratory method for assigning points differed in one major respect from the modified hynes point method used in the field during 1978 and described by Griffiths *et al.* (1975). In the laboratory we assessed the total volume of the stomach contents after instead of before they had been removed from the stomach and bottled.

Twenty points were assigned to the fullest stomach analyzed of a particular species of bird. The fullness of each additional stomach from that species was subsequently gauged against the fullest stomach and a corresponding number of points was assigned. After the sample had been sorted, and after each major taxon had been bottled, the total number of points thus assigned to each stomach was partitioned among the major invertebrate taxa present according to the relative volume of each. No distinction was made between whole organisms and fractions thereof. Pieces of unidentified organisms were classified as such.

As noted above, feeding habitat samples for oldsquaws during 1977 were collected using three different types of sampling techniques, each designed to sample a different stratum of lagoon water. Two of these techniques used during 1977 were quantitative and the third (the epibenthic tow) was qualitative. In 1978 only epibenthic sampling was conducted and a quantitative method was adopted. Habitat samples for gulls and phalaropes during 1977 and for phalaropes during 1978 were collected by yet another method. Therefore, volumes of materials sampled using the various methods were not directly comparable between years nor between species, and only relative volumes of different taxa were considered.

Each habitat sample was sorted and bottled by major taxon. Twenty points were assigned to the total volume of each sample and then appropriate proportions of the total 20 points were assigned to the various major taxa in the sample. During 1977, the two most important taxa (mysids and amphipods) present in the stomachs and habitat samples of key bird species were further sorted, identified to the species level and weighed (formalin wet weight). For a size comparison, (20 individuals each) of mysids and amphipods were randomly selected from all oldsquaw stomachs, and from all oldsquaw habitat samples taken during 1977; these individuals were measured to the nearest millimeter. During 1978, a much more detailed system of sorting and measurements was adapted; all taxa present in the stomachs and habitat samples of key bird species were sorted to major taxa, identified to the species level, counted and weighed. (Length of the telson plus first urosome was also measured.) Further details of the sorting, counting, weighing and measuring procedures followed during 1977 and 1978 are described in Griffiths and Craig (1978) and Griffiths and Dillinger (1979).

RESULTS

Migration Studies

Spring Migration

As previously noted, migration data from 1977 and 1978 have not yet been completely analyzed, so this section presents only a preliminary outline of the findings. Migration watches during 1977 began at Oliktok Point on 17 May, and on this date four glaucous gulls were recorded flying east. On 18 May 1977, the only prior date to 26 May when the radar was available, radar showed almost no eastward movement but a minor westward movement. Broad-front eastward movements of moderate density occurred on 26-28 May 1977; westward movement was much less pronounced. Both radar and visual data indicated that peak spring migration during 1977 began on 28-29 May, and it continued until about 12 June according to visual observations.

The 1978 ornithological program did not begin until 4 June. Casual observations on 4 and 5 June indicated an eastward movement of common eiders past Milne Point. The first migration watches during 1978, conducted on 6 June, indicated an eastward trend of movement by jaegers, gulls, shorebirds and eiders, primarily along the mainland shoreline and through the lagoon. Westward movement was less pronounced during this early period, but some shorebirds, eiders and geese (primarily white-fronted geese) were recorded flying both locally and westward. During 1978, the peak of the spring migration continued until the second and third weeks of June.

Loons, glaucous gulls, jaegers, pintails, oldsquaws, common and king eiders and black brant were the most commonly observed species during spring migration in both 1977 and 1978 (Table 5). During continuous time-lapse and intermittent polaroid photography of the radar PPI display in 1977; birds were detected regularly at distances up to 70 km, and occasionally up to 90 km, from Oliktok radar. Radar was not used during 1978.

Eastward movements visible on radar during 1977 were invariably broad-front in nature, with birds visible over the North Slope, coast, lagoon, barrier islands and Beaufort Sea. Some birds observed on radar changed course to follow mainland or island shorelines, and radar often showed more birds over the barrier island-lagoon system than inland or offshore; however, radar never showed an intense, narrow stream of birds along the mainland coast, lagoon, islands or elsewhere. This situation contrasts with that found along the coast of the northern Yukon in the spring of 1975 (Richardson *et al.* 1975), where radar often showed a narrow, concentrated stream along the coast, and where coastal visual observations recorded many more spring migrants than were seen in this study.

Visual observations revealed very little westward migration through the Simpson Lagoon area in the spring of 1977 or 1978. However, radar sometimes revealed major westward movements, invariably broad-front and often extending far inland and offshore. The species composition of these flights remains uncertain, but some shorebird species probably contributed.

Early in the season of 1977 and 1978 no open water was available and waterbirds seen during migration watches all flew past, primarily toward the east. Runoff from the Kuparuk and other smaller rivers began to flow onto the lagoon ice on 7 June 1977 and 8 June 1978. Thereafter during 1977 a few of the eastbound brant, eiders and oldsquaw occasionally landed on the runoff water near Oliktok Point, but apparently not near Pingok Island. During 1978, very few observations were recorded of oldsquaw and eiders landing in runoff water near Milne Point. Some of the few migrants that landed near Oliktok during 1977 took off again within a few seconds or minutes; others remained for longer periods, particularly in the latter part of the spring migration season (mid-June). Flight directions of eiders also became less consistently eastward as the spring of 1977 progressed. No evidence of a return westward movement of jaegers

Table 5. List of All Avian Species Recorded During Migration Watches Conducted During Spring 1977 at Oliktok Point and Pingok Island and During Spring 1978 at Milne Point, Alaska.

Species	First Observed*	Number Seen[†]		Periods of Peak Abundance		Predominant Migration Direction[§]		Peak Migration Rates (# Birds/Hour)**	
	(1977)	(1977)	(1978)	(1977)	(1978)	(1977)	(1978)	(1977)	(1978)
Yellow-billed Loon	3 Ju	27 (31)	- (-)	3-9 Ju	-	E	-	0.74	-
Arctic Loon	9 Ju	39 (48)	7 (80)	9-13 Ju	16-17 Ju	E	E	1.27	2.33
Red-throated Loon	9 Ju	25 (27)	2 (9)	9-13 Ju	21 Ju	E	E	0.84	0.44
Unidentified Loons	2 Ju	285 (300)	12 (67)	3-13 Ju	16 Ju	E	E	3.98	5.33
Pomarine Jaeger	28 Ma	238 (316)	11 (39)	28 Ma-6 Ju	6 Ju	E	E	8.93	25.38
Parasitic Jaeger	29 Ma	85 (96)	2 (15)	29 Ma	11 Ju	E	E	6.07	1.00
Long-tailed Jaeger	7 Ju	6 (10)	2 (2)	11-14 Ju	-	E	-	0.19	-
Unidentified Jaegers	28 Ma	109 (151)	4 (15)	29 Ma-10 Ju	22 Ju	E	W[††]	5.50	0.67
Black-legged Kittiwake	9 Ju	3 (3)	- (1)	9 Ju	-	E	-	0.22	-
Glaucous Gull	17 Ma	701 (1142)	13 (733)	11-14 Ju	11 Ju	E	E	4.16	6.50
Herring/Thayer Gull	2 Ju	5 (9)	1 (1)	-	-	-	-	-	-
Mew Gull	13 Ju	2 (2)	- (-)	-	-	-	-	-	-
Sabine's Gull	7 Ju	4 (5)	7 (41)	7-12 Ju	7 Ju	E	W[††]	0.12	1.50
Unidentified Gulls	1 Ju	14 (19)	- (-)	9-13 Ju	-	E	-	0.71	-
Arctic Tern	6 Ju	26 (51)	22 (46)	13-14 Ju	16-21 Ju	E	E	0.37	1.78
Mallard	5 Ju	5 (5)	- (-)	-	-	-	-	-	-
American Wigeon	10 Ju	4 (7)	- (-)	-	-	-	-	-	-
Green-winged Teal	10 Ju	3 (3)	- (-)	-	-	-	-	-	-
Shoveler	7 Ju	7 (7)	- (-)	-	-	-	-	-	-
Pintail	1 Ju	495 (1338)	24 (79)	5-12 Ju	9 Ju	L	E[††]	23.06	6.11
Oldsquaw	28 Ma	2778 (3461)	396 (2252)	2-10 Ju	19-20 Ju	E	E	175.33	69.75
Steller's Eider	4 Ju	2 (2)	- (-)	-	-	-	-	-	-
Spectacled Eider	6 Ju	20 (26)	2 (7)	9-10 Ju	9 Ju	E	E	0.65	0.51

Common Eider	30 Ma	889 (962)	12 (74)	4-10 Ju	24 Ju	E	W[++]	26.98	4.00
King Eider	30 Ma	553 (902)	15 (117)	1-10 Ju	21 Ju	E	W[++]	13.28	3.33
Unidentified Eiders	2 Ju	323 (404)	70 (252)	9-14 Ju	19-20 Ju	E	E	6.74	10.80
Unidentified Mergansers	-	-	2 (3)	-	20 Ju	-	-	-	0.40
Unidentified Diving Ducks	1 Ju	530 (708)	60 (80)	1-11 Ju	24 Ju	E	W	27.75	20.00
Unidentified Ducks	31 Ma	1032 (1535)	50 (89)	1-11 Ju	22 Ju	E	W	84.50	8.33
Lesser Snow Goose	10 Ju	22 (22)	50 (68)	10-11 Ju	27 Ju	E	W[++]	0.65	15.00
White-fronted Goose	17 Ma	74 (201)	7 (45)	-	18-19 Ju	L	W	-	1.00
Pacific Brant	31 Ma	626 (995)	329 (2707)	10-12 Ju	11 Ju	E	E	14.77	164.50
Canada Goose	-	- (-)	85 (85)	-	13 Ju	-	W	-	21.25
Unidentified Dark Geese	3 Ju	256 (284)	38 (126)	5-10 Ju	20 Ju	E	W	14.32	15.00
Unidentified Geese	3 Ju	322 (353)	- (-)	11-13 Ju	-	-	-	-	-
Whistling Swan	1 Ju	14 (16)	- (6)	-	-	-	-	-	-
Unidentified Waterfowl	5 Ju	166 (295)	- (-)	5-9 Ju	-	E	-	14.13	-
Red Phalarope	3 Ju	45 (79)	4 (17)	8-12 Ju	16-19 Ju	E	W	1.53	1.17
Northern Phalarope	12 Ju	2 (4)	2 (5)	-	18 Ju	-	-	-	-
Unidentified Phalarope	12 Ju	4 (4)	- (12)	-	-	-	-	-	-
Common Snipe	24 Ma	1 (1)	- (-)	-	-	-	-	-	-
Rufous-necked Sandpiper	2 Ju	1 (1)	- (-)	-	-	-	-	-	-
Pectoral Sandpiper	6 Ju	13 (20)	- (2)	7-12 Ju	-	L	L	-	-
Baird's Sandpiper	31 Ma	26 (934)	- (3)	3-7 Ju	-	L	L	-	-
Buff-breasted Sandpiper	-	- (-)	- (27)	-	-	-	L	-	-
Dunlin	29 Ma	18 (22)	1 (4)	3-12 Ju	-	L	-	-	-

Table 5. continued.

Species	First Observed*	Number Seen†		Periods of Peak Abundance		Predominant Migration Direction§		Peak Migration Rates (# Birds/Hour)**	
	(1977)	(1977)	(1978)	(1977)	(1978)	(1977)	(1978)	(1977)	(1978)
Sanderling	-	- (-)	- (7)	-	-	-	L	-	-
Semipalmated Sandpiper	1 Ju	8 (8)	- (3)	3 Ju	-	L	L	-	-
Black-bellied Plover	1 Ju	6 (7)	- (-)	1 Ju	-	L	-	-	-
American Golden Plover	29 Ma	12 (19)	4 (7)	29 Ma-3 Ju	19 Ju	L	E	-	1.00
Killdeer	12 Ju	1 (1)	- (-)	12 Ju	-	-	-	-	-
Unidentified Plovers	2 Ju	1 (2)	- (-)	-	-	-	-	-	-
Ruddy Turnstone	24 Ma	32 (48)	- (6)	29 Ma-9 Ju	-	L	L	-	-
Unidentified Shorebirds	29 Ma	84 (136)	- (19)	29 Ma-11 Ju	-	E	L	2.60	-
Willow Ptarmigan	18 Ma	1 (1)	- (-)	18 Ma	-	L	-	-	-
Rock Ptarmigan	28 Ma	7 (7)	- (-)	6 Ju	-	L	-	-	-
Rough-legged Hawk	6 Ju	1 (2)	- (-)	-	-	-	-	-	-
Short-eared Owl	31 Ma	2 (4)	- (-)	-	-	-	-	-	-
Horned Lark	6 Ju	2 (2)	- (-)	-	-	-	-	-	-
Unidentified Swallows	1 Ju	3 (3)	- (-)	-	-	-	-	-	-
Black-billed Magpie	27 Ma	3 (3)	- (-)	27-28 Ma	-	L	-	-	-
Common Raven	25 Ma	9 (9)	- (-)	31 Ma-3 Ju	-	L	-	-	-
Snow Bunting	17 Ma	102 (102)	- (-)	27 Ma-8 Ju	-	L	-	-	-
Lapland Longspur	27 Ma	83 (100)	- (-)	28 Ma-7 Ju	-	L	-	-	-
Savannah Sparrow	2 Ju	2 (2)	- (-)	2-3 Ju	-	L	-	-	-
White-crowned Sparrow	24 Ma	2 (2)	- (-)	24 Ma-3 Ju	-	L	-	-	-
Dark-eyed Junco	29 Ma	1 (1)	- (-)	29 Ma	-	L	-	-	-
Unidentified Redpolls	31 Ma	6 (15)	- (-)	13 Ju	-	L	-	-	-

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[*] Dates of first observation during 1977 include incidental records as well as records during migration watches. During 1978, migration watches were not begun until 4 June; hence many dates of first arrival were not recorded.

[†] Numbers to left of parentheses are total birds seen migrating during the period of peak abundance. Numbers in parentheses are total birds seen (migrants and others) during all spring migration watches and during casual observations.

[§] E = East, W = West, L = Local.

[**] Peak migration rate is number of migrants seen per hour during the date of peak movement.

[††] Unexpected direction, perhaps attributable to small sample size and/or late date of initiation of study in 1978.

was evident by the time the 1977 spring migration watches ended on 15 June. On 22 June 1978, however, a few unidentified jaegers were noted migrating westward, similar to results in the Yukon in June 1975 when a large-scale westward migration of jaegers was documented (Richardson *et al.* 1975).

Visible eastward migration during 1977 was noticeably less pronounced by 13-15 June than it had been earlier. However, radar showed that major broad-front eastward and westward movements continued--largely invisible during migration watches--until the last day of radar observations (17 June 1977). During 1978, the peak of eastward migration by many water-birds continued until the 16-24 June period (Table 5).

Continuation of migration past the dates of peak visible movement was recorded in the Yukon in 1975. The composition of these late spring flights is largely unknown, but the paucity of visual sightings of migrants late in the spring indicates that most of the birds involved must fly at high altitudes. There was no indication that late spring flights were more concentrated over the barrier island-lagoon system than over the adjacent North Slope or Beaufort Sea.

Mid-Summer Molt Migration

The westward molt migration of male oldsquaws was first noted during both 1977 and 1978 on approximately 26 June and it continued to approximately 24 July during 1977 and until 28 July during 1978. Peak numbers were seen moving west from 2 to 4 July 1977 and from 3 to 7 July 1978 (Table 6). During 1977, migration watch stations were located on Pingok Island; consequently movements were detectable along the lagoon shoreleads and over the fractured lagoon ice, as well as over the frozen Beaufort Sea seaward of the barrier islands. The migration watch station during 1978 was located on the mainland

Table 6. Numbers of Oldsquaws, Eiders, Scoters and Unidentified Diving Ducks Sighted Flying in Various Directions Through Simpson Lagoon During the Mid-summer Molt Migration in 1977 and 1978. Includes casual observations as well as sightings during systematic migration watches.

	1977								1978							
	June	July						Total	June	July						Total
	26-30	1-5	6-10	11-15	16-20	21-25	26-31		26-30	1-5	6-10	11-15	16-20	21-25	26-31	
Oldsquaws																
Eastbound	3	61	20	2	0	6	0	92	97	209	363	5	0	11	0	685
Westbound	240	1373	4	571	135	451	0	2774	1064	3122	3127	447	11	1133	168	9072
Other*	140	264	126	1722†	131	361	0	2744	2221	2472†	32505†	67	6709	628	66	44668
Eiders																
Eastbound																
Common Eider	0	0	0	0	0	6	0	6	23	8	4	0	0	0	0	35
King Eider	0	2	0	0	0	6	0	8	9	9	3	0	0	0	0	21
Unidentified Eiders	0	0	0	0	0	0	0	0	0	1	4	0	0	0	0	5
Westbound																
Common Eider	0	16	12	12	618	1002	250	1910	6	152	164	3	40	54	386	805
King Eider	0	51	0	86	115	1679	0	1931	14	33	18	0	0	0	0	65
Unidentified Eiders	1	53	0	5	7	166	0	232	3	226	124	37	15	26	42	437
Other*																
Common Eider	4	1	0	5	0	20	0	30	0	38	30	0	0	0	0	68
King Eider	0	2	0	0	0	2	0	4	37	52	30	4	0	5	0	128
Unidentified Eiders	0	7	2	12	41	61	0	123	4	8	19	2	0	41	71	145
Scoters																
Eastbound																
Surf Scoter	0	0	0	0	0	0	0	0	0	3	19	0	0	0	0	22
White-winged Scoter	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Unidentified Scoters	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	1
Westbound																
Surf Scoter	0	0	0	0	0	0	0	0	0	384	110	251	0	161	0	906
White-winged Scoter	0	0	0	0	0	0	0	0	0	3	1	15	0	0	0	19
Unidentified Scoters	0	0	0	0	0	0	0	0	0	121	33	0	0	0	0	154
Other*																
Surf Scoter	0	0	0	0	0	0	0	0	0	13	41	1	0	0	0	55
White-winged Scoter	0	0	0	0	0	0	0	0	3	0	0	0	0	0	0	3
Unidentified Scoters	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Unidentified Diving Ducks																
Eastbound	0	0	0	0	0	0	0	0	0	142	27	0	0	0	0	169
Westbound	0	0	0	0	0	600	0	600	8	637	164	0	43	55	20	927
Other*	0	0	0	12	45	20	0	77	1	64	43	6	2	4	49	169

*'Other' includes birds flying north or south and birds present locally.

† The ice on the surface of Simpson Lagoon began to break up on 9 July 1977 and on 5 July 1978 and had departed the study area by 11 July 1977 and by 6 July 1978. For a short period after those dates, the number of locally flying oldsquaws in the study area increased dramatically.

shoreline at Milne Point and many movements by migrating birds seaward of the barrier islands were undoubtedly undetected.

During 1978, a westward molt migration by scoters, primarily male surf scoters and to a lesser extent male white-winged scoters, coincided with that of oldsquaws. The first westbound scoters were recorded on 1 July and the peak of westward movement by scoters occurred during the 5 through 12 July period. A second peak of movement by scoters occurred on 24 and 25 July 1978. Observations during migration watches and other activities in 1977 and 1978 indicated that during the molt migration, oldsquaws and a few scoters made moderate use of water-filled cracks in the lagoon ice and of the shoreleads around the perimeters of the barrier islands and along the mainland shoreline. A detailed quantitative analysis of habitat use by migrants has not yet been undertaken.

The westward molt migration of male common and king eiders was first noted on 1 July 1977 and 24 June 1978 and continued until approximately 31 July 1977 and 12 August 1978. Most westward movement by eiders occurred after the lagoon ice had broken up and had been flushed westward, out of the study area (Simpson Lagoon began breaking up on 9 July 1977 and 5 July 1978 and was virtually ice-free within 1 or 2 days). Peak numbers of eiders were seen moving west from 21 to 25 July 1977 and from 10 to 30 July 1978. Eiders made only light use of lagoon and nearshore marine habitats during molt migration.

Results of molt migration watches and casual observations indicate that fewer than half as many eiders were recorded in 1978 as in 1977 (1745 eiders in 1978 compared with 4244 eiders in 1977). All molt migration watches and most casual observations during 1977 were conducted at locations near the seaward shoreline of Pingok Island, or along the barrier islands at locations where birds migrating through barrier island offshore and lagoon habitats could be recorded. During 1978, in contrast, all molt migration watches were conducted and most casual observations were made near the mainland shoreline at Milne Point where birds migrating through barrier island and offshore habitats were less detectable than at the Pingok Island station. The smaller number of eiders recorded during 1978 may be a reflection of poorer detectability rather than fewer birds migrating. Table 6 shows the chronology and magnitude of molt migration of seaducks through the study area.

Fall Migration

Fall migration by waterbirds out of the coastal Beaufort Sea area during 1977 first became evident during mid-August when large noisy flocks of adult and juvenile arctic terns were observed moving westward at high altitudes along the Jones Islands (Table 7). The fall migration of arctic terns had terminated by 30 August 1977. Possibly because the field camp was situated on the mainland and because systematic migration watches were not conducted during fall 1978; no such movement of arctic terns was noted during fall 1978.

The majority of flocks of premigratory staging phalaropes that were abundant in Simpson Lagoon and along the Jones Islands during mid-August of 1977 and 1978 had departed by early September; however, during 1977 some flocks were observed in the study area as late as 14 September. Although no phalaropes were recorded in the study area after 3 September 1978, a flock of approximately 400 was recorded in the Sagavanirktok River delta on 23 September 1978, and two small flocks of four and eight phalaropes were seen in an area of open water along the east side of the ARCO Causway (Prudhoe Bay) on 14 and 15 October 1978, respectively.

A peak westward movement of black brant through the study area occurred during 22 August to 6 September in 1977 and 17 to 31 August in 1978 (Table 7). During both years this migration occurred primarily along the mainland shoreline and appeared to be related to the occurrence of favorable tail winds (from the E or NE). During both years some brant stopped in the study area during periods of unfavorable head winds. During the aerial surveys conducted on 30 August 1977 and on 15 and 25 August 1978, all brant observed were flying westward.

A small westward movement by loons also occurred during the last days of August and during early September of 1977. A similar westward movement by loons through the study area was noted on 9 September 1978.

During 1977 and 1978, the numbers of both glaucous gulls and oldsquaws present in the study area increased during September. Both of these species reached maximum abundance in the study area during the fourth week in September, when the field observations were terminated because the lagoon was beginning to freeze over. Thus, no direct information about fall migrations by these two species is presented. It is noteworthy, however, that approximately 250 oldsquaw were present in an area of open water east of the ARCO causeway in Prudhoe Bay on 15 October 1978. Table 7 summarizes the important species and events during fall migration of waterbirds in the Simpson Lagoon area during 1977 and 1978.

Nesting Studies

The numbers, densities and fates of nests of the various bird species that were found nesting in the study area during 1977 and 1978 are presented in Tables 8, 9, 10 and 11. Fifty active nests were found on the barrier islands during 1977, representing a total density of 11.4 nests/km^2. Of these 50 nests, 38 (21.1 nests/km^2) were found on the Pingok Island tundra plots and on the tundra-covered portions of the other barrier islands; many of these nests (18 of 38, or 10.0 nests/km^2) were of lapland longspurs. The remaining 12 nests (9.24 nests/km^2) were found on the portions of the barrier islands, spits and bars that were comprised of gravel and sand.

Table 7. List of Avian Species Recorded During Fall Migration, 1977 and 1978, at Simpson Lagoon, Alaska.

Species	Number Seen*		Periods of Peak Abundance		Predominant Migration Direction		Peak Migration Rate (# birds per day)	
	(1977)	(1978)	(1977)	(1978)	(1977)	(1978)	(1977)	(1978)
Yellow-billed Loon	2 (5)	0 (4)	1 Se	29 Au	W	-	2	-
Arctic Loon	0 (25)	0 (1)	24 Au-14 Se	5 Se	L	-	-	-
Red-throated Loon	9 (17)	0 (2)	30 Au-1 Se	5 Se	W	-	7	-
Unidentified Loons	88 (332)	39 (65)	25 Au-6 Se	9 Se	W	W	20	39
Pomarine Jaeger	1 (5)	0 (0)	1 Se	-	W	-	1	-
Parasitic Jaeger	0 (3)	0 (0)	22 Au-1 Se	-	L	-	-	-
Long-tailed Jaeger	0 (13)	0 (0)	24-31 Au	-	L	-	-	-
Unidentified Jaegers	1 (5)	0 (0)	30 Au	-	W	-	1	-
Black-legged Kittiwake	0 (1)	0 (0)	19 Se	-	-	-	-	-
Glaucous Gull	275 (1044)	0 (12)	28 Au-15 Se	-	W	L	200	-
Sabine's Gull	0 (2)	0 (3)	22 Au	14 Au	-	-	-	-
Arctic Tern	100 (380)	20 (85)	15-28 Au	12 Au	W	W	32	20
Pintail	11 (69)	6 (17)	24 Au	5 Se	E	E	11	6
Greater Scaup	0 (0)	8 (8)	-	21 Au	-	E	-	8
Unidentified Scaup	0 (2)	0 (0)	18 Se	-	-	-	-	-
Oldsquaw	1730 (114266)	0 (21032)	27 Au-21 Se	14-29 Au	W	L	1000	-
Common Eider	57 (57)	135 (185)	24-26 Au	12 Au	W	W	47	135
King Eider	0 (0)	0 (5)	-	-	-	-	-	-
Unidentified Eiders	600 (600)	180 (202)	23-28 Au	5-13 Au	W	W	225	90
Unidentified Mergansers	300 (300)	0 (0)	23 Se	-	W	-	300	-
Unidentified Diving Ducks	35 (110)	20 (24)	22 Au-6 Se	13 Au	W	W	20	20
Unidentified Ducks	373 (409)	700 (2184)	27-29 Au	13 Au	W	W	333	700
White-fronted Goose	280 (288)	0 (12)	19-24 Au	-	W	L	270	-
Pacific Brant	4638 (4686)	10885 (11148)	22 Au-6 Se	17-31 Au	W	W	2261	2605

Unidentified geese	852 (908)	656 (696)	24-29 Au	24 Au	W	W	800	650
Red Phalarope	0 (27)	0 (108)	22-28 Au	12 Au	L	L	-	-
Northern Phalarope	0 (0)	0 (160)	-	12 Au	-	L	-	-
Unidentified Phalaropes	28 (1143)	0 (1307)	25 Au	23 Au	W	L	28	-
Loon-billed Dowitcher	13 (78)	0 (47)	19 Au	25 Au	W	L	13	-
Unidentified Dowitchers	0 (12)	0 (9)	31 Au	29 Au	L	L	-	-
Pectoral Sandpiper	0 (6)	0 (6)	24 Au-2 Se	18 Au	L	L	-	-
Dunlin	3 (310)	0 (39)	28 Au	17 Au	W	L	3	-
Sanderling	0 (8)	0 (0)	30 Au-2 Se	-	L	-	-	-
Semipalmated Sandpiper	0 (18)	0 (0)	19 Au	-	-	-	-	-
Whimbrel	0 (1)	0 (0)	17 Au	-	-	-	-	-
Black-bellied Plover	6 (181)	0 (0)	28-30 Au	-	W	-	4	-
American Golden Plover	0 (27)	0 (0)	22-27 Au	-	L	-	-	-
Unidentified Plovers	7 (11)	0 (0)	22 Au	-	W	-	7	-
Ruddy Turnstone	0 (30)	0 (0)	22-31 Au	-	L	-	-	-
Unidentified Shorebirds	29 (581)	0 (0)	21-28 Au	-	W	-	6	-
Thick-billed Murre	0 (0)	0 (1)	-	17 Au	-	L	-	-
Peregrine Falcon	0 (1)	0 (0)	22 Au	-	-	-	-	-
Varied Thrush	0 (1)	0 (0)	7 Se	-	-	-	-	-
Yellow Warbler	0 (1)	0 (0)	5 Se	-	-	-	-	-
Snow Bunting	0 (64)	0 (0)	21 Au-2 Se	-	L	-	-	-
Lapland Longspur	0 (2)	8 (16)	22-24 Au	4 Se	L	W	-	8

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* Numbers inside parentheses represent the total number of birds seen during migration watches and during incidental observations. Numbers to the left of those in parentheses represent the number of birds seen migrating during the period of peak abundance.

Table 8. Active Bird Nests Found During 1977 on the Jones Islands and on Adjacent Spits and Bars in Simpson Lagoon, Alaska.

	Type of Nesting Habitat				Fate of Nest				
	Tundra (3.9 km^2)		Gravel/Sand (2.6 km^2)		Successful*				
Species	Nests (#)	Density (nests/km^2)	Nests (#)	Density (nests/km^2)	Nests (#)	Density (nests/km^2)	Predated	Deserted	Other/ Unknown
Lapland Longspur	18	10.00†	0	0.00**	7	3.89	8	0	3
Willow Ptarmigan	1	0.56	0	0.00	0	0.00	0	0	1
Snow Bunting	4	2.22	2	0.77	3	1.32	0	0	3
Oldsquaw	0	0.00	2	0.77	0	0.00	1	1	0
Dunlin	3	1.67	0	0.00	0	0.00	0	0	3
Ruddy Turnstone	1	0.56	0	0.00	0	0.00	0	0	1
Baird's Sandpiper	8	4.44	0	0.00	1	0.56	3	0	4
American Golden Plover	1	0.56	0	0.00	1	0.56	0	0	0
Parasitic Jaeger	1	0.56	0	0.00	1	0.56	0	0	0
Common Eider	0	0.00	2	0.77	0	0.00	1	1	0
King Eider	1	0.56	0	0.00	0	0.00	1	0	0
Arctic Tern	0	0.00	3	1.15	0	0.00	2	0	1
Glaucous Gull	0	0.00	3	1.15	2	0.77	0	0	1
Total	38	21.13	12	4.61	15	7.66	16	2	17

* A nest was judged to be successful if evidence (many times only circumstantial evidence) suggested that some young from the nest had fledged.

† Density calculations are based on the 1.8 km^2 of tundra area surveyed during nest searches.

**Density calculations are based on the 2.6 km^2 of gravel/sand area surveyed during nest searches.

Table 9. A Comparison of Bird Densities on Two Tundra Plots on Pingok Island and on the Total Area of Tundra Surveyed During Nest Searches on the Jones Islands, 1977*.

Species	Pingok Plot 1 (0.625 km² tundra)				Pingok Plot 2 (0.300 km² tundra)				Total Tundra Surveyed During Nest Searches (1.80 km²)	
	Nest Searches		Counts of Π ♂♂		Nest Searches		Counts of Π ♂♂			
	# Nests	Density	#Π ♂♂	Density	# Nests	Density	#Π ♂♂	Density	# Nests	Density
Lapland Longspur	6	9.60	14	22.40	8	26.70	6	20.00	18	10.00
Willow Ptarmigan	-	-	-	-	-	-	-	-	1	0.56
Snow Bunting	-	-	-	-	-	-	-	-	4	2.22
Dunlin	-	-	-	-	3	10.00	-	-	3	1.67
Ruddy Turnstone	1	1.60	-	-	-	-	-	-	1	0.56
Baird's Sandpiper	2	3.20	1	1.60	-	-	-	-	8	4.44
American Golden Plover	1	1.60	-	-		-	-	-	1	0.56
Parasitic Jaeger	1	1.60	-	-	-	-	-	-	1	0.56
King Eider	-	-	-	-	-	-	-	-	1	0.56
Total	11	17.60	15	24.00	11	36.70	6	20.00	38	21.13

*Counts of territorial males (Π ♂♂) were conducted only on Plots 1 and 2 on Pingok Island. All densities are per km².

Table 10. A Comparison of Bird Nest Densities on a Mainland Tundra Plot and a Barrier Island Tundra Plot in the Simpson Lagoon-Jones Islands Area of Alaska (1977-1978).

	Pingok Plot 2 (0.300 km^2)						Milne Pt. Plot (0.250 km^2)		
	1977			1978			1978		
Species	#Nests	Density*	Fate[§]	#Nests	Density	Fate[§]	#Nests	Density	Fate[§]
Pintail	-	-		-	-		1	4.00	+
King Eider	-	-		-	-		1	4.00	+
Spectacled Eider	-	-		-	-		1	4.00	+
Baird's Sandpiper	-	-		-	-		2	8.00	+
Dunlin	3	10.00	-	2	6.67	+	1	4.00	+
Semipalmated Sandpiper	-	-		2	6.67	+	1	4.00	+
Buff-breasted Sandpiper	-	-		-	-		1	4.00	+
Pectoral Sandpiper	-	-		-	-		1	4.00	+
American Golden Plover	-	-		-	-		1	4.00	+
Lapland Longspur	8	26.67	5+	2	6.67	+	5	20.00	+
TOTAL	11	36.67		6	20.01		15[†]	60.00	

*All densities are per km^2

[†] Within a linear distance of approximately 2.50 km E and 0.25 km S, W and N of the Milne Pt. tundra plot, an additional 18 nests were recorded. These included nests of the arctic (1) and red-throated (1) loon, white-fronted goose (1), king eider (2), spectacled eider (2), dunlin (1), oldsquaw (2), Sabine's gull (4), arctic tern (3) and snow bunting (1). No additional nests were either observed or suspected in areas similarly adjacent to the comparable tundra plot on Pingok Island. All densities are per km^2.

[§] During 1978, no evidence was found of predation or desertion of nests on mainland or barrier island tundra plots; apparently all of these nests were successful. During 1977 all three dunlin nests were predated and three of the eight longspur nests were predated.

Table 11. A Comparison of the Numbers of Nests Found on Two Gravel-Covered Barrier Islands in the Jones Islands-Simpson Lagoon Area of Alaska, 1977-1978.

Island	Species									
	Common Eider		Arctic Tern		Glaucous Gull		Brant		Total	
	1977	1978	1977	1978	1977	1978	1977	1978	1977	1978
Spy Island*										
# Active Nests	0	4	2	5	0	4	0	0	2	13
# Nest Scrapes or Inactive Nests	72	84	41	29	0	2	0	0	113	115
# Destroyed Nests	15	1†	-	-	8	0	0	0	23	1
Thetis Island*										
# Active Nests	-	34	-	2	-	5	-	9	-	50
# Nest Scrapes or Inactive Nests	-	198	-	8	-	4	-	1	-	211
# Destroyed Nests	-	0	-	-	-	0	-	0	-	0

* Arctic foxes have been present on Spy Island for 2 of the past three years; none was present during 1978. Arctic foxes have never been reported on Thetis Island in summer. Thetis Island was not intensively surveyed during 1977.

† A snowy owl killed a female common eider as she incubated a clutch of eggs on Spy Island. We recorded no other evidence of nest predation during 1978.

During 1978, the complete study area was not censused for nesting birds. Only Plot 2 on Pingok Island was monitored as representative barrier island tundra habitat. On this plot six nests (20 nests/km^2) representing three species were found during 1978 compared with 11 nests (37 nests/km^2) representing two species during 1977. The average density of birds on this plot for the two-year period of study was 28 nests/km^2, which is approximately half the density of birds (60 nests/km^2) found nesting on the comparative mainland tundra plot (Plot 3) established at Milne Point during 1978 (Table 10). Furthermore, the diversity of bird species on the mainland tundra plot (10 species on the plot and an additional seven species nearby) was over three times greater than that on the Pingok Island tundra plot (three species during 1978 and two species during 1977; no additional species nested near the barrier island tundra plot during either year).

Based on the total number of nests found in the tundra-covered portions of the barrier islands in the study area, the overall density of all species of birds nesting in this type of habitat was 21.1 nests/km^2 during 1977 and 20.0 nests/km^2 during 1978; an overall value of 20.6 nests/km^2 for this habitat was calculated for the two-year period of the study. Similarly, the numbers of territorial male (π♂♂) birds recorded on tundra plots 1 and 2 on Pingok Island during 1977 were 24.0/km^2 and 20.0/km^2, respectively. No counts of territorial males were made during 1978 on either the barrier island or the mainland tundra plot.

Table 9 compares the species composition, numbers of nests and numbers of territorial males observed on the two census plots on Pingok Island during 1977; the total numbers of nests found in all tundra habitats throughout the study area are also shown.

No nests were found along the section of the mainland shoreline between Oliktok Point and Beechey Point during 1977; however, two active nests (one common eider nest and one glaucous gull nest) were found on the Beechey Point gravel bar, and at least two active glaucous gull nests were present on the Oliktok Point gravel bar. These bars are separated from the mainland by water and are comprised of sand and gravel substrates similar to those found on the barrier islands. This mainland shoreline was not surveyed for nesting birds during 1978.

Most nests were checked twice during the early summers of 1977 and 1978 in order to assess their fates (Tables 8 and 10). However, probable fates of some nests are identified only by using circumstantial evidence of fledging of young, desertion of eggs or young by adults, or predation on eggs or young by jaegers, gulls or arctic foxes. Approximately eight arctic foxes (1.2 foxes/km^2) were present on the Jones Islands after the ice retreated from the coasts of the islands in mid-July during 1977. Their distribution in 1977 is shown below:

Island	Number of Foxes
Spy	2
Leavitt	1
Pingok	2
Bertoncini	1
Bodfish	1
Cottle	1

Fox predation accounted for a high proportion of nest failures on the Jones Islands, and especially on Spy Island, during 1977. Foxes were observed searching for bird nests on the tundra on Pingok, Bertoncini and Bodfish Islands during 1977. Fox tracks and scats were abundant around active and inactive nests in all suitable nesting habitats along beaches and on the gravel portions of Spy, Leavitt and Cottle islands during 1977. Foxes probably preyed more heavily on birds during 1977 than during 1975 and 1976 because of the marked decline in the lemming population along the central Beaufort Sea coast during the winter of 1976 and the spring of 1977 (L. Eberhardt, pers. comm. 1977).

Arctic foxes were recorded on only four occasions during the June through September 1978 period; all of these sightings were on the mainland tundra near the field camp at Milne Point (Fig. 1). Lemming numbers remained low during the summer of 1978, and no foxes or fresh fox tracks were recorded on any of the barrier islands in the study area during 1978.

During both 1977 and 1978 Spy Island was included within the intensive study area. Two arctic foxes were present there throughout the summer of 1977 and as a consequence only two active nests (both of arctic terns) were found on this island during that year--both of these nests were predated by foxes (Table 11).

Thetis Island, which lies off the mouth of the Colville River and west of Spy Island (Fig. 1), historically has been without arctic foxes in summer. Although this island was not intensively surveyed during 1977, extensive nesting by at least four species of marine-associated birds was recorded there (J.W. Helmericks, pers. comm. 1977 and 1978). During 1978, when no arctic foxes were recorded on any of the gravel-sand barrier islands in the study area, the number of nests on Spy and Thetis islands were compared (Table 11). Bird production on Spy Island increased from two active nests (1.3 nests/km^2) of one species (arctic tern) during 1977, to 13 active nests (8.7 nests/km^2) of three species (arctic tern, glaucous gull, and common eider) during 1978. Many additional scrapes, inactive nests or destroyed nests were present in each year (Table 11). On Thetis Island, bird production remained high; in 1978, 54 nests (34 nests/km^2) and 207 scrapes of four species were recorded there.

In summary, barrier island tundra generally supports fewer species and much lower densities of nesting birds (approximately 20 nests/km^2 of two species during 1978) than does mainland tundra

(60 nests/km^2 of 10 species during 1978). Gravel/sand barrier islands similarly support few species of nesting birds; however, those species that do nest in this habitat seldom nest in other habitats (e.g., common eider and brant). Although arctic foxes prey heavily on eggs of all birds nesting on barrier islands, species nesting on the gravel/sand islands, possibly because they are more conspicuous (generally large size and less nesting cover) appear most susceptible to fox predation.

Nesting potential on the gravel/sand barrier islands is high, but may not be realized during years when arctic foxes become stranded on these islands and prey heavily on birds eggs. During years when arctic foxes are absent from the barrier islands, bird production on the gravel/sand islands increased markedly.

Molting: Oldsquaw

Pre-molt Period

Low densities of oldsquaws were present in all Simpson Lagoon habitats on 5 and 20 June 1977 and 23 June 1978 (Table 12). On these dates the highest density of oldsquaws recorded on any transect in the intensive study area was only 3.2 birds/km^2, and this transect was over tundra habitats south of Simpson Lagoon on 20 June 1977 (Transect 5; see Table 12).

The 5 July 1977 and 5 July 1978 aerial surveys were conducted just after (in 1977) and during (in 1978) the peak of the male oldsquaw molt migration through the intensive study area. The peak densities of oldsquaws in Simpson Lagoon during this survey in 1977 (26.2 birds/km^2) and during 1978 (160.4 birds/km^2) were recorded in the only significant areas of available open water: in the shoreleads along the southern margins of the barrier islands (Transect 2; see Table 12). During both 1977 and 1978, the mid-lagoon area (Transect 3) remained ice-covered until after 5 July and

Table 12. Densities (Birds/km^2)* of Oldsquaws Recorded in All Habitats During Aerial Surveys of Five Transects in the Jones Islands-Simpson Lagoon Area, 5 June to 22 September 1977, and 23 June to 23 September 1978.

Transect	1977						
	5 June	20 June	5 July	28/29 July	15 August	30 August	22 September
1	0.0	0.0	2.2	0.1	-	3.3	3.4
2	0.0	1.6	26.2	401.7[†]	811.3	73.1	21.6
3	0.0	0.0	2.9	501.1	-	184.6	928.1
4	0.2	0.9	21.6	516.4	161.9	68.0	220.0
5	2.6	3.2	1.9	1.2	5.8	0.0	0.0
Mean (unweighted)	0.6	1.1	11.0	284.1	326.3	65.8	234.6

Transect	1978									
	23 June	5 July	15 July	25 July	5/6 August	15 August	25 August	5/6 September	15 September	23 September
1	0.0	0.1	2.5	17.7	0.2	0.0	50.2	20.2	193.3	1.6
2	1.3	160.4	1344.8	284.7	324.7	994.2	337.4	150.2	47.0	9.9
3	0.0	5.4	39.0	73.0	62.5	7.3	33.3	12.3	29.6	231.8
4	0.2	2.2	70.8	19.1	6.4	0.0	0.8	0.1	7.1	138.5
5	1.4	1.4	0.2	0.0	0.0	0.0	2.0	0.1	0.0	0.0
Mean (unweighted)	0.6	33.9	291.5	78.9	78.8	200.4	84.7	36.6	55.4	76.4

*All oldsquaws recorded as 'On-Transect' (<200m of each side of the aircraft), regardless of the habitat with which they were associated, have been included in these density calculations.

[†] Densities in this portion of the table may be lower than those that may be calculated from numbers presented in Table 14. In Table 14, the proportion of the total area surveyed, which has been used in density calculations, includes only lagoon habitats, and birds used in density calculations include only those that were associated with lagoon rather than terrestrial habitats.

it therefore supported very low densities of oldsquaws until after that date (Table 12). The nearshore marine habitat adjacent to Simpson Lagoon (Transect 1) was similarly covered with ice until after 5 July; however, densities of oldsquaws in this habitat remained relatively low throughout the pre-molt period, regardless of ice cover.

The overall density of oldsquaws (0.7/km^2; 109 birds seen) recorded on 5 July 1978 during surveys west of the Simpson Lagoon study area was low (Fig. 3) compared to the overall density recorded in Simpson Lagoon (24.9/km^2; 2482 birds). Furthermore, although the number of oldsquaws (2736) recorded during surveys east of Simpson Lagoon as far as Flaxman Island was approximately equal to the number recorded in Simpson Lagoon, the overall density of oldsquaws east of Simpson Lagoon on this date (4.9/km^2) was considerably lower than that in Simpson Lagoon (Table 13, Fig. 3).

Satellite imagery indicated that by 13 July 1977 and by 6 July 1978, the ice had moved westward out of the coastal systems along the entire Beaufort Sea coast, and that the ice seaward of the barrier islands had moved offshore, away from most of the barrier islands.

Male Molt Period

The aerial surveys conducted on 28-29 July 1977 and on 15 July 1978 indicated that the area seaward of the barrier islands continued to support low densities of oldsquaws after the ice had retreated from this area (0.1 birds/km^2 on 29 July 1977 and 2.5 birds/km^2 on 15 July 1978). The highest density of oldsquaws recorded there during the molt period of either 1977 or 1978 was 17.7 birds/km^2 on 25 July 1978. The majority of the birds recorded then were in two flocks of 75 and 50 birds associated with brash-ice and small ice pans seaward of Pingok Island.

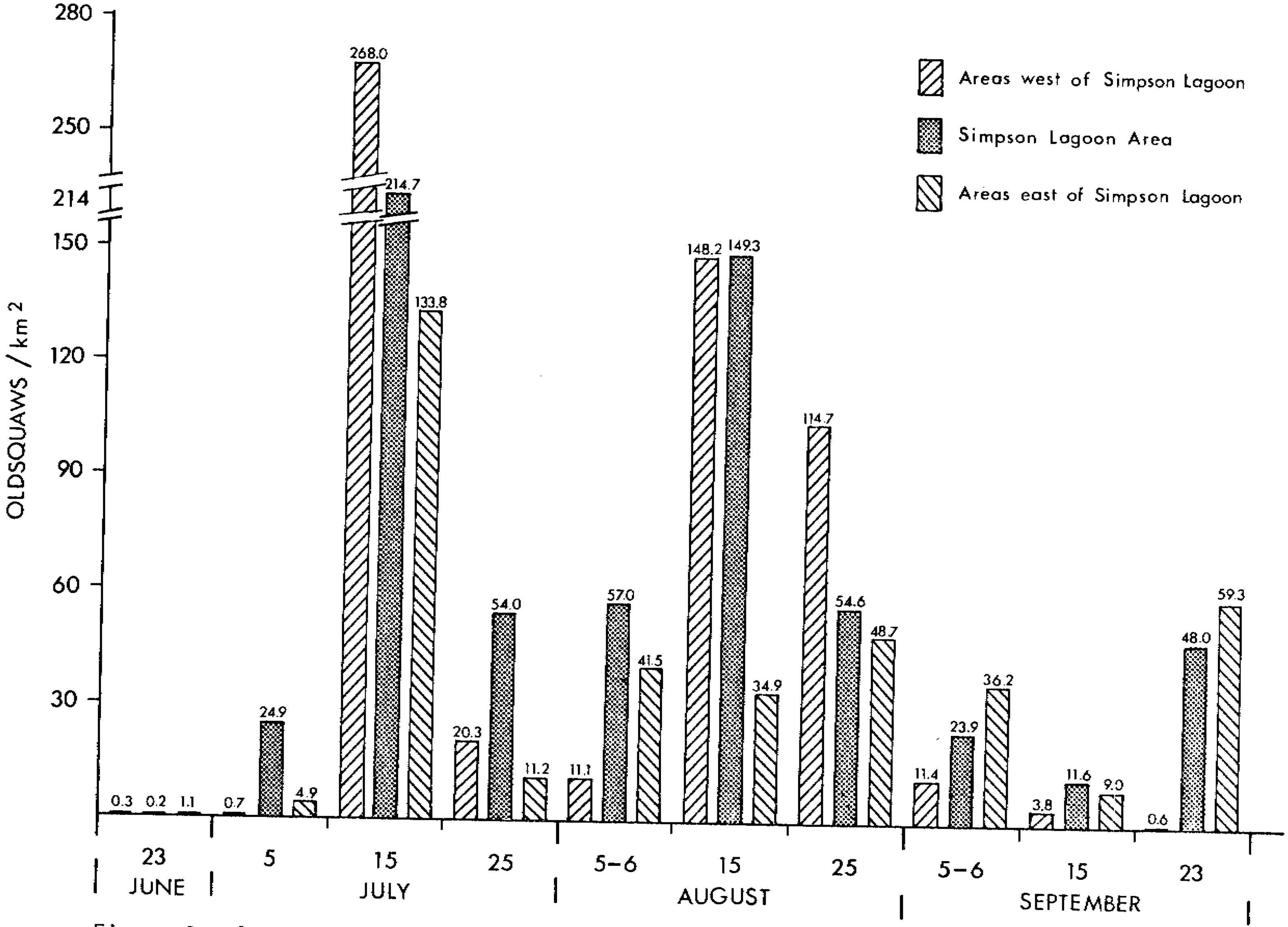

Figure 3. A Comparison of the Unweighted Mean Densities of Oldsquaws in Barrier Island-Lagoon Habitats to the East, West and In Simpson Lagoon, Alaska, June-September 1978.

Table 13. Numbers of Oldsquaws Recorded On-transect along Various Sections of the Beaufort Sea coast in Northeastern Alaska, 23 June to 23 September 1978.

Survey Date	West of Simpson Lagoon*		Simpson Lagoon		East of Simpson Lagoon†	
	# km Surveyed	# Oldsquaws on transect	# km Surveyed	# Oldsquaws on transect	# km Surveyed	# Oldsquaws on transect
23 June	29.9	10	99.8	22	78.2	82
5 July	163.7	109	99.8	2,482	557.0	2,736
15 July	29.9	8,013	99.8	21,423	78.2	10,463
25 July	163.7	3,326	99.8	5,384	404.9	4,552
5-6 August	163.7	1,813	99.8	5,688	787.8	32,661
15 August	29.9	4,431	99.8	14,903	78.2	2,731
25 August	13.8	1,583	99.8	5,444	317.2	15,445
5-6 August	163.7	1,862	99.8	2,388	787.8	28,543
15 September	29.9	112	99.8	1,156	78.2	705
23 September	29.9	17	99.8	4,792	317.2	18,819
All Dates	818.1	21,276**	998.0	63,682††	3484.7	116,737***

* This area included as many as six transects (163.7 km); it extended as far west as Atigaru Pt. and included most of the Colville River delta (see Figure 2A-B).

† This area included as many as 11 transects (787.8 km); it extended as far east as the Canada-U.S. border and as far north as the Midway Islands, north of Prudhoe Bay (see Figure 2C-G).

** Of the total 21,275 oldsquaws recorded on the 35 surveys of transects in areas west of Simpson Lagoon, 19,146 oldsquaws (90.0%) were recorded during the 10 surveys of one transect which included the south shoreline of Thetis Island.

†† Of the total 63,682 oldsquaws recorded on the 30 surveys of transects in Simpson Lagoon, 54,428 oldsquaws (85.5%) were recorded during the 10 surveys of one transect along the south shoreline of the Jones Islands.

***Of the total 115,040 oldsquaws recorded on the 46 surveys of transects in areas east of Simpson Lagoon, 87,559 oldsquaws (76.1%) were recorded during the 32 surveys of four transects along the south shoreline of barrier islands.

During this same period, oldsquaws became much more abundant in the lagoon. The weighted average density of birds recorded in all habitats in Simpson Lagoon (Transects 2, 3 and 4) had increased from 6.0 birds/km^2 on the 5 July 1977 survey to at least 321.1 (and possibly 566.1) birds/km^2 on the 28-29 July 1977 aerial survey (Table 14), and from 15.5 birds/km^2 on 5 July 1978 to 184.4 birds/km^2 on 15 July 1978. Between 15 July and 25 July 1978, however, the average density of oldsquaws recorded in lagoon habitats had decreased from 184.4 birds/km^2 to 83.6 birds/km^2; this density remained substantially higher, however, than the 15.5 birds/km^2 recorded several weeks earlier, on 5 July 1978. The density of 1344.8 birds/km^2 recorded on the 15 July 1978 survey of Transect 2 was the highest single-transect density of oldsquaws recorded during this study. On this date, about 20,026 oldsquaws were crowded along the south shoreline of the Jones Islands from Spy Island in the west to Cottle Island in the east. A very significant porportion (99%; 19,827 birds) of these birds were recorded on the shoreline side of the aircraft. Throughout the ice-free period of 1978 in Simpson Lagoon, significantly higher densities of oldsquaws were recorded on the barrier island shoreline transect (Transect 2) than on either the mid-lagoon or mainland shoreline transects (Transects 3 and 4, respectively) (Friedman χ^2=10.34, n=8, k=3, P=0.003). In fact, during the entire 1978 aerial survey program, a very large proportion (78%; 250,670 birds) of all oldsquaw sightings on surveys of all transects (from Thetis Island in the west to Demarcation Bay in the east) were during the surveys of five transects located immediately south of barrier islands. Furthermore, most oldsquaws recorded on-transect on these five barrier island transects were seen on the shoreline side of the aircraft (85%; 159,037 birds; Wilcoxon z=3.86; n=30 transect/date combinations; P<0.001).

By 15 July 1978, both the number and densities of oldsquaws had increased dramatically throughout the eastern Beaufort Sea

Table 14. Estimates of the Total Number of Oldsquaws Present in Simpson Lagoon During Aerial Surveys Conducted in 1977 and 1978.†††

Transect Number*	Location	Approximate Lagoon Area Represented (km²)	Lagoon Area Surveyed (km²)	1977						
				5 June	20 June	5 July	28/29 July	15 August	30 August	22 September
2	Barrier Island-North Lagoon (<1.82 m deep)	22	7.77	0 (0)†	23 (23)	398 (398)	14,284 (5,045)	33,951 (11,991)	419 (148)	841 (297)
3	Mid-Lagoon (>1.82 m deep)	102	12.24	0 (0)	0 (0)	292 (35)	51,375 (6,165)	- (-)**	18,829 (2,271)	95,142 (11,417)
4	South Lagoon (<1.82 m deep)	36	9.66	0 (0)	11 (11)	269 (269)	24,921 (6,687)	7,808 (2,095)	2,687 (721)	10,617 (2,849)
Total		160	29.67	0 (0)	34 (34)	959 (702)	51,375 (6,165)††	41,759 (14,086)	21,935 (3,140)	106,600 (14,563)
Mean Density (weighted)				0.0	0.2	6.0	321.1***	(261.0)***	137.1	666.3

Transect Number*	Location	Approximate Lagoon Area Represented (km²)	Lagoon Area Surveyed (km²)	1978									
				23 June	5 July	15 July	25 July	5 August	15 August	25 August	5 September	15 September	23 September
2	North Lagoon (<1.82 m deep)	22	14.80	19 (19)	2,388 (2,388)	20,415 (20,026)	5,273 (4,239)	5,571 (4,836)	15,939 (14,813)	6,723 (5,024)	2,672 (2,236)	896 (700)	215 (147)
3	Mid-Lagoon (>1.82 m deep)	102	12.24	0 (0)	66 (66)	4,000 (480)	7,483 (898)	6,409 (769)	750 (90)	3,417 (410)	1,258 (151)	3,033 (364)	23,758 (2,851)
4	South Lagoon (<1.82 m deep)	36	12.88	3 (3)	28 (28)	5,090 (915)	621 (247)	462 (83)	0 (0)	33 (10)	5 (1)	461 (92)	9,651 (1,794)
Total		160	39.92	22 (22)	2,482 (2,482)	29,505 (21,421)	13,377 (5,384)	12,442 (5,688)	16,689 (14,903)	10,173 (5,444)	3,935 (2,388)	4,390 (1,156)	33,624 (4,792)
Mean Density (weighted)				0.1	15.5	184.4	83.6	77.8	104.3	63.6	24.6	27.4	210.2

* Transect numbers 1 and 5 were seaward and landward, respectively, of Simpson Lagoon. Densities of oldsquaws on these transects were low (see Table 12) and estimates have not, therefore, been calculated for these transects.

† Numbers in parentheses represent the total number of oldsquaws recorded 'on-transect' (<200 m on either side of the aircraft) in lagoon habitats only.

** Incomplete survey; transects 1 and 3 were not surveyed on this date.

†† Since the surveys of transects 2 and 4 were conducted on 28 July and that of transect 3 was conducted on 29 July, it is possible that some or all of the birds recorded on 28 July were also recorded on 29 July. We have, therefore, used the larger of the two estimates (the estimate from transect 3 rather than the sum of the values from transects 2 and 4), as a total for the survey.

*** Minimum estimate.

††† During 1978, estimates of the total numbers of oldsquaws in Simpson Lagoon were calculated differently than they were in 1977. See Appendix 2 for a discussion of these differences.

coast of Alaska. However, even though similar proportions of each area were not surveyed, both the number and density of oldsquaws at barrier island shoreline locations in Simpson Lagoon plus Harrison Bay (south of Thetis Island) were markedly higher than at locations farther east (Table 13; Fig. 3).

The raw densities of oldsquaws recorded on the three lagoon transects on 28-29 July 1977 were very similar--401.7, 501.1 and 516.4 birds/km^2 for transects 2, 3 and 4, respectively--but actual densities in the water along transects 2 and 4 (which included some land) were somewhat higher. Nonetheless, the high density in mid-lagoon is noteworthy, and because of the similar densities on all lagoon transects, the estimates for 28-29 July 1977 in Table 14 are not very sensitive to the specific weighting procedure used. In contrast, on 25 July 1978, the density of oldsquaws in lagoon habitats immediately south of the barrier islands was markedly higher (284.7 birds/km^2) than in either the mid-lagoon area (73.0 birds/km^2) or along the mainland shoreline (19.1 birds/km^2).

The estimated peak number of oldsquaws present in Simpson Lagoon during the oldsquaw molt period was on the 28-29 July 1977 survey when at least 50,000 birds were estimated to be present--this was a substantial increase from the estimated total of 959 birds present during the preceding survey on 5 July 1977 (Table 14). Since no aerial surveys were conducted in areas east or west of the Simpson Lagoon study area during 1977 it is not known what proportion of the total number of oldsquaws present along the Beaufort Sea coast of Alaska were molting in Simpson Lagoon during this period in 1977.

In 1978, the estimated peak number of oldsquaws (approximately 30,000 birds; Table 14) present in Simpson Lagoon during the molt period was recorded on 15 July--approximately two weeks earlier than the peak date in 1977 (28-29 July).

During the remaining two surveys in the oldsquaw molt period of 1978, on 25 July and 5 August, the estimated numbers of oldsquaws present in Simpson Lagoon (13,377 and 12,442 birds, respectively) were less than half those estimated to be present on 15 July 1978. On 25 July 1978, the densities of oldsquaws had declined not only in the Simpson Lagoon area, but also west of Simpson Lagoon as far as Atigaru Point and east of Simpson Lagoon as far as Flaxman Island (Fig. 3). During the extensive 5-6 August 1978 surveys, although the mean density of oldsquaws in Simpson Lagoon remained relatively unchanged from the density during the 25 July survey, the mean density of oldsquaws had declined further in the area west of Simpson Lagoon. On the other hand, the number and mean density of oldsquaws east of Simpson Lagoon had increased dramatically (Table 13, Fig. 3), no doubt due to the inclusion during this survey of the extensive barrier island-lagoon system east of Flaxman Island as far as the Alaska-Canada border (see Fig. 2).

Oldsquaws were not evenly distributed within Simpson Lagoon during the molting period. On 28 July 1977, oldsquaws were most heavily concentrated at locations along the south sides of the barrier islands in Simpson Lagoon (Table 15). On this same date (28 July 1977) along the mainland shoreline of Simpson Lagoon and on 29 July at mid-lagoon locations, fewer concentrations of oldsquaws were recorded (Table 15).

During 1978, fewer oldsquaws molted in Simpson Lagoon than during 1977 (see Table 14 and Fig. 4). Furthermore, fewer major concentrations of oldsquaws were noted in Simpson Lagoon in 1978 than in 1977; concentrations that were recorded were along the south shorelines of barrier islands, as in 1977 (Table 15).

At locations west and east of Simpson Lagoon, major concentrations of molting male oldsquaws were recorded primarily at barrier island locations (Table 16). West of Simpson Lagoon, concentrations were recorded only at one location--south of Thetis Island. East

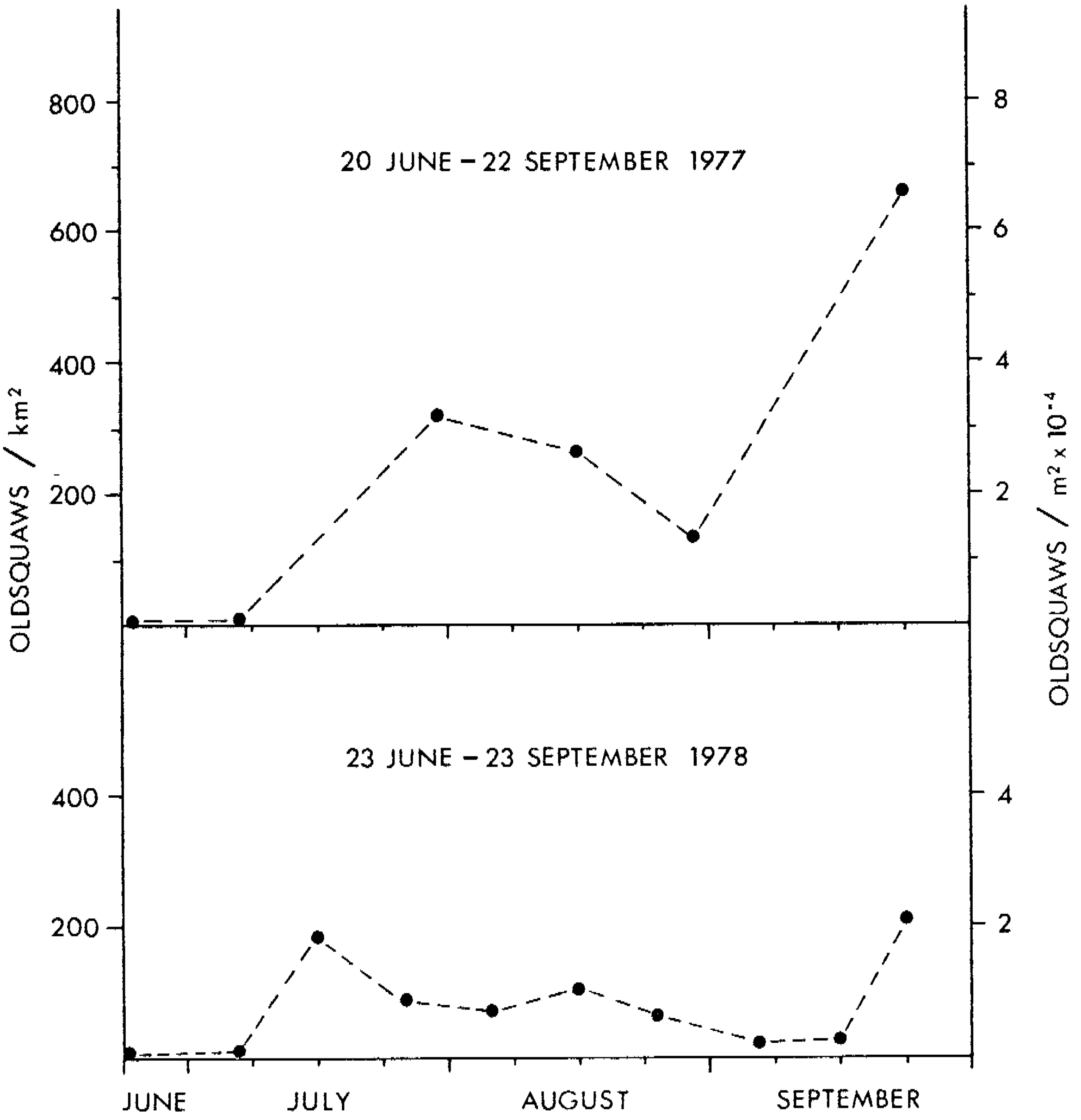

Figure 4. The Change in the Weighted Mean Density of Oldsquaws (from Table 14) Throughout the Seasons of 1977 and 1978 in Simpson Lagoon, Alaska.

Table 15. Locations of Major Oldsquaw Concentrations Recorded During the Period of Summer Molt in Simpson Lagoon, Alaska, 1977 and 1978.

1977	# Oldsquaws
Barrier Island Shoreline Locations (28 July)	
SE Shore Spy Island	3,100
S Shore Leavitt Island	3,065
SE Shore Cottle Island	5,200
	11,365
Mainland Shoreline Locations (28 July)	
NW Shore Oliktok Pt.	2,700
SW Shore Milne Pt.	2,875
SW Shore Kavearak Pt.	1,225
	6,800
Mid-Lagoon Locations (29 July). Totals probably under estimated due to incomplete coverage.	
Between Beechey Pt.-E End Cottle Is.	1,750
Between Kavearak Pt.-Bertoncini Is.	4,575
	6,325

1978*	# Oldsquaws
Barrier Island Shoreline Locations (25 July)	
SW of Spy Island	1,371
	1,371
Barrier Island Shoreline Locations (5 August)	
SW of Spy Island	997
SW of Leavitt Island	1,000
SW of Pingok Island	1,022
S Cottle Island	964
	3,983

*During aerial surveys conducted in 1978 no major oldsquaw concentrations were recorded along mainland shorelines or at mid-lagoon locations in Simpson Lagoon.

Table 16. Locations of Major Oldsquaw Concentrations Recorded During the Period of Summer Molt at Barrier Island-Lagoon Locations Along the Beaufort Sea Coast of NE Alaska, 1978.

	# Oldsquaws
25 July 1978	
Barrier Island Shoreline Locations	
S Shore Thetis Island	2,500
SW of Spy Island	1,371
SW Shore Long Island	2,644
	6,515
5 August 1978	
Barrier Island Shoreline Locations	
S Shore Thetis Island	1,275
S Shore Jones Islands (see Table 15)	3,983
SW Shore Long Island	3,844
SE Shore Long Island	1,262
S Shore Flaxman Island	5,835
SW Shore Arey Island	1,415
SE Shore Arey Island	2,625
S Shore Jago-Tapaurak Spits	5,932
S Shore Icy Reef	4,309
S Shore Demarcation Spit	1,550
	32,030
Mid-Lagoon Locations	
Arey Lagoon	2,070
Jago Lagoon	1,660
Flaxman Lagoon	2,305
	6,035

of Simpson Lagoon, major concentrations were recorded south of Flaxman Island, south of the Jago-Tapaurak Spit, and south of Icy Reef. The largest concentrations found at mid-lagoon locations were in Arey Lagoon, Jago Lagoon and Flaxman Lagoon (Table 16 and see Fig. 2A-G).

Based on the sex ratios of oldsquaws shot during the 29 July to 5 August 1977 and 1978 collection periods (Table 17), approximately 85% and 93%, respectively, of the oldsquaws present in the study area during this period were males. Several types of evidence indicated that the molt of male oldsquaws began in late July during 1977: the large proportion of males present then, the considerable interval since the peak of the molt-migration, the fact that the peak number of birds was recorded in late July, and the abrupt decrease in the mean wing length of males from the 17 June-27 July collection period to the 29 July-5 August period (Table 17). During 1978, however, the peak of oldsquaw abundance in the Simpson Lagoon area was several weeks earlier than during 1977 (Table 14; Fig. 4). Furthermore, the mean wing lengths of male oldsquaws collected during the 17 June to 27 July and the 29 July to 5 August periods were markedly (though not statistically) different (shorter during the early period and longer during the later period) and more variable (Table 17; Fig. 5). than they were in 1977. Also, although the period of maximum subcutaneous fat thickness was similar during 1977 and 1978, oldsquaws attained maximum weight earlier during 1978 (within the 17 June to 27 July period) than during 1977 (29 July to 5 August period). These factors suggest that during 1978 male oldsquaws began to molt several weeks earlier than in 1977.

Although the weights of male oldsquaws collected in Simpson Lagoon did not significantly change throughout the summer of 1977, they did so during the summer of 1978 with the peak in weight occurring during the late September period (Table 18). During the summer of both 1977 and 1978 the thickness of the subcutaneous fat layer on the males did vary significantly and was

Table 17. The Change in Adult Oldsquaw Wing Length, Weight and Subcutaneous Fat Thickness During the Premolt, Molt and Postmolt Periods at Simpson Lagoon, Alaska (1977-1978). Values given are mean ± sd.

		Collection Intervals				
		17 June-27 July*	29 July-5 August	7-18 August	20-31 August	4-23 September
MALE		Premolt	Molt	Postmolt		
Wing Length (cm)	1977	23.1 ± 1.0 (n=13)	12.9 ± 2.0 (n=15)	19.3 ± 2.2 (n=10)	21.9 ± 1.1 (n=12)	22.8 ± 1.0 (n=7)
	1978	18.9 ± 5.1 (n=24)	14.2 ± 3.7 (n=14)	18.5 ± 1.5 (n=18)	19.1 ± 1.2 (n=13)	22.4 ± 1.4 (n=14)
Weight (g)	1977	869.3 ± 128.4 (n=13)	914.2 ± 64.7 (n=15)	879.0 ± 52.4 (n=10)	862.5 ± 72.1 (n=12)	949.3 ± 62.9 (n=7)
	1978	925.7 ± 71.2 (n=28)	920.8 ± 70.7 (n=14)	839.1 ± 49.5 (n=18)	853.9 ± 39.8 (n=13)	939.6 ± 85.7 (n=14)
SubQ Fat	1977	4.6 ± 0.9 (n=8)	5.6 ± 1.7 (n=10)	3.7 ± 1.5 (n=10)	3.2 ± 1.1 (n=12)	3.8 ± 1.7 (n=7)
Thickness (mm)	1978	4.7 ± 1.5 (n=28)	5.4 ± 1.2 (n=14)	3.6 ± 1.1 (n=18)	3.2 ± 0.8 (n=13)	3.5 ± 2.5 (n=14)
FEMALE		Premolt		Molt	Postmolt	
Wing Length (cm)	1977	22.3; 21.1 (n=2)	20.6; 22.2; 20.5 (n=3)	13.9 ± 1.7 (n=5)	17.2 ± 3.3 (n=5)	20.8 ± 0.4 (n=12)
	1978	-†	23.7 (n=1)	16.7 ± 7.5 (n=5)	16.6 ± 2.2 (n=7)	20.0 ± 1.8 (n=9)
Weight (g)	1977	653 ; 685 (n=2)	742 ; 699 ; 814 (n=3)	761.0 ± 88.8 (n=5)	737.0 ± 57.3 (n=5)	800.7 ± 62.9 (n=12)
	1978	-	675 (n=1)	745.0 ± 63.6 (n=5)	691.4 ± 61.2 (n=7)	775.6 ± 93.4 (n=9)
SubQ Fat	1977	heavy; light (n=2)	8.0; 3.0; 2.0 (n=3)	3.5 ± 1.6 (n=5)	3.9 ± 2.0 (n=5)	2.4 ± 1.0 (n=12)
Thickness (mm)	1978	-	3.0 (n=1)	4.0 ± 1.4 (n=5)	3.5 ± 1.0 (n=7)	3.0 ± 1.6 (n=9)
Sex Ratio**	1977	1/ 6.5 (n=15)	1/ 5.0 (n=18)	1/2.0 (n=15)	1/2.4 (n=17)	1/0.6 (n=19)
(F/M)	1978	0/28.0 (n=28)	1/14.0 (n=15)	1/3.6 (n=23)	1/1.9 (n=20)	1/1.6 (n=23)

*Five male and two female oldsquaws were accidentally caught in gill nets during the period 17 June to 27 June 1977 and one male oldsquaw was accidentally caught in a gill net on 28 June 1978. These eight birds were salvaged and have been included in the wing length and weight calculations. All other birds were adults collected during the period 11 to 27 July 1977 and 10 to 27 July 1978, respectively.

†No female oldsquaws were collected on this date.

**During the collection of birds no attempt was made to collect either males or females; hence, sex ratios are probably a true reflection of flock composition.

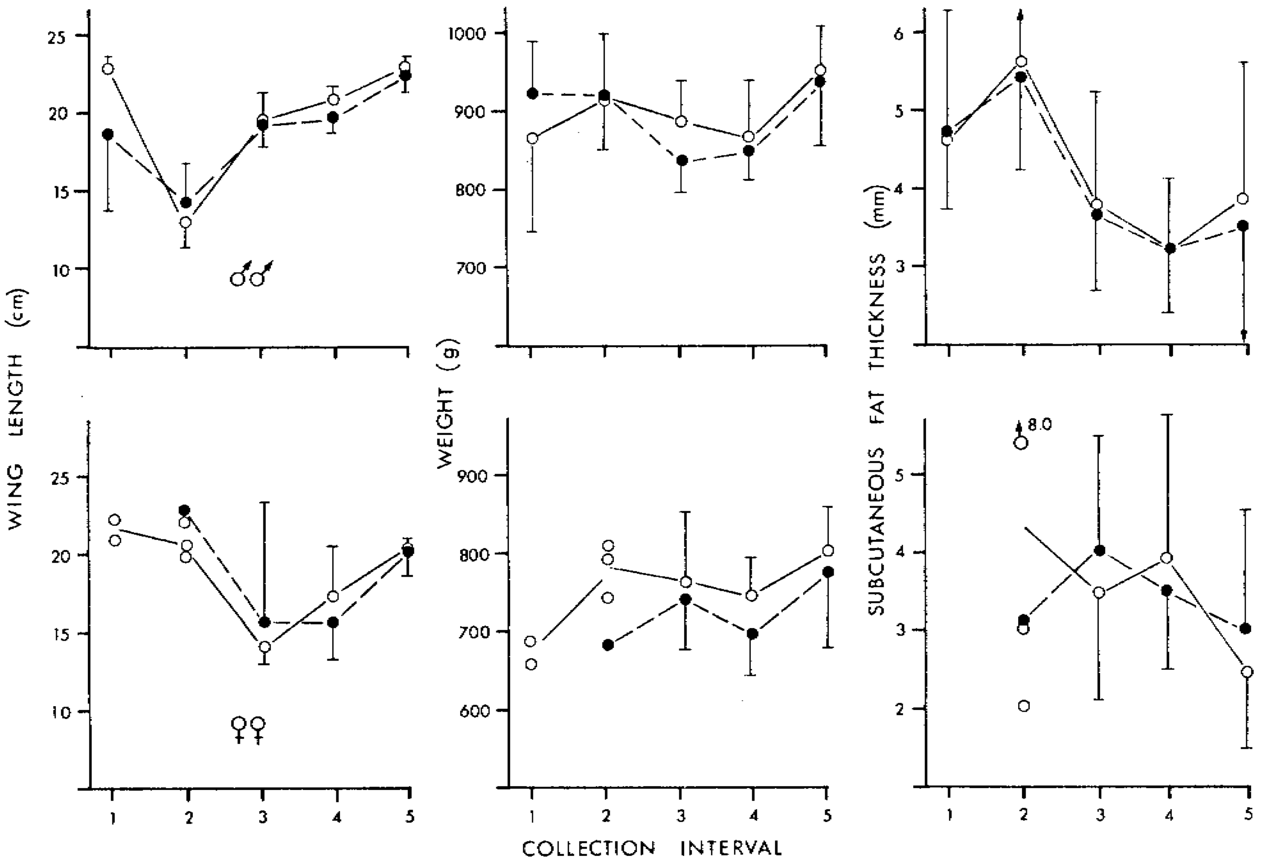

Figure 5. A Comparison of the Changes in Wing Length, Body Weight and Subcutaneous Fat Thickness of Male and Female Oldsquaws During Five Collection Periods In Simpson Lagoon During 1977 (○) and 1978 (●). (Collection intervals 1-5 correspond to dates presented in text Table 17.)

Table 18. Statistical Comparisons of the Change in Adult Male Oldsquaw Weights and Subcutaneous Fat Thickness Throughout the Summers of 1977 and 1978.

Kruskal-Wallis One-way ANOVA	1977 wt (gms)	1977 SubQ Fat Thickness (mm)	1978 wt (gms)	1978 SubQ Fat Thickness (mm)
'H'	4.21	16.12	24.28	26.08
d.f.	4	4	4	4
N	57	51	86	86
P	>0.02	<0.005	<0.001	<0.001

greatest (5.6 ± 1.7 cm during 1977 and 5.4 ± 1.2 cm during 1978; Table 17) in the 29 July-5 August collection period, during the latter part of the molt.

Female oldsquaws are largely restricted to tundra nesting habitats during the early June to late July period. This may explain the low numbers of females present in the lagoon habitats during the 17 June to 5 August period in both 1977 and 1978.

Female Molt Period

During both 1977 and 1978, the ratio of female to male oldsquaws present in the study area was markedly higher during 7-18 August than it had been on 29 July-5 August (Table 17). This shift in the sex ratio was probably a result of an influx of female birds, apparently failed breeders, from inland tundra locations. The greatly reduced wing-lengths of females collected on 7-18 August of each year compared with values prior to this period (Table 17) indicated that the females collected then had very recently molted their flight feathers.

The larger and more variable mean wing lengths of the five female oldsquaws collected during the 7-18 August 1978 period compared with the wing-lengths of the five females collected during the same period in 1977 (Table 17) suggests that, similar to males, female oldsquaws may have initiated molt earlier in 1978 than in 1977.

Post-molt Period

Although female oldsquaws were molting during mid-August of 1977 and 1978, males had nearly completed replacement of their flight feathers by then (Table 17). The aerial survey conducted on 15 August 1977 was incomplete; overwater Transects 1 and 3 were not surveyed. However, high densities of oldsquaws were recorded on the two lagoon transects that were surveyed--811.3 birds/km^2 on Transect 2, and 161.9 birds/km^2 on Transect 4 (Table 12). During the 15 August 1978 survey, very few birds were recorded in habitats other than the shoreline transect south of the Jones Island, and the density of oldsquaws at this location was high (994.2 birds/km^2).

The estimated total number of oldsquaws present in the study area on 15 August 1977 (at least 41,759 birds) was smaller than the estimated total present during the previous survey of 28/29 July 1977 (at least 51,375 birds). However, had Transect 3 been surveyed on 15 August the total for this date would probably have been larger. The estimated total number of oldsquaws present in the study area on 15 August 1978 (16,683 birds) was slightly larger than the estimated number present during the preceding two surveys on 25 July and 5 August 1978 (13,377 and 12,442 birds, respectively).

During both 1977 and 1978, a very large proportion of the oldsquaws present in Simpson Lagoon during the 15 August aerial survey were concentrated in waters immediately south of the Jones Islands (Tables 12 and 14). In fact, on 15 August 1978, 95.5% (15,939 birds) of the estimated total number of oldsquaws (16,683) present in the study area were recorded on the transect immediately south of the barrier islands (Transect 2).

The density of oldsquaws recorded on tundra habitats during the 15 August 1977 survey (5.81 birds/km^2) was noticeably higher than that recorded there during the preceding survey on 28 July 1977 (1.2 birds/km^2). This increase may be explained by the fact that female oldsquaws with broods would probably be more conspicuous on tundra ponds on 15 August than they were on 28 July (Bellrose 1976; King 1977).

During 1978, oldsquaws were not detected on mainland tundra lakes and ponds until the 25 August survey (Table 12).

By late August of both 1977 and 1978, although female oldsquaws were still flightless, most males had regained flight (mean wing length= 21.9 ± 1.1 cm during 1977 and 19.1 ± 1.2 cm during

1978; Table 17) and were capable of long-distance movements away from Simpson Lagoon. Possibly related to this, there was a marked decline from 15 to 30 August 1977 and from 15 August to 5 September 1978 in the number of oldsquaws observed in the study area (Tables 12 and 14). Raw densities of oldsquaws along the barrier island transect (Transect 2) were 811.3 and 73.1 birds/km^2 on 15 and 30 August 1977. Raw densities on this same date along the mainland coast (Transect 4) were 161.9 and 68.0 birds/km^2. Similarly, the estimated total number of oldsquaws present in Simpson Lagoon had declined from at least 41,759 on 15 August 1977 to approximately 21,935 on 30 August 1977.

Over the period 15 August to 5 September 1978 a similar decline from 994.2 to 337.4 to 150.2 oldsquaws/km^2 was noted along the barrier island transect (Transect 2). During the same period the estimated total number of oldsquaws in Simpson Lagoon decreased from 16,689 to 10,173 to 3935 birds (Tables 12 and 14). No clear trend in numbers or densities of oldsquaws on these surveys was noted at mid-lagoon or mainland locations in Simpson Lagoon; densities there remained relatively low (Tables 12 and 14).

The largest concentration of oldsquaws recorded in Simpson Lagoon during the 30 August 1977 survey was of approximately 2775 individuals seen in the mid-lagoon area between Kavearak Point and Bertoncini Island. The only other large group of oldsquaws recorded in the study area on this date in 1977 was a concentration of 1800 birds SE of Oliktok Point.

The largest concentrations of oldsquaws seen in Simpson Lagoon during the 15 August to 5 September 1978 period were as follows:

Date	Location	No. Oldsquaws
15 August 1978	SW Spy Island	8296
	SE Spy Island	4085
	S Pingok Island	2910
25 August 1978	SW Leavitt Island	3526
5 September 1978	SW Cottle Island	1745

The sex ratios of oldsquaws collected during the 20-31 August periods of both 1977 and 1978 remained in favor of males (71% and 66%, respectively). During 1977, no oldsquaws were recorded on tundra habitats during the 30 August survey. During 1978, however, the density of oldsquaws on the tundra transect (Transect 5) increased from 0.0 birds/km^2 on 15 August to 2.0 birds/km^2 on 25 August and then declined to 0.1 birds/km^2 on 5 September 1978. Apparently female and young oldsquaw had begun departing the tundra for coastal habitats after 25 August; juveniles were collected in Simpson Lagoon for the first time during the 25-31 August collection periods in 1977 and 1978.

The density of oldsquaws in nearshore marine habitats seaward of the barrier islands on 30 August 1977 was low (3.3 birds/km^2), and the few oldsquaws that were sighted on-transect on this date were associated with ice pans and chunks of ice that had drifted landward from the pack ice, located farther offshore from the barrier islands. During the comparable survey in nearshore marine habitat on 25 August 1978, approximately 1800 oldsquaws (50.2 birds/km^2) were recorded on-transect among the many loose and scattered ice pans present off the coast of the Jones Islands. On this date the edge of the Beaufort Sea pack ice was only about 10 km offshore from the barrier islands. During the survey of this same nearshore marine transect (Transect 1) on 5 September, approximately 850 oldsquaws (20.2 birds/km^2) were recorded in these waters which were then ice-free.

During the 22 September 1977 aerial survey, the weighted average density of oldsquaws recorded on the three Simpson Lagoon transects was 666.3 birds/km^2, a substantial increase from the average value of 137.1 birds/km^2 recorded on these same three transects during the previous survey on 30 August (Table 14). The density of oldsquaws recorded on Transect 3, in the mid-lagoon portion of the study area, was about 930.0 birds/km^2--the highest transect density of this species recorded during 1977. The estimated total number of oldsquaws present in the study area during the 22 September 1977 aerial survey was 106,600 birds (Table 14). Approximately 90% of these birds (95,142) were present in mid-lagoon waters. No major concentrations of oldsquaws were observed along the southern margin of the barrier islands on 22 September. Over 90% (19,183 of 21,068) of all oldsquaws actually observed in the mid-lagoon area (including off-transect sightings) on 22 September were in the eastern half of the study area--east of a line from Jones Sound on the mainland to the survey marker at mid-Pingok Island. The largest concentration of oldsquaws observed during the 22 September 1977 survey (4082 oldsquaws) was in the mid-lagoon region between Kavearak Point and the west end of Cottle Island. Other major concentrations of oldsquaws were seen in mid-lagoon waters between Milne Point and Shacklo Point on Pingok Island (approximately 3000 oldsquaws) and in mid-lagoon waters between Milne Point and the survey marker at mid-Pingok Island (approximately 3000 birds).

Of the 8585 oldsquaws seen along the mainland shoreline of Simpson Lagoon on 22 September 1977, 95% (8009) were observed in the eastern portion of the study area. Major concentrations along the mainland shoreline were noted SW of Milne Point (2023 oldsquaws), SW of Kavearak Point (3425 oldsquaws), and SE of Kavearak Point (1631 oldsquaws).

During the 15 September 1978 aerial survey the weighted mean density of oldsquaws in Simpson Lagoon was 27.4 birds/km^2, only slightly higher than the density (24.6 birds/km^2) recorded during the preceding survey of the lagoon on 5 September. Of the estimated total 4390 birds present in Simpson Lagoon on this date, 69% (3033) were estimated to be present in mid-lagoon habitats. The density of oldsquaws recorded on the adjacent mainland tundra transect had declined from 0.1 birds/km^2 during the preceding survey to 0.0 birds/km^2 on 15 September. The surprising feature of the 15 September survey was the very high density (193.3 birds/km^2) of oldsquaws in the icefree nearshore marine habitat seaward of the Jones Islands. Approximately 7000 oldsquaws were recorded on and off transect in this area on 15 September; this was the largest number of oldsquaws recorded in this habitat during either year of the study. No other large numbers of oldsquaws were noted on this date in the study area.(Table 12).

On 23 September 1978, the weighted mean density of oldsquaws in Simpson Lagoon had increased to the highest level recorded during 1978, a feature also noted during the final survey of Simpson Lagoon in 1977, on September (Table 14). Another remarkable similarity between this survey in 1978 and the one on 22 September 1977 is the fact that oldsquaws were again recorded in highest densities at mid-lagoon (231.8 birds/km^2) and mainland shoreline (138.5 birds/km^2) locations (Tables 12 and 14). During almost all other surveys in both years, densities along the barrier islands exceeded those along the mainland shoreline. The densities of oldsquaws in nearshore marine habitats seaward of the islands was especially low on 23 September 1978 (1.6 birds/km^2) compared to the remarkably high value recorded in this habitat during the preceding survey. The estimated total number of oldsquaws present in Simpson Lagoon during this last survey in 1978 was 33,624, of which 71% (23,759 birds) were estimated to be present in mid-lagoon habitats and 29% (9651 birds) were estimated to be present along the mainland shoreline (Table 14).

Contrary to the situation in 1977 when the majority of oldsquaws recorded during the final aerial survey were in the eastern half of Simpson Lagoon, the majority of oldsquaws (81%; 7193 of 8891 birds) recorded on and off transect during 23 September 1978 were in the western half of the lagoon, i.e., west of a line from Milne Point to the survey marker at mid-Pingok Island. The only large concentration of oldsquaws recorded in Simpson Lagoon during this final survey was of 4013 birds seen on and off transect in the large bay SW of Milne Point.

Table 19 gives the locations of major oldsquaw concentrations during the 1978 period of post-molt in barrier island-lagoon habitats along the entire Beaufort Sea coast of NE Alaska. The

Table 19. Locations of Major Oldsquaw Concentrations* Recorded During the Postmolt Period (15 August to 23 September 1978) at Barrier Island-Lagoon Locations Along the NE Coast of Alaska.

	# Oldsquaws
15 August	
Harrison Bay between Thetis Is. and Oliktok Pt.	3,245
SE Shoreline of Long Island	1,927
	5,172
25 August	
S Shoreline Thetis Island	1,022
SW Shoreline Long Island	2,347
S Shoreline Egg Island	2,315
S Shoreline Pole Island	1,479
S Shoreline Flaxman Island	6,111
	13,274
5-6 September	
Harrison Bay between Thetis Is. and Oliktok Pt.	1,335
S Shoreline Flaxman Island	5,603
ESE Brownlow Pt. (Canning Lagoon)	8,058
SE Konganevik Pt.	3,055
S Shoreline Icy Reef	1,212
Flaxman Lagoon	32,027
	51,290
23 September	
8 km N Heald Pt.	1,859
S Shoreline Narwhal Island	1,197
S Shoreline Pole Island	18,073
Flaxman Lagoon	7,338
Mikklesen Bay	5,009
Foggy Island Bay	4,717
N Howe Island	1,500
Gwydyr Bay	3,651
	43,344

*This table includes birds recorded both on- and off-transect. Information regarding concentrations of birds recorded in the Simpson Lagoon study area is mentioned in the text.

extensive surveys conducted on 5-6 September indicated that very large concentrations of oldsquaws (approximately 8058 birds seen) was present in the barrier island-lagoon system ESE of Brownlow Point. Slightly west of this location, in the lagoon area behind Flaxman Island, the single largest concentration of oldsquaws directly observed (approximately 32,000 birds) during the two-year study was recorded. Similar large concentrations of oldsquaws in barrier island-lagoon habitats east of Prudhoe Bay as far as Flaxman Island were recorded during the final aerial survey on 23 September (Table 19).

By 23 September of 1977 and 1978 both sexes of adult oldsquaws as well as juvenile birds were capable of flight; of the 12 and 9 female oldsquaws collected during the 4-23 September 1977 and 1978 collection periods (Table 14), four and one, respectively, were juveniles. Also noteworthy is the fact that the sex ratio of adult oldsquaws collected in the lagoon during the 4 to 23 September period had shifted in favor of females, especially during 1977 (female/male ratio=0.42 and 0.52 during 20-31 August 1977 and 1978, respectively; 1.67 and 0.62 during 4-23 September 1977 and 1978, respectively).

The weights of oldsquaws collected throughout the 1977 and 1978 seasons indicate that both males and females were very heavy during the September collection period. Suprisingly, the subcutaneous fat layer of both male and female oldsquaws tended to be thinnest during this same mid-September collection period (Fig. 5 and Table 14).

In summary, fewer male oldsquaws molted in Simpson Lagoon during 1978 than in 1977 and the molt for some males began up to two weeks earlier during 1978. Both of these factors may be related to an early spring break-up in 1978 and early flushing of ice not only from Simpson Lagoon but from the entire northeast coast of Alaska. During 1978 oldsquaws continued to concentrate in very high densities immediately south of the Jones Islands. During more extensive coastal surveys in 1978, concentrations of oldsquaws were recorded south of most barrier islands along the entire NE coast of Alaska from Thetis Island in the west to the Alaska-Canada border in the east. Male oldsquaws were generally fattest and heaviest during the peak of the molt in both 1977 and 1978.

After the period of molt by males in both 1977 and 1978 the numbers and densities of oldsquaws in Simpson Lagoon declined and remained low until late September. At this time, large numbers of female and young-of-the-year oldsquaws arrived in Simpson Lagoon. Observations of large numbers of oldsquaws at locations east of Simpson Lagoon during surveys conducted in early and mid-September suggested that some of these late-arriving oldsquaws in Simpson Lagoon may have come from the east; others probably came from tundra ponds and lakes that typically freeze over during late September. During the late September peak of abundance, oldsquaws were concentrated primarily at mid-lagoon locations.

Pre-migratory Staging

Shorebirds

Although phalaropes were not the only species of shorebird observed in the study area during 1977 and 1978, thery were the most common shorebirds recorded and they were highly concentrated, especially during 1977, at certain shoreline locations in the study area during mid-August. Therefore, phalaropes were considered key species. Other species of birds recorded on shoreline transects but thought to be of less relative importance than phalaropes are shown in Appendix 1.

The movement of juvenile phalaropes from rearing areas on the tundra to coastal staging areas was in 1977 at Pingok Island on 1 August. On this date a total of 150 red phalaropes were recorded on 15 shoreline transects in the study area. During 1977 no northern phalaropes were recorded during transect surveys in the study area until 3 August (Table 20). During 1978, red and northern phalaropes (37 and 6 birds, respectively) were first recorded along the barrier islands on 4 August.

The overall ratio of northern to red phalaropes recorded in the study area during the month of August was 1:4.0 in both 1977 and 1978. This ratio during 1977 was 0:150 on 1 August before northern phalaropes had arrived in the study area, 1:2.8 on 16 August during the peak of phalarope abundance, and 1:1.4 on 26 August--the last date when both species were recorded in the study area. Seventeen red phalaropes (in winter plumage) were recorded on Pingok Island on 14 September; these were the last phalaropes seen in the study area during 1977.

During 1978, the ratio of northern to red phalaropes varied from 0:277 on 14 August during the peak of phalarope abundance to 1:2.1 during the survey on 29 August. Although the overall ratio of northern to red phalaropes (1:4.0) was the same during 1977 and 1978, the number of phalaropes recorded during 1978 was much smaller than that during 1977 (Table 20). Even though no phalaropes were recorded in the Simpson Lagoon area after 3 September 1978, two small flocks (4 and 8 birds, respectively) were recorded in an area of open water near the ARCO causeway (Prudhoe Bay) on 14 and 15 October 1978.

During August and early September of 1977 and 1978, densities of shorebirds differed significantly among the three types of beach transects surveyed (for 1977, Friedman $X^2=6.4$, $k=3$, $n=5$, $P=0.04$; for 1978 $X^2=11.1$, $k=3$, $n=8$, $P=0.002$--see Table 21 and Seigel 1956). During both years, mean densities were highest along oceanside beaches of the barrier islands, intermediate along lagoonside beaches of these islands, and lowest along mainland beaches.

During August of 1978, markedly fewer phalaropes were recorded in the study area than during the same month in 1977 (Tables 21 and 22).

Table 20. Numbers of Red and Northern Phalaropes Observed on Beach Transects in the Simpson Lagoon-Jones Islands Area During August, 1977 and 1978.

	August 1977											
	1	2	3	6	8	12	14	16	23	24	26	Total
Number of Red Phalaropes	150	4	77	193	525	69	16	3470	262	1340	24	6130
Number of Northern Phalaropes	0	0	53	60	51	23	0	1220	52	40	17	1516
Northern/Red Ratio	0/150	0/4	1/1.5	1/3.3	1/10.3	1/3	0/16	1/2.8	1/5	1/33.5	1/1.4	1/4.0
Number of Transects Surveyed	15	1	1	1	1	1	1	15	1	15	1	53

	August 1978															
	2	4	7	9	11	13	14	17	19	21	24	26	28	29	31	Total
Number of Red Phalaropes	0	37	0	23	22	4	277	4	242	0	104	7	0	232	97	1049
Number of Northern Phalaropes	0	6	0	2	0	0	0	0	103	0	10	1	0	112	27	261
Northern/Red Ratio	0/0	1/6.2	0/0	1/11.5	0/22	0/4	0/277	0/4	1/2.4	0/0	1/10.4	1/7	0/0	1/2.1	1/3.6	1/4.0
Number of Transects Surveyed	1	16	1	16	1	1	16	1	16	1	16	1	1	16	1	105

Table 21. Average Linear Densities (Bird/km of Shoreline)* of all Shorebirds Recorded on Three Beach Types Surveyed During 1977 and 1978.

Date of Survey	Beach Type					
	Barrier Island Oceanside Beach (n=5)		Barrier Island Lagoonside Beach (n=5)		Mainland Beach (n=5)	
	1977	1978	1977	1978	1977	1978
31 July	-	6.2(1.0)	-	0.0(0.0)	-	2.6(0.0)
1 August	5.0(4.0)[†]	-	2.2(1.2)	-	1.6(0.0)	-
4 August	-	9.4(7.0)	-	1.6(1.6)	-	0.0(0.0)
9 August	-	2.0(2.0)	-	3.0(3.0)	-	0.0(0.0)
14 August	-	0.2(0.2)	-	54.2(53.8)	-	0.6(0.0)
16 August	132.3(131.8)	-	38.0(32.8)	-	32.8(29.8)	-
19 August	-	36.0(34.8)	-	36.4(35.0)	-	5.2(1.0)
24 August	2.2(0.0)	15.2(14.8)	39.8(32.6)	26.4(23.8)	1.2(0.0)	7.6(2.4)
29 August	-	67.4(61.6)	-	18.4(17.4)	-	3.4(0.0)
1 September	11.2(0.0)	-	3.0(0.0)	-	3.8(0.0)	-
3 September	-	0.6(0.4)	-	24.0(12.6)	-	0.0(0.0)
14 September	15.0(0.0)	-	2.0(0.0)	-	0.0(0.0)	-

*Beach transects were 1 km long x 20 m wide (10 m either side of the shoreline) = 0.02 km^2. Only those birds seen on transect have been included in this table.

[†] Parentheses enclose the mean densities of all phalaropes (red, northern and unidentified phalaropes) recorded during each survey.

Table 22. Estimated Numbers of Shorebirds and Gulls/Terns Present Along the Oceanside and the Lagoonside Beaches of the Jones Islands from Spy to Cottle Island, and Along the Mainland Beach of Simpson Lagoon From Oliktok Point to Beechey Point, 1977 and 1978.

Date of Survey* and Species	Beach Type					
	Barrier Island Oceanside Beach (30.5 km long)		Barrier Island Lagoonside Beach (34.2 km long)		Mainland Beach (32.2 km long)	
	1977	1978	1977	1978	1977	1978
31 July						
All Shorebirds	-	189(31)	-	0(0)	-	84(0)
All Gulls/Terns	-	37(37)	-	7(0)	-	19(19)
1 August						
All Shorebirds	153(122)†	-	75(41)	-	52(0)	-
All Gulls/Terns	24(18)**	-	109(21)(14)	-	6(6)	-
4 August						
All Shorebirds	-	287(44)	-	55(55)	-	0(0)
All Gulls/Terns	-	18(18)	-	0(0)	-	6(6)
9 August						
All Shorebirds	-	61(61)	-	103(103)	-	0(0)
All Gulls/Terns	-	6(6)	-	27(7)	-	0(0)
14 August						
All Shorebirds	-	6(6)	-	1854(1840)	-	19(0)
All Gulls/Terns	-	0(0)	-	55(41)	-	6(6)
16 August						
All Shorebirds	4035(4020)	-	1300(1122)	-	1056(960)	-
All Gulls/Terns	79(6)(6)	-	1156(27)	-	6(6)	-
19 August						
All Shorebirds	-	1098(1061)	-	1245(1197)	-	169(32)
All Gulls/Terns	-	18(15)	-	0(0)	-	0(0)
24 August						
All Shorebirds	67(0)	464(451)	1361(1115)	903(814)	39(0)	245(77)
All Gulls/Terns	24(24)	6(6)	150(150)	0(0)	0(0)	0(0)
29 August						
All Shorebirds	-	2056(1879)	-	625(595)	-	110(0)
All Gulls/Terns	-	55(55)	-	0(0)	-	0(0)
1 September						
All Shorebirds	342(0)	-	103(0)	-	122(0)	-
All Gulls/Terns	451(451)	-	0(0)	-	13(13)	-
3 September						
All Shorebirds	-	18(12)	-	821(431)	-	0(0)
All Gulls/Terns	-	49(49)	-	185(185)	-	32(32)
14 September						
All Shorebirds	458(0)	-	68(0)	-	0(0)	-
All Gulls/Terns	31(31)	-	27(27)	-	0(0)	-

*Beach transects were 20 m wide (10 m either side of the shoreline) and 1 km long. Estimates are based on mean densities of birds recorded during each survey along 5 transects on each type of beach.

†Parentheses enclose the estimated number of all phalaropes present along the beach type.

**Parentheses enclose the estimated number of glaucous gulls present along the beach type. Where two parenthetical values appear, the first refers to glaucous gulls and the second refers to Sabine's gulls.

The dates of peak densities of phalaropes along barrier island beaches were similar in 1977 and 1978, except that the peak density on the seward beaches was recorded earlier in 1977 than in 1978, whereas the peak density along the lagoonside beaches was earlier in 1978 than in 1977 (Table 21). During both 1977 and 1978 phalaropes were recorded along mainland beaches only during the period of their peak abundance in the study area (29.8 birds/km on 16 August 1977 and 1.0 and 2.4 birds/km on 19 and 24 August 1978; Table 21). Few phalaropes were present in the study area after the end of August in 1977 and after 3 September 1978.

During August of both 1977 and 1978, red phalaropes accumulated a substantial amount of fat during the period of pre-migratory staging in the study area (Table 23). Northern phalaropes in both years arrived in the study area substantially fatter than red phalaropes and no distinct increase in fatness of northern phalaropes was noted during August.

All phalaropes collected for the feeding studies during both 1977 and 1978 were juveniles. Sex ratios of both species of phalaropes varied greatly between collection periods (Table 23). For both species during 1977, the proportion of females was lower on 19-25 August than on 3-12 August, but the difference was not statistically significant for either species. During 1978, the opposite was true; the proportion of females of both species was lower (although not statistically so) during the 6-18 August period than during the 20-31 August period.

To summarize, significant numbers of phalaropes were present in the study area only during August, although some flocks apparently remain along the Beaufort Sea coast until freeze-up is nearly complete. Markedly fewer phalaropes were recorded in the Simpson Lagoon-Jones Islands study area in 1978 compared to 1977. During the month of August of both 1977 and 1978 red phalaropes accumulated fat and outnumbered northern phalaropes by a ratio of 4.0:1. The period of peak phalarope

Table 23. Changes in Subcutaneous Fatness* and Sex Ratios of Red and Northern Phalaropes in Simpson Lagoon During August, 1977 and 1978. All specimens were juveniles.

Species	August 1977								
	3	4	5	6	12	19	21	23	25
Red Phalarope									
Fatness x̄	2.4	2.1	2.4	2.3	2.7	3.0	3.2	4	3.3
S.D.	0.55	0.30	1.14	0.50	0.82	0.89	0.98	0	0.98
n	5	11	5	4	6	6	6	1	12
Sex Ratio (M/F)	3/2	5/6	3/2	1/3	1/2†	6/0	4/1†	-†	5/5†
Northern Phalarope									
Fatness x̄	-	3.5	3.5	3.0	3.4	-	4.5	3.8	4
S.D.	-	0.58	0.71	0	1.41	-	0.58	0.84	0
n	-	4	2	4	8	-	4	5	1
Sex Ratio (M/F)	2/2	2/0†	2/0	1/1†	1/5†	3/1	3/1	1/0†	-

...cont'd

Table 23. (cont'd)

Species	August 1978														
	6	7	10	12	17	18	20	21	22	23	26	27	28	30	31
Red Phalarope															
Fatness $\bar{x}$	1.3	2	2	2	3	2.5	2.5	3.5	2	2	3.3	-	3.5	4	2
S.D.	0.75	-	0.5	-	0.33	0.4	0.4	0.29	-	-	0.30	-	0.29	0.25	-
n	3	1	3	1	2	6	2	2	1	1	3	-	2	3	1
Sex Ratio (M/F)	2/0†	1/0	2/0†	0/0†	1/1	2/3†	0/2	1/1	0/1	1/0	1/2	-	1/1	1/2	1/0
Northern Phalarope															
Fatness $\bar{x}$	-	-	2.3	4	4	2.8	3	4	2	2	-	2.7	-	3	3
S.D.	-	-	0.43	-	0.25	0.35	0.33	-	0.5	-	-	0.38	-	0.33	-
n	-	-	3	1	2	6	2	1	3	1	-	3	-	3	1
Sex Ratio (M/F)	-	-	2/1	1/0	1/1	2/3†	1/1	0/1	2/1	0/1	-	0/2†	-	1/2	0/1

*Fatness classifications conform to OCS fatness codes: 1=no fat; 2=light fat; 3=moderate fat; 4=heavy fat; 5=excessive fat.

†Some birds of undetermined sex were collected on this day.

abundance was during mid-to late August when high densities were recorded along oceanside (the highest densites) and lagoonside beaches of barrier islands. Few phalaropes were recorded along mainland beaches during either year of study.

Arctic Tern

Although some arctic terns nested in the study area, all large groups of this species were transients. A relatively large westward movement of arctic terns through the study area occurred during mid-August of 1977 (Tables 22 and 24). Peak numbers recorded during the 15 August 1977 aerial survey were along the barrier islands (Transect 2) where a total of 355 were observed. During this survey no arctic terns were observed in offshore marine habitats, in mid-lagoon habitats or in tundra habitats.

In general, far fewer arctic terns were recorded in the Jones Island-Simpson Lagoon study area during 1978 compared with 1977. During 1978 the field camp and migration watch station were located near the mainland coast rather than on Pingok Island where they had been during 1977. Probably for that reason, westward fall migration of arctic terns was recorded along the barrier islands in August 1977 but not in 1978. However, the peak of tern abundance in the study area in 1978 was again recorded during aerial surveys conducted on 15 August at barrier island locations (Table 25). During the aerial survey programs of both 1977 and 1978, the majority of all arctic terns recorded in the study area (98.2% in 1977 and 86.5% in 1978) were recorded at locations along the barrier islands (see Table 25). The fact that few arctic terns were recorded at nearshore locations seaward of the Jones Islands during late August of both 1977 and 1978 suggests that a westward fall movement may occur there or that terns may feed at locations seaward of as well as along the barrier islands. During the entire two-year study only five arctic terns (three during 1977 and two during 1978) were observed during aerial surveys along the mainland shoreline of the study area. The few arctic terns that nested in an area of lakes and ponds SW of the mainland tundra nesting plot (Plot 3; Fig. 1) were commonly observed flying to and from the barrier islands to feed.

Terns concentrated to feed at several locations along the barrier islands during fall westward movements. The most notable of these concentration areas during 1977 were at the east ends of Spy Island (about 220 observed on 16 August) and Pingok Island (maximum of 167 observed on 16 August). During 1978, the only feeding concentration of terns noted in the study area was of approximately 10 individuals recorded at the east end of Pingok Island on 29 August.

The detailed survey of barrier island beach transects on 16 August 1977 indicated that the number of arctic terns was greater along the lagoonside beaches of the barrier islands (33.0 terns/km of shoreline) than along the oceanside beaches of the islands (2.2 terns/km) or the mainland beaches (no terns observed). Based on these results, the estimated number of arctic terns along all beaches in the study area on 16 August 1977 were as follows: barrier island oceanside shorelines, 67 arctic terns; barrier island lagoonside shorelines, 1129; mainland shorelines, none (Tables 21 and 22). Only 109 arctic terns were observed during the 30 August 1977 aerial survey of the barrier islands. No terns were recorded in the study area after 30 August 1977 or 25 August 1978.

During 1978, the only significant numbers of arctic terns recorded in the study area were during shoreline surveys on 9 and 14 August (Table 24) and during the 15 August aerial survey along the barrier island shoreline of Simpson Lagoon (Transect 2; Table 25).

Table 24. Average Linear Densities (Birds/km of Shoreline)* of Gulls and Terns[†] Recorded on Three Beach Types Surveyed During 1977 and 1978.

Date of Survey	Beach Type: Barrier Island Oceanside Beach (n=5) 1977	Barrier Island Oceanside Beach (n=5) 1978	Barrier Island Lagoonside Beach (n=5) 1977	Barrier Island Lagoonside Beach (n=5) 1978	Mainland Beach (n=5) 1977	Mainland Beach (n=5) 1978
31 July	-	1.2(1.2)	-	0.2(0.0)	-	0.6(0.6)
1 August	0.8(0.6)	-	3.2(1.0)	-	0.2(0.2)	-
4 August	-	0.6(0.6)	-	0.0(0.0)	-	0.2(0.2)
9 August	-	0.2(0.2)	-	0.8(0.2)	-	0.0(0.0)
14 August	-	0.0(0.0)	-	1.6(1.2)	-	0.2(0.2)
16 August	2.6(0.4)	-	33.8(0.8)	-	0.2(0.2)	-
19 August	-	0.6(0.5)	-	0.0(0.0)	-	0.0(0.0)
24 August	0.8(0.8)	0.2(0.2)	4.4(4.4)	0.0(0.0)	0.0(0.0)	0.0(0.0)
29 August	-	1.8(1.8)	-	0.0(0.0)	-	0.0(0.0)
1 September	14.8(14.8)	-	0.0(0.0)	-	0.4(0.4)	-
3 September	-	1.6(1.6)	-	5.4(5.4)	-	1.0(1.0)
14 September	1.0(1.0)	-	0.8(0.8)	-	0.0(0.0)	-

*Beach transects were 1 km long x 20 m wide (10 m either side of the shoreline) = 0.02 km^2. Only those birds seen on transect have been included in this table.

[†] Parentheses enclose the mean densities of all gulls (both glaucous and Sabine's gulls) recorded during each survey. To determine the linear density of arctic terns, subtract the density within the parentheses from the number immediately to the left.

Table 25. Total Numbers of Terns Recorded During Aerial Surveys of Five Transects in the Jones Islands-Simpson Lagoon Area, June to September, 1977 and 1978.

Transect #	1977						
	5 June	20 June	5 July	28/29 July	15 August	30 August	22 September
1	0 (0)†	0 (0)	0 (0)	0 (0)	- (-)	5 (0)	0 (0)
2	0 (0)	7 (0)	22 (0)	23 (36)	355 (1)	109 (0)	0 (0)
3	0 (0)	0 (0)	0 (2)	0 (2)	- (-)	0 (0)	0 (0)
4	0 (0)	0 (0)	0 (0)	3 (0)	0 (0)	0 (0)	0 (0)
5	0 (0)	0 (0)	0 (0)	0 (0)	0 (0)	0 (0)	0 (0)
Total	0 (0)	7 (0)	22 (0)	26 (38)	355 (1)**	114 (0)	0 (0)

Transect #	1978									
	23 June	5 July	15 July	25 July	5/6 August	15 August	25 August	5 September	15 September	23 September
1	0 (0)	0 (0)	0 (0)	0 (0)	0 (0)	0 (0)	9 (0)	0 (0)	0 (0)	0 (0)
2	3 (0)	12 (0)	12 (4)	3 (0)	2 (3)	35 (3)	0 (0)	0 (0)	0 (0)	0 (0)
3	0 (0)	0 (0)	0 (0)	0 (0)	0 (0)	0 (0)	0 (0)	0 (0)	0 (0)	0 (0)
4	0 (0)	0 (0)	2 (0)	0 (0)	0 (0)	0 (0)	0 (0)	0 (0)	0 (0)	0 (0)
5	0 (0)	0 (0)	1 (0)	0 (0)	0 (0)	0 (0)	0 (0)	0 (0)	0 (0)	0 (0)
Total	3 (0)	12 (0)	15 (4)	3 (0)	2 (3)	35 (3)	9 (0)	0 (0)	0 (0)	0 (0)

* Transects 1 and 3 were surveyed on 29 July 1977; Transects 2, 4 and 5 were surveyed on 28 July 1977.

† Parentheses enclose the number of terns recorded off-transect (>200 m from either side of the aircraft). Numbers to the left of parentheses are birds seen on-transect.

**Minimum number.

Glaucous Gull

Of the total of 1112 glaucous gulls recorded during aerial surveys in Simpson Lagoon during 1978, 95.1% (1058) were seen at shoreline locations (Transects 2 and 5) and 80.9% (856) of these birds were observed along barrier island shorelines (Transect 2; Table 26).

Although mid-lagoon waters were little used in either year, considerably more glaucous gulls were recorded at mid-lagoon locations in Simpson Lagoon during 1978 than during 1977 (20 during 1978; two during 1977). Only six glaucous gulls were seen during 1978 along the transect seaward of the Jones Islands, and only four were seen there during 1977. Similarly, a total of only 28 glaucous gulls were seen in 1978 during surveys of the mainland tundra transect approximately 7 km inland from Simpson Lagoon; 27 were seen there during surveys in 1977 (a few glaucous gulls nest at inland locations).

During 1977, the number of glaucous gulls recorded in shoreline habitats of the study area within any one survey did not exceed 23 birds (1.6 birds/km^2; Transect 2; 5 July 1977) until 28 July. On this date a total of 98 glaucous gulls (3.5 birds/km^2) were recorded along the barrier islands (Table 24).

By 15 August 1977, the density of glaucous gulls along the barrier islands had more than doubled since the previous survey (from 3.5 to 7.5/km^2). The 112 glaucous gulls seen along the barrier islands on 15 August represented 88% of the total number recorded during the aerial survey on that date. The mid-lagoon portion of the study area was not surveyed on 15 August, but along the mainland shoreline the number of glaucous gulls had declined from 7.6 to 1.1 birds/km^2 (from 98 to 14 birds seen on-transect).

By 30 August 1977, the number of glaucous gulls observed in the study area had increased most markedly along the barrier islands (Transect 2), where a density of 25.6 birds/km^2 (377 gulls) was recorded. The number of glaucous gulls seen on this transect represented 95% (377 of 399 gulls) of the total number seen on-transect

Table 26. Total Numbers of Glaucous Gulls Recorded in All Habitats During Aerial Surveys of Five Transects in the Jones Islands-Simpson Lagoon Area, 5 June to 22 September 1977 and 23 June to 23 September 1978.

	1977						
Transect #	5 June	20 June	5 July	28/29 July*	15 August	30 August	22 September
1	0 (0)+	0 (0)	0 (0)	1 (0)	- (-)	1 (25)	0 (0)
2	20 (0)	2 (0)	23 (0)	52 (4)	112 (0)	377 (44)	2857 (52)
3	1 (1)	0 (0)	0 (0)	0 (0)	- (-)	0 (0)	0 (0)
4	1 (1)	2 (0)	4 (1)	98 (1)	14 (0)	18 (0)	240 (5)
5	2 (1)	3 (0)	1 (3)	2 (0)	1 (1)	3 (0)	0 (0)
TOTAL	24 (3)	7 (0)	28 (4)	153 (5)	127 (1)	399 (69)	3097 (57)

	1978									
Transect #	23 June	5 July	15 July	25 July	5/6 August	15 August	25 August	5 September	15 September	23 September
1	1 (0)	2 (0)	1 (0)	0 (0)	0 (0)	0 (0)	0 (1)	0 (0)	1 (0)	0 (0)
2	34 (0)	23 (8)	48 (18)	61 (2)	1 (12)	13 (37)	0 (4)	66 (121)	93 (61)	238 (16)
3	0 (0)	0 (0)	0 (1)	16 (0)	0 (0)	0 (0)	1 (1)	0 (0)	0 (0)	1 (0)
4	1 (0)	1 (1)	25 (0)	67 (51)	2 (0)	5 (2)	2 (0)	9 (5)	1 (3)	18 (9)
5	0 (0)	0 (6)	0 (3)	0 (4)	0 (8)	1 (0)	1 (1)	1 (1)	1 (0)	1 (0)
TOTAL	36 (0)	26 (15)	74 (22)	144 (57)	3 (20)	19 (39)	4 (7)	76 (127)	96 (64)	258 (25)

*Transects 1 and 3 were surveyed on 29 July 1977; Transects 2, 4 and 5 were surveyed on 28 July 1977.

+Parentheses enclose the number of glaucous gulls recorded 'off-transect' (>200 m from either side of the aircraft). Numbers to the left of the parentheses are birds seen on-transect.

during this aerial survey. The estimated total number of glaucous gulls present along the barrier islands on 1 September 1977 (451 birds; see Table 22), based on the surveys of barrier island beach transects, was remarkably similar to the number recorded on and off-transect during the 30 August 1977 aerial survey (421 birds, see Table 26). The shoreline surveys indicated that most gulls were along the seward beaches of the islands.

The estimated total number of glaucous gulls present along the barrier islands on 14 September 1977, during the final beach survey was 58 birds (Table 24). This number represented a substantial decrease from numbers observed and estimated for 30 August and 1 September 1977.

During the period 18-20 September 1977, the ponds and lakes on the mainland tundra of the North Slope froze over and no open water was available to gulls at inland locations. Consequently, the estimated and observed numbers of glaucous gulls (and oldsquaws, see above) present in the study area were higher during the 22 September 1977 aerial survey than on any other date during 1977 (or during the entire study). In view of the low numbers of glaucous gulls present during the 14 September beach survey (Table 24), this increase apparently occurred during the period between 14 and 22 September. Of the 3099 glaucous gulls observed on 22 September 1977, approximately 95% (2857 birds) were along the barrier islands (Transect 2; Table 26). This number represents a density of 192.0 glaucous gulls/km^2--the highest density of this species recorded during the entire study. On this date 240 glaucous gulls (13.5 birds/km^2) were recorded along the mainland shoreline.

In 1978, the number of glaucous gulls recorded on-transect in shoreline habitats, along both barrier islands and the mainland shoreline, increased to a peak of 138 birds (5.0 birds/km^2) on 25 July. Thereafter the number of glaucous gulls on-transect in all lagoon habitats did not exceed 18 birds (0.46 birds/km^2; 15 August 1978; Table 24) until the 5 September aerial survey when 66 birds (4.5 birds/km^2) were recorded along the barrier island transect (Table 26). Two days earlier (3 September) a density of 5.4 glaucous gulls/km was recorded on shoreline transects south of the barrier islands; this density extrapolated to an estimated total of 185 gulls present along the entire length of the lagoonside beaches of the Jones Islands (Table 24). During 1978, the final shoreline surveys were conducted on 3 September. However, during the last two aerial surveys, on 15 and 23 September, the number of glaucous gulls present along lagoonside beaches of the barrier islands increased to the highest levels recorded in the study area during 1978; 93 birds (6.3 birds/km^2) and 238 birds (16.1 birds/km^2), respectively. This late-season increase of glaucous gulls along the barrier islands, although of lower amplitude, follows the same general trend in distribution and abundance as was observed during 1977 (Tables 22, 24 and 26). Very few glaucous gulls were recorded in areas away from the Jones Islands during these last two aerial surveys (see Table 26).

No glaucous gulls were collected during 1978; however, of the 27 collected in Simpson Lagoon during the 16 July to 19 September 1977 period, eight were adult males and one was a two-year old male. Eleven female glaucous gulls, nine of which were adults, and seven subadult glaucous gulls (two one-year-old birds and five juveniles) were also collected.

Feeding Studies

Oldsquaw

Of the 91 oldsquaws collected as part of the feeding ecology investigations during 1977, 15 had empty stomachs and 18 had only unidentifiable material present in their stomachs. Four birds were accidentally captured in gill nets and may have regurgitated some food while drowning; these birds were omitted from the stomach analyses. The average diet of the remaining 54 birds included, on a percent estimated volume basis, 58.7% mysids and 14.2% amphipods (Table 27). The remaining portions of the diet of oldsquaws during 1977 consisted primarily of bivalves (8.1%), isopods (2.3%), small fishes (2.3%), and a relatively large proportion of unidentifiable material (14.2%) (Table 27).

The results of the oldsquaw feeding ecology studies conducted in Simpson Lagoon during 1978 indicate a surprising level of similarity to 1977 results. Of the 108 oldsquaws collected during 1978, 34 had empty stomachs and two had only unidentifiable material present in their stomachs. The average diet of the remaining 72 birds included, on a percent estimated volume basis, 68.5% mysids and 15.5% amphipods (Table 27). The remaining portions of the oldsquaw diet during 1978 consisted primarily of bivalves (12.1%). Unlike the 1977 oldsquaw diet, the proportion of the 1978 diet that was comprised of unidentifiable material (1.5%) was small (Table 27).

Griffiths and Craig (1978) discussed the limitations and biases associated with conventional equipment and procedures used in sampling marine zooplankton and epibenthic animals. Epibenthic invertebrates of the types important to oldsquaws are especially difficult to sample quantitatively. Methods used to sample such animals in 1978 were much improved over those used during 1977. These problems should be considered when interpreting the data concerning food availability.

During 1977, few mysids or amphipods were collected from the surface-waters of the lagoon (see Johnson 1978, Fig. 3). This evidence, plus observations of the diving behavior of oldsquaws, indicates that oldsquaws probably rarely feed in this layer. The predominant invertebrate taxa present in the surface layer during

Table 27. A Comparison of Food Organisms Consumed by Oldsquaws Throughout the Season at Simpson Lagoon, Alaska, During 1977 and 1978.

	1977 (n=54; total points=443*)		1978 (n=72; total points=422)	
	% Total	% Total Identifiable	% Total	% Total Identifiable
Mysids	58.7	68.4	68.5	69.5
Amphipods	14.2	16.6	15.5	15.7
Bivalves	8.1	9.5	12.1	12.3
Isopods	2.3	2.6	1.0	1.0
Fish	2.3	2.6	0.2	0.2
Copepods	0.1	0.1	0.2	0.2
Polychaetes	0	0	0.7	0.7
Euphausiids	0	0	0.2	0.2
Priapulids	0	0	0.1	0.1
Tunicates	0	0	0.1	0.1
Unidentifiable	14.2	-	1.5	-
TOTAL	99.9	99.8	100.1	100.0

*See Griffiths *et al.* (1975) for a description of the points method for assessing the relative importance of food organisms.

1977 were, on an estimated percent of total volume basis, copepods (68.1%) and cnidarians (16.7%). Small proportions of amphipods (5.7%) and chaetognaths (3.3%) comprised most of the remainder of the organisms collected in this habitat (see Johnson 1978, Fig. 3).

Copepods also represented almost two-thirds (64.4%) of the total volume of invertebrate organisms present in the mid-water habitat samples collected during 1977 (see Johnson 1978, Fig. 3); this proportion of copepods was similar to that found in the surface water samples. Mysids and amphipods both comprised larger proportions (11.7 and 9.4%, respectively) of the mid-water samples than of the surface samples. Cnidarians, chaetognaths and ctenophores comprised the major proportion of the remainder of the mid-water samples during 1977.

Copepods, mysids and amphipods comprised the major proportions (33.8, 28.1 and 27.5%, respectively) of the epibenthic samples collected during 1977 (Table 28). Observations by a SCUBA diver at several locations in Simpson Lagoon during 1977 (and 1978), including a series of dives where flocks of oldsquaws had been feeding, indicated that mysids and amphipods were the most conspicuous invertebrate organisms present in the epibenthos (Griffiths and Craig 1978; Griffiths and Dillinger 1979).

Because both mysids and amphipods, the organisms that comprised the major proportions of the diet of oldsquaws during 1977, were proportionately most abundant in the lagoon epibenthos, it is probable that oldsquaws fed from this habitat rather than from either the surface or the mid-water layers, where mysids and amphipods were relatively uncommon. Copepods are extremely small, and although they comprised one-third of the volume of samples collected from the epibenthos during 1977*, they were not

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*The device used to sample the epibenthos during 1977 was a small (0.25 m^2) circular plankton net. This net sampled while being lowered to and retrieved from the epibenthos, and may have collected some copepods from the surface and mid-water layers of the lagoon.

Table 28. A Comparison of Oldsquaw Total Season Diet and the Composition of Oldsquaw Epibenthic Feeding Habitat Samples in the Jones Islands-Simpson Lagoon Area of Alaska During 1977 and 1978.

Taxon	1977		1978	
	Oldsquaw Diet (n = 54; total points* = 443)	Epibenthic Habitat Samples (n = 8; total points = 160)	Oldsquaw Diet (n = 72; total points = 422)	Epibenthic Habitat Samples (n = 39; total points = 166½)
	% Total	% Total	% Total	% Total
Mysids	58.7	28.1	68.5	48.9
Amphipods	14.2	27.5	15.5	36.6
Bivalves	8.1	1.9	12.1	7.1
Isopods	2.3	0	1.0	1.4
Fishes	2.3	0	0.2	0.3
Copepods	0.1	33.8	0.2	0.5
Polychaets	0	1.9	0.7	2.4
Euphausiids	0	0	0.2	0
Priapulids	0	0	0.1	1.1
Tunicates	0	0	0.1	0.6
Cnidarians	0	2.5	0	0.8
Pteropods	0	3.1	0	0
Ostracods	0	0.6	0	0
Foraminiferans	0	0.6	0	0
Sponges	0	0	0	0.1
Chaetognaths	0	0	0	0.1
Cumaceans	0	0	0	0.1
Unidentifiable	14.2	0	1.5	0
TOTAL	99.9	100.0	100.1	100.0

*See Griffiths *et al.* (1975) for a description of the points method for assessing the relative importance of food organisms.

observed by the divers during that year in the epibenthos. Possibly for the same reason (small and difficult to detect by feeding oldsquaws) copepods did not comprise a significant proportion of the diet of oldsquaws during 1977 (see Table 27 and Johnson 1978, Fig. 3). The very small proportion of copepods in the diet during 1977 may have been taken incidentally during the process of feeding on other epibenthic invertebrates.

Studies conducted during 1977 indicated that oldsquaws were feeding primarily from the epibenthos; samples, therefore, were collected only from this region of the lagoon during 1978. Gear used to sample the epibenthos (see Methods section) during 1977 and 1978 were different; therefore, comparisons of the data from these two years should be made with caution.

During 1978 the relative abundance and importance of the invertebrate taxa present in the epibenthos when and where feeding oldsquaws were collected was more similar to that found in oldsquaw stomachs than was the case during 1977 (Table 28). Probably because more effective sampling gear was used during 1978, the apparent importance of copepods in the epibenthos was markedly lower during 1978 (0.5% of estimated volume) than in 1977 (33.8%).

Mysids and amphipods collectively comprised 85.5% of the estimated volume of invertebrates in the 1978 epibenthos samples. Although the drop net sampling technique (see Griffiths and Dillinger 1979) was not an adequate infaunal sampler, a notably larger proportion of the volume of samples consisted of bivalves in 1978 (7.1%) than in 1977 (1.9%). Table 28 gives a comparison for both 1977 and 1978 of the major taxa present in the stomachs of oldsquaws and in the corresponding epibenthic feeding habitat samples in Simpson Lagoon. The results from 1978, when more effective epibenthic sampling gear was used, show the close relationship between the relative volumes of major invertebrate taxa in oldsquaw stomachs and in feeding habitats. In both 1977 and 1978, the relative proportions of mysids found in oldsquaw stomachs were approximately twice those found in feeding habitats. Similarly, during both 1977 and 1978, the proportions of amphipods in oldsquaw stomachs were about half those found in feeding habitats.

When stomach contents of oldsquaws collected at one place and time were compared with food availability in the epibenthos at that same place and time, a positive and highly significant correlation was found (Fig. 6A). Oldsquaws were more effective predators in areas where prey organism were present in relatively high densities. The total density of prey organisms (on a dry weight/m^2 basis) used in this analysis include not only mysids and amphipods, but also bivalves and an array of relatively less abundant organisms that are probably taken only incidentally by feeding oldsquaws. However, the correlation remained significant when only mysids, the single most important taxon in the diet of oldsquaws were considered (Fig. 6B).

Data from both 1977 and 1978 indicate that the mean sizes of mysids and amphipods consumed by oldsquaws are significantly larger than the mean sizes of the same species found in oldsquaw feeding habitat samples (see Johnson 1978:82 and Fig. 7 of this report). In 1978, the mean lengths of *Mysis litoralis*, *M. relicta* and *O. glacialis* in oldsquaw stomachs were all significantly greater than the mean lengths of these taxa in corresponding habitat samples (Wilcoxon matched-pairs tests; $P<0.01$; $P<0.02$ and $P<0.01$, respectively). Hence, feeding oldsquaws apparently tend to select larger individuals of at least the most common prey species (mysids and amphipods) found in epibenthic feeding habitats.

During 1978, a major effort was made to conduct detailed laboratory analyses of the invertebrates consumed by oldsquaws and found in their feeding habitat samples (see Griffiths and Dillinger 1979). Table 29 gives a comparison of the proportions of

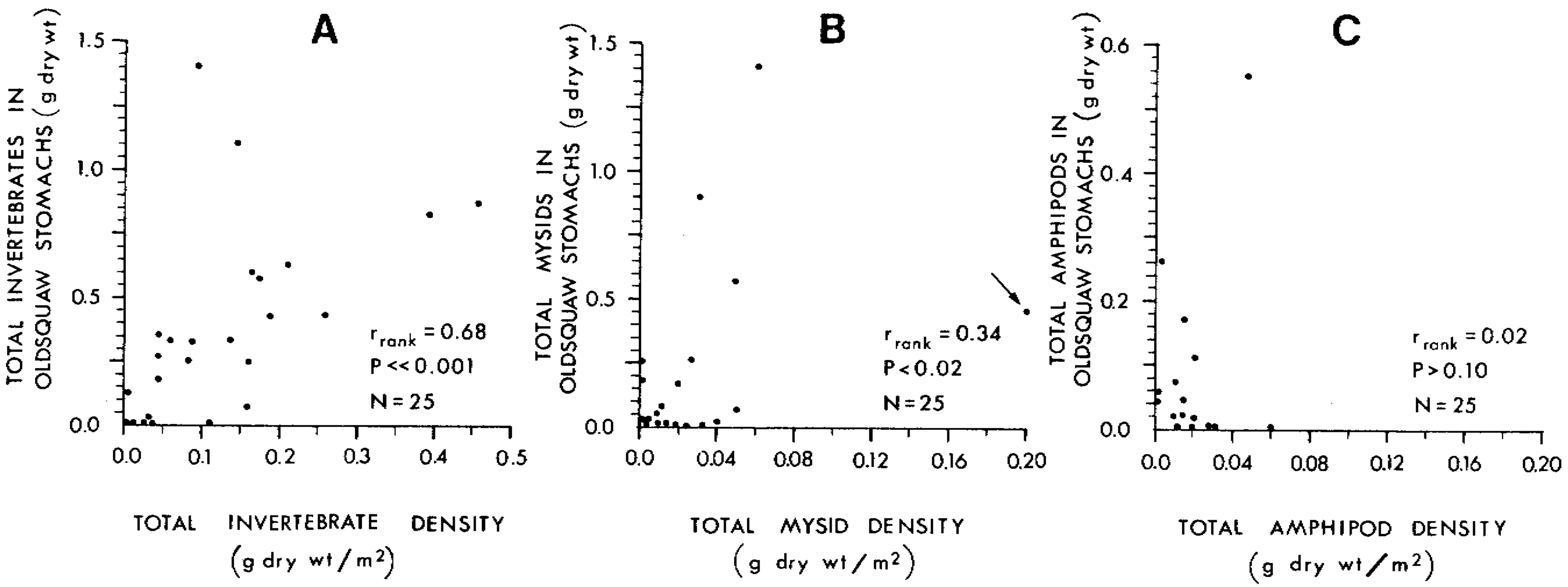

Figure 6. The Relationship Between the Density of Invertebrates in Oldsquaw Feeding Habitats and the Amount of Invertebrates Consumed by Oldsquaws in Simpson Lagoon, Alaska.

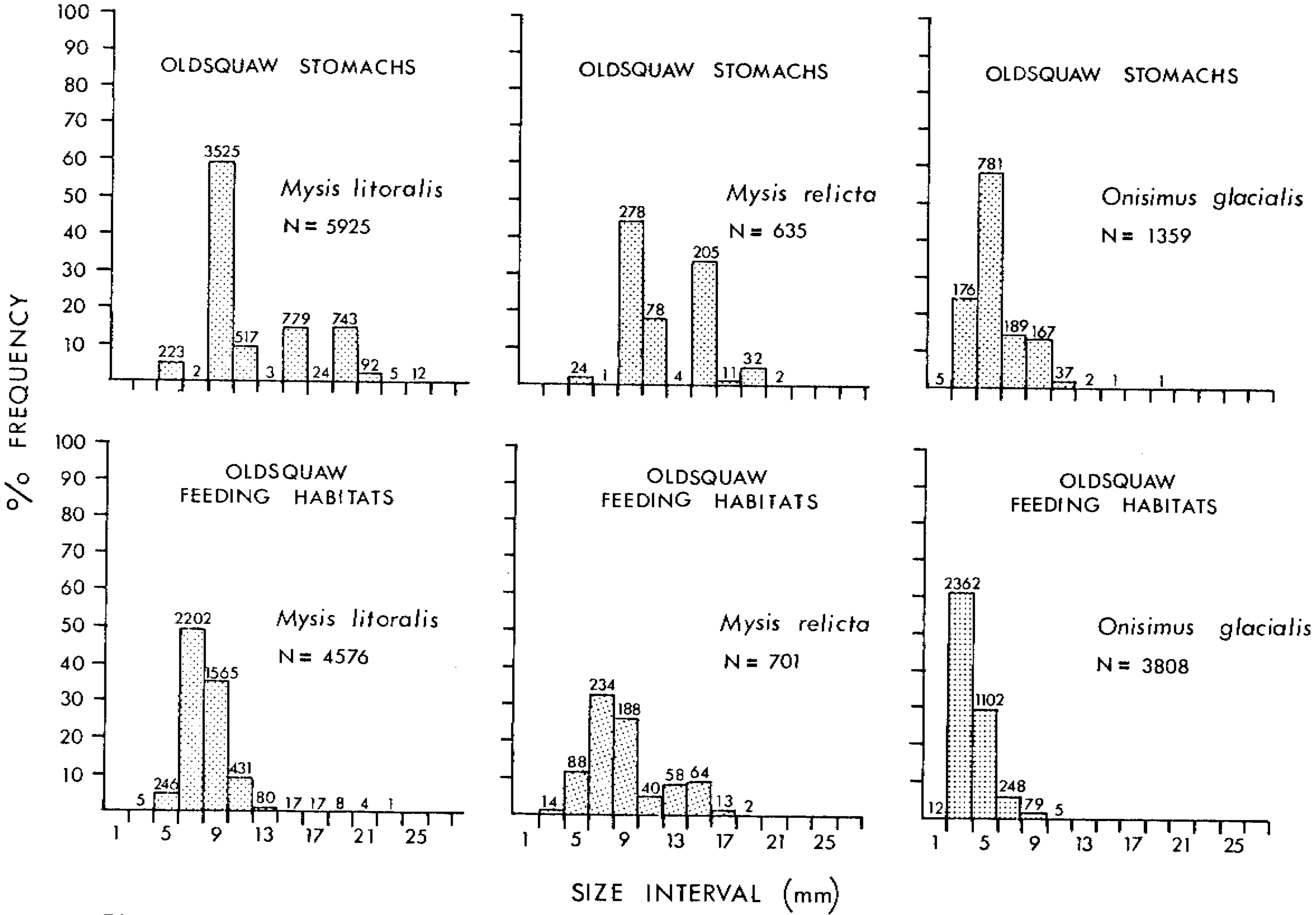

Figure 7. A Comparison of the Distributions of Sizes of the Three Most Important Invertebrate Prey Species Consumed by Oldsquaws and Found in Oldsquaw Feeding Habitats.

Table 29. The Diet of Oldsquaws in Simpson Lagoon During 1978 as Determined by Estimated Relative Volume, Abundance, Wet Weight Biomass, Dry Weight Biomass and Energy Content.

	Volume		Abundance		Wet Weight		Ash-free Dry Weight		Energy Content	
	Points*	%	#	%	g	%	g	%	kcal	%
Mysids	289	68.5	6464	75.0	155.1	77.4	17.9	69.7	97.5	69.8
Amphipods	65 ¼	15.5	1845	21.4	23.7	11.8	4.2	16.3	21.3	15.3
Bivalves	51 ¼	12.1	260	3.0	13.3	6.6	2.6	10.1	14.7	10.5
Other Taxa	16 ½	3.9	48	0.6	8.3	4.1	1.0	3.9	6.1	4.4
Total	422	100.0	8617	100.0	200.4	99.9	25.7	100.0	139.6	100.0

*See Griffiths *et al.* (1975) for a description of the points method for assessing the relative importance of food organisms. Points listed in this table are only those of identifiable taxa; the unidentified portions of stomach contents are presumed to be comprised of remnants of organisms of the same taxa and present in the same proportions as those in the identified portions of stomach contents.

these major taxa found in oldsquaw stomachs as determined by precise measurements of wet weight, ash-free dry weight, energy content (kilocalories) and abundance (total numbers of individuals) as well as the less precise and more qualitative modified Hynes point method (Hynes 1950; Griffiths *et al.* 1975). This comparison suggests that the qualitative Hynes point method used in both 1977 and 1978, when compared with the more precise and quantitative approaches to stomach analyses was a relatively accurate indicator of the proportions and importance of various major taxa of prey organisms consumed.

Craig and Griffiths (1978b) examined the similarity of the stomach contents of the key bird and fish species present in Simpson Lagoon during 1977. The results of that analysis show that the diet of oldsquaws was very similar to the diets of arctic cisco (0.98 on a similarity scale ranging from a low of 0.00 to a high of 1.00), fourhorn sculpin (0.96) and arctic cod (0.92), and less similar to the diets of the least cisco (0.80) and the arctic char (0.75). No such comparison has yet been made between oldsquaws and fishes collected during the 1978 sampling season.

Phalaropes

Of the 83 red and northern phalaropes collected in the study area during the 3 to 24 August 1977 period, 62 birds had food organisms in their stomachs when they were collected. Almost one-third (30%) of their stomach contents was unidentifiable material. The major components of the identifiable portion were copepods (40%), amphipods (14.0%) and mysids (14.0%; Table 30). The remainder of the diet was comprised of very small amounts of fish (striated muscle), and small amounts of pteropods and insects.

Table 30. A Comparison of Phalarope* Total Season Diet and the Composition of Phalarope Feeding Habitat Samples in the Jones Islands-Simpson Lagoon Area of Alaska During 1977 and 1978.

	1977		1978	
	Phalarope Diet (n=46; points** = 269¾)	Feeding Habitat Samples (n=17; points = 140)	Phalarope Diet (n=26; points = 197¾)	Feeding Habitat Samples (n=30; points = 111¾)
Taxon	%	%	%	%
Copepod	40.2	31.1	22.6	12.3
Amphipod	14.0	12.1	72.6	13.9
Mysid	14.0	26.1	2.5	71.8
Chaetognaths	0.0	12.9	0.0	0.9
Euphausiids	0.2	1.1	0.0	0.4
Cnidaria	0.0	10.0	0.0	0.0
Fish	0.0	4.3	0.0	0.7
Pteropods	0.7	2.1	0.0	0.0
Decapod	0.0	0.4	0.0	0.0
Branchiopods	0.2	0.0	0.0	0.0
Insect	0.6	0.0	0.0	0.0
Unidentifiable	30.0	0.0	2.3	0.0
Total	99.9	100.1	100	100.0

*Northern phalarope and red phalarope have been treated as a single group.

**See Griffiths *et al.* (1975) for a description of the points method for assessing the relative importance of food organisms.

Organisms collected from phalarope feeding habitats during 1977 were in proportions similar to those found in phalarope stomachs (Table 30). Copepods comprised the largest proportion (31.1%), with mysids (26.1%) and amphipods (12.1%) also present in significant proportions. These data suggest that when phalaropes fed along lagoon shorelines during 1977, they consumed small organisms in approximately the same proportions in which they were present. The apparent absence of cnidarians from stomachs was probably artifactual; these animals are very fragile, and phalaropes were observed to feed upon them (Johnson 1978). Similarly, chaetognaths comprised an estimated 12.9% of the food volume available in feeding habitats during 1977, but were not identified in the phalarope stomachs collected that year.

Of the 59 red and northern phalaropes collected in the Simpson Lagoon study area during the 6 August to 3 September 1978 period, 27 had food organisms in their stomachs. Unlike 1977, only a small proportion of the diet during 1978 was comprised of unidentifiable material (2.3% vs 30.0%). Almost three-fourths (72.6%) of the 1978 diet of phalaropes was comprised of amphipods, even though mysids represented a much larger proportion of the organisms (on a volume basis) in the habitat samples (Table 30). This result is quite different from that in 1977 when copepods represented slightly over 40% of the diet of phalaropes and represented 31.1% of the estimated volume of the organisms in phalarope feeding habitat samples (Table 30). In 1978, copepods represented only 12.3% of the food available.

Hence, during 1977, phalaropes fed on organisms approximately in the same proportions as the organisms occurred along the shorelines where these birds fed; copepods were the most important and the most available prey. During 1978, however, phalaropes preyed selectively on small amphipods and copepods, both of which were approximately five times less abundant than mysids, which represented a very small proportion of the phalarope diet (Table 30).

Comparisons of the diets of major bird and fish species collected during 1977 showed that the diet of northern phalaropes was most similar to that of arctic char (0.78), least cisco (0.74) and red phalaropes (0.74; Craig and Griffiths 1978). During 1977 the diet of red phalaropes was most similar to that of northern phalaropes (0.74) and fourhorn sculpins (0.57). Similar comparisons of the 1978 diet of phalaropes have not yet been made.

Glaucous Gull

The glaucous gull was initially considered a key species and a small sample was collected during 1977; however, no glaucous gulls were collected during 1978. Of the 28 glaucous gulls collected during the 16 July to 19 September 1977 period, all but one was collected along the shoreline of a barrier island or the mainland; the one glaucous gull collected at a mid-lagoon location had an empty stomach. The diets of the remaining 27 glaucous gulls consisted largely of isopods (33.4% of the volume), amphipods (22.8%), small birds (18.1%) and small fish (11.7%) (Table 31). Mysids and copepods comprised smaller proportions of the diet of glaucous gulls (6.7% and 3.1%, respectively). Euphausiids, bivalves, tunicates, hydroids and unidentifiable materials, all in small proportions, comprised the remainder of the diet. The diverse nature of the diet of this species, which included organisms ranging in size from small copepods and mysids to larger organisms such as isopods, small fish and small birds, suggests that glaucous gulls feed opportunistically along shorelines in the lagoons.

Table 31. A Comparison of the Organisms Found in the Stomachs and in the Feeding Habitat Sample of Glaucous Gulls in the Simpson Lagoon Area of Alaska, 16 July to 19 September 1977.

Taxon	% Total Contents of Stomach (n=27; points=193*)	% Total Contents of Habitat Samples (n=7; points=140)
Mysids	6.7	11.8
Amphipods	22.8	8.2
Isopods	33.4	0.2
Copepods	3.1	48.6
Bivalves	0.5	0.0
Fish	11.7	3.6
Cnidaria (Medusae)	0	6.8
Pteropods	0	2.1
Chaetognaths	0	12.5
Euphausiids	1.0	2.0
Decapod Larvae	0	0.2
Tunicates	0.5	0.0
Tunicate Larvae	0	0.5
Hydroids	0.3	0
Larvaceans	0	0.2
Cumacean	0	0.9
Oligochaete	0	0.7
Ctenophore	0	1.3
Birds	18.1	0
Unidentified	1.8	0
TOTAL	99.9	100.1

*See Griffiths *et al.* 1975 for a description of the points method of assessing the relative importance of food organisms.

The relative proportions of invertebrates collected in shallow waters along shorelines where the glaucous gulls were feeding bore little resemblance to the relative proportions of invertebrates in the glaucous gull stomachs (Table 31). The most conspicuous invertebrates where glaucous gulls fed were copepods (48.6%), chaetognaths (12.5%), mysids (11.8%), amphipods (8.2%) and cnidarians (6.8%). Isopods, which comprised 33.4% of the total diet of glaucous gulls, represented only 0.2% of the available food.

The analysis of dietary overlap in glaucous gulls and the key fish species found in Simpson Lagoon (Craig and Griffiths 1978) indicated that the diet of glaucous gulls was most similar to that of the least cisco (0.64).

Recommended Further Research

This part of the Barrier Island-Lagoon Program will be updated and revised during the next few months after further analysis of data. This revised version will be included as a chapter in the final report, which is scheduled for completion by 30 September 1979.

Summary of 4th Quarter Operations

The fourth quarter was spent preparing the annual report.

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Appendix I. Numbers of Charadriiformes Sighted on a Frequently Surveyed Shoreline Transect* on Pingok Island, Alaska, During 1977 and 1978.

	SPECIES																							
	Black-bellied Plover		Ruddy Turnstone		Pectoral Sandpiper		Baird's Sandpiper		Dunlin		Semipalmated Sandpiper		Sanderling		Red Phalarope		Northern Phalarope		All Phalaropes		Glaucous Gull		Arctic Tern	
Date	1977	1978	1977	1978	1977	1978	1977	1978	1977	1978	1977	1978	1977	1978	1977	1978	1977	1978	1977	1978	1977	1978	1977	1978
August																								
2	0	0	0	0	0	0	1	0	2	0	29	0	0	0	4	0	-	0	4	0	0	0	0	0
3	0	-	1	-	0	-	5	-	1	-	2	-	0	-	77	-	53	-	130	-	0	-	0	-
4	-	0	-	0	-	0	-	0	-	0	-	0	-	0	-	1	-	0	-	0	-	1	-	0
6	0	-	7	-	0	-	1	-	0	-	0	-	0	-	193	-	60	-	253	-	1	-	3	-
7	-	0	-	0	-	0	-	0	-	0	-	0	-	0	-	0	-	0	-	0	-	0	-	0
8	0	-	18	-	0	-	1	-	0	-	1	-	0	-	525	-	51	-	686	-	0	-	1	-
9	-	0	-	0	-	0	-	0	-	0	-	0	-	0	-	0	-	0	-	0	-	0	-	0
10	0	-	5	-	0	-	0	-	0	-	0	-	0	-	0	-	0	-	338	-	3	-	0	-
11	-	0	-	0	-	0	-	0	-	3	-	0	-	0	-	30	-	0	-	33	-	0	-	0
12	0	-	1	-	3	-	6	-	1	-	1	-	0	-	69	-	23	-	116	-	0	-	0	-
13	-	0	-	1	-	0	-	0	-	0	-	0	-	0	-	4	-	0	-	4	-	0	-	0
14	0	2	11	0	6	0	3	0	29	2	6	0	0	0	16	7	0	0	16	0	0	-	0	-
17	-	0	-	0	-	0	-	0	-	0	-	0	-	0	-	4	-	0	-	4	-	0	-	0
19	-	0	-	0	-	0	-	0	-	0	-	0	-	0	-	26	-	8	-	34	-	0	-	0
21	-	0	-	0	-	0	-	0	-	0	-	0	-	0	-	0	-	0	-	0	-	0	-	0
23	0	-	0	-	2	-	0	-	13	-	0	-	0	-	262	-	52	-	364	-	0	-	60	0
24	-	0	-	0	-	0	-	0	-	0	-	0	-	0	-	0	-	0	-	0	-	0	-	0
26	2	0	0	1	2	0	0	0	7	5	0	0	1	0	24	7	17	1	41	8	6	0	15	0
28	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0
31	4	2	0	-	0	0	0	0	9	8	0	0	3	0	0	0	0	0	0	238	1	0	26	0
September																								
2	3	2	0	2	0	0	0	0	9	6	1	0	5	1	0	0	0	0	0	0	0	0	0	0
3	-	2	-	0	-	0	-	0	-	0	-	0	-	0	-	3	-	1	-	4	-	12	-	3
4	0	-	0	-	0	-	0	-	0	-	0	-	1	-	0	-	0	-	0	-	0	-	0	-
6	0	-	2	-	0	-	0	-	37	-	0	-	0	-	0	-	0	-	0	-	2	-	0	-
8	1	-	0	-	0	-	0	-	0	-	0	-	3	-	0	-	0	-	0	-	0	-	0	-
12	6	-	0	-	0	-	0	-	66	-	0	-	17	-	17	-	0	-	17	-	18	-	0	-
16	0	-	0	-	0	-	0	-	0	-	0	-	0	-	0	-	0	-	0	-	0	-	0	-
18	6	-	0	-	0	-	0	-	2	-	0	-	2	-	0	-	0	-	0	-	2	-	0	-

*This transect was located along the lagoonside shoreline of Pingok Island, (see Fig. 1). The dimensions of this transect, 1.2 km x 20 m (0.024 km^2), were slightly different from other shoreline transects.

Appendix 2. Methods of Estimating the Total Number of Oldsquaws Present in Simpson Lagoon, Beaufort Sea, Alaska, During 1977 and 1978.

Because of a difference in the aerial survey procedures between 1977 and 1978 (see Methods section), the methods of estimating the total number of oldsquaws present in Simpson Lagoon during these years were also different.

During aerial surveys conducted in 1977, lagoon Transects 2 and 4 were designed to sample largely lagoon habitats, but small amounts of barrier island and mainland habitats were also sampled on these transects. Oldsquaws observed in these terrestrial habitats were not included in oldsquaw density calculations. The mean densities of oldsquaws in lagoon habitats were extrapolated to the appropriate limits of similar habitats off-transect to arrive at an estimate of the total number of oldsquaws present in Simpson Lagoon.

During 1978, surveys of Transects 2 and 4 were redesigned to sample only lagoon habitats. This design enabled the numbers and densities of oldsquaws in lagoon habitats on each side of the aircraft (0-200 m and 200-400 m from shore) to be counted and calculated separately (this was not possible during 1977). Only the density of oldsquaws on the lagoon side of the aircraft was extrapolated to adjacent lagoon habitats. This provided an estimate that, when added to the total number of oldsquaws counted on the opposite side of the aircraft (the side immmediately adjacent to the shoreline), provided the best approximation of the total number of oldsquaws present in a given section of the lagoon.

Transect 3, located at mid-lagoon, was surveyed using identical procedures during both 1977 and 1978. Calculations and extrapolations of densities on this transect are straightforward.

The final estimate of the total number of oldsquaws present in Simpson Lagoon was calculated by simply totalling the estimated numbers present in habitats represented by Transects 2, 3 and 4 (see Table 14).

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BEAUFORT SEA BARRIER ISLAND-LAGOON
ECOLOGICAL PROCESS STUDIES

ECOLOGY OF FISHES IN SIMPSON LAGOON, BEAUFORT SEA, ALASKA

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TABLE OF CONTENTS

Page

SUMMARY vi

ACKNOWLEDGEMENTS viii

INTRODUCTION 1

General Nature and Scope of Study 1

Specific Objectives 1

CURRENT STATE OF KNOWLEDGE 2

STUDY AREA 2

The Annual Cycle 5

Temperature and Salinity 6

Turbidity 9

Dissolved Oxygen 9

METHODS AND RATIONALE OF DATA COLLECTION 9

Summer Methodology 11

Gill Nets 14

Fyke Nets 15

Faber Net 16

Beach Seine 16

Other Methods 17

Winter Methodology 19

Estimation of Daily Ration 19

Stomach Evacuation Rate 24

Feeding Periodicity 24

Physical and Chemical Measurements 25

RESULTS AND DISCUSSION 25

Fish Populations in Simpson Lagoon 25

Species Composition 25

Relative Abundance 26

Biomass 30

Habitat Utilization 31

Nearshore Versus Offshore Distribution 33

The "Edge Effect" 37

The Shoreline Corridor 42

Summer Distribution 48

TABLE OF CONTENTS (cont'd)

Page

- Winter Distribution 50
  - Colville Delta 50
  - Coastal Areas 51
- Abundance of Fish Versus Physical Factors 53
- Fish Movements 55
  - Seasonal Movements 57
    - Arctic Cisco 59
    - Least Cisco 64
    - Arctic Char 65
    - Arctic Cod 66
    - Fourhorn Sculpin 66
    - Boreal Smelt 68
    - Broad and Humpback Whitefish 68
    - Pink Salmon 68
  - Residency Time in Simpson Lagoon 69
    - Pattern of Recaptures 69
    - Net Rate of Movement 72
- Fish Densities 73
  - Population Size and Structure of Arctic and Least Cisco .. 73
  - Estimated Densities of Combined Species 76
- Trophic Relationships 80
  - Feeding Periodicity 82
  - Gastric Evacuation Rate 85
  - Calculation of Daily Ration 87

CONCLUSIONS 89

RECOMMENDED FURTHER RESEARCH 91

SUMMARY OF 4th QUARTER OPERATIONS 93

LITERATURE CITED 94

APPENDIX 98

LIST OF TABLES

Table		Page
1	Descriptions of Sampling Gear.	13
2	Sampling Dates and Gear Used during Winter Surveys.	22
3	Physical Conditions at Winter Sampling Stations.	23
4	Relative Abundance of Fish Caught during the Open-water Season by Different Methods in Simpson Lagoon.	28
5	Comparisons of Gill Net Data at Five Sampling Locations During the Open Water Season, 1977.	35
6	Seasonal Densities of Young-of-the-Year Arctic Cod Collected by Faber Net during 1977.	36
7	Beach Seine Data for Mainland and Barrier Island Shorelines during the Open-Water Season, 1978.	38
8	Comparisons of Fyke Net Data for Mainland and Island Sites, 8 August to 21 September 1977.	40
9	Summary of Winter Catch Data, 1978-79.	52
10	Summary of Fishes Tagged in Simpson Lagoon, 1977 and 1978.	58
11	Tagging and Recapture Distribution of Fourhorn Sculpin in Simpson Lagoon, 1977 and 1978.	71
12	Estimates of the Catchable Populations of Arctic Cisco and Least Cisco in the Colville River Sea-going Population during 1976 and 1978.	75
13	Estimated Densities of Small Fish & Large Fish in Two Habitats in Simpson Lagoon, 1978.	79
14	Major Food Groups Eaten by Five Fish Species, Simpson Lagoon, 1977.	81
15	Age-Length Relationship and Age-Specific Maturity of Arctic Cod in Simpson Lagoon, 1977.	83

LIST OF FIGURES

Figure		Page
1	Map of Simpson Lagoon Area in Alaska, showing Locations of Sampling Stations in 1977 and 1978.	3
2	Temperatures and Salinity at Stations 1-5, 1977.	7
3	Temperatures and Salinity during 1978 at Stations 1, 3, 5, 6, and 7.	8
4	Turbidity Profiles at Milne Point, 1978.	10
5	Fish Sampling Gear used During Open-Water Studies.	12
6	Sites Sampled with a 91.4 m Beach Seine, 26 July - 1 September 1978.	18
7	Locations of Winter Gill Net Samples in the Colville Delta.	20
8	Winter Sampling Sites Between the Colville Delta and Narwhal Island.	21
9	Comparison of Relative Abundance and Biomass for the 1978 Fyke Net Catch.	32
10	Cross-Section of Simpson Lagoon Study Area Showing Relative Numbers of Fish Caught at 5 Sampling Stations, 1977.	34
11	Shoreline Distribution of Fish at Two Sites.	44
12	Distances of Fish from Shore off Points of Land on Seven Calm Days in 1978.	46
13	Distances of Three Anadromous Species of Fish from Shore off Points of Land on Seven Calm Days in 1978.	46
14	Dispersed Distribution of Anadromous Fish during Stormy, Rough-Water Conditions and in a Relatively Shallow Bay between Milne and Kavearak Points.	47
15	Hypothetical Density Distribution of Nearshore Fishes in the Study Area.	49
16	Seasonal Abundance of Fish Caught by Gill Net along Mainland and Pingok Island Shoreline, 1977.	60

LIST OF FIGURES (cont'd)

Figure Page

17 Comparison of Daily Fyke Net Catches along the Mainland Shoreline in 1977 and 1978. 62

18 Coastal Movements of Tagged Fish during a Single Year. 63

19 Comparisons of Daily Fyke Net Catches along the Mainland Shoreline in 1977 and 1978. 67

20 Size Distributions of Subsamples of Arctic Cisco Caught in the 1977 and 1978 Commercial Fishery, Colville Delta. 77

21 Feeding Periodicity and Daily Ration of Juvenile Arctic Cod in Simpson Lagoon. 84

22 Evacuation of Food from Stomachs of Juvenile Arctic Cod 86

LIST OF APPENDICES

Appendix Page

1 Tag and recapture data for fish recovered during this study, Simpson Lagoon 1977-8. 98

SUMMARY

The 1978 fisheries program consisted of both summer and winter studies in Simpson Lagoon and nearby waters. Data gathered during this field season substantiated some previous findings, refined others, and demonstrated the magnitude of year-to-year variability in fish populations that can occur in the lagoon. In addition, several observations in 1978 have substantially broadened our conception of fish utilization of nearshore Beaufort Sea waters.

In both 1977 and 1978, the same five fish species were identified as key species in the lagoon system (arctic cisco, least cisco, arctic char, arctic cod, fourhorn sculpin). Densities of fish were again highest along the mainland shoreline (0.01 fish/m^2, species combined), averaging 3.6 and 24 times greater, respectively, than densities of fish along lagoonside and oceanside shorelines of the barrier islands. Fish were often concentrated within 100 m of the mainland shore.

Despite similarities between data gathered in 1977 and 1978, several differences were recorded. For example, in 1978 eight new fish species were encountered, and there was a small-scale run of pink salmon, unlike the previous year when no salmon were caught. More importantly, however, in 1978 tremendous numbers of arctic cod, estimated to be several million (far greater than numbers encountered in 1977), entered Simpson Lagoon in mid-August. It appears possible that this large influx of fish, coupled with their daily food requirement of approximately 6% of their body weight per day (determined in field tests), may have contributed to a reduction in the biomass of mysids (favored food of the fish) that occurred in the lagoon at about this time. The superabundance of fish food that apparently occurred in Simpson Lagoon in 1977 may not be a representative condition in nearshore areas in some years; even so, biomass of invertebrate food resources in Simpson Lagoon appeared to be about two orders of magnitude greater than total food requirements of fish in the lagoon.

Winter studies showed that nearshore areas may provide important habitat for fish during winter months. In late winter (April 1978), both anadromous and marine fishes (arctic cisco, least cisco, fourhorn sculpin, boreal smelt, saffron cod) were caught in an overwintering site in the brackish waters of the lower Colville Delta (-1.0 to -1.5°C, 18 to 32 ppt salinity). In winter (November 1978 and February 1979), four marine fishes (arctic cod, boreal smelt, fourhorn sculpin, saffron cod) were caught under the ice in the Prudhoe Bay - Simpson Lagoon region. It appears, then, that nearshore waters are used in the winter by some marine species for feeding and/or spawning, and that selected nearshore sites are used by anadromous fish for feeding and overwintering. In summer, with the exception of shallow-water areas that freeze solid or become hypersaline, the nearshore coastal environment supports year-round populations of fish, though numbers, species composition and distribution differ between summer and winter periods.

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Special mention must be made of the unique contribution of Howard McElderry, who played an especially active and interested role in modifying and carrying out the field program. Jim Helmericks provided reliable logistical support and invaluable knowledge of arctic fish. Benny Gallaway and Joe Margraff contributed fresh ideas and insight into the design of the field program and the analyses of the results. Joe Truett and John Richardson provided useful editorial comments.

INTRODUCTION

General Nature and Scope of Study

The nearshore environment along the Beaufort Sea coastline provides essential habitat for several arctic fishes, particularly the anadromous species utilized by man. During the short arctic summer, large numbers of fish enter coastal waters and feed extensively on nearshore food resources. These fish must accumulate food reserves to support them through the arctic winter, and adult fish must reach a critical level of food reserves or they will not spawn (Bolotova 1976). During winter months, several species of marine fish use nearshore water for feeding and spawning.

Ongoing petroleum activities at Prudhoe Bay and the recent construction of the trans-Alaska pipeline demonstrate the nature of demands industry makes on arctic water and gravel resources, and the subsequent disruptions of habitat and inevitable oil spills. As part of the program to assess the environmental impacts of offshore petroleum development, it is necessary to understand the utilization of nearshore habitats by anadromous and marine fish populations.

The present study examines nearshore fishes and their ecological role in a barrier island-lagoon complex along the Beaufort Sea coast to evaluate in what ways petroleum development may affect fish populations. It is part of a more comprehensive program designed to study ecological processes as a means of assessing impacts of petroleum development. Truett (1978) provides a summary of the general objectives of the program.

Specific Objectives

Specific objectives of the program were to

1. determine habitat utilization in time and space by key fish species,

2. assess food sources and feeding dependencies of fishes in nearshore waters, and
3. determine species composition and life history characteristics of fishes in the barrier island-lagoon ecosystem.

CURRENT STATE OF KNOWLEDGE

Petroleum discoveries in the arctic have prompted a variety of fisheries studies over the past decade. Craig and McCart (1976) summarized much of the research done prior to 1976; more recent studies include those by Bendock (1977) and Doxey (1977). Topics such as species distribution, relative abundance, general food habits, age-length relationships and basic life-history data have been the emphasis of most studies, and a general picture of fish use of nearshore waters has gradually emerged. However, only recently has attention been paid to the problems of trophic relationships, locations of over-wintering areas, stock identification, effects of offshore petroleum development and resource management.

STUDY AREA

Simpson Lagoon, located between Prudhoe Bay and the Colville River delta on Alaska's North Slope (Fig. 1), is a large and partially enclosed body of water measuring approximately 35 km in length and 3 - 6 km in width. To the north, Simpson Lagoon is protected from direct ocean exposure by a chain of barrier islands in the Jones Island group. Some of these islands are composed of gravel and sand (Spy and Leavitt islands) while others are in addition partly covered by tundra (Pingok, Peat, Bertoncini, Bodfish and Cottle islands). The mainland forms the southern boundary of the lagoon and is characterized by slumping tundra banks (1.5 - 3.0 m in height) and narrow beaches composed of silt, sand and gravel.

There are three principal pathways for water exchange into and out of Simpson Lagoon: (1) the far western entrances between Spy

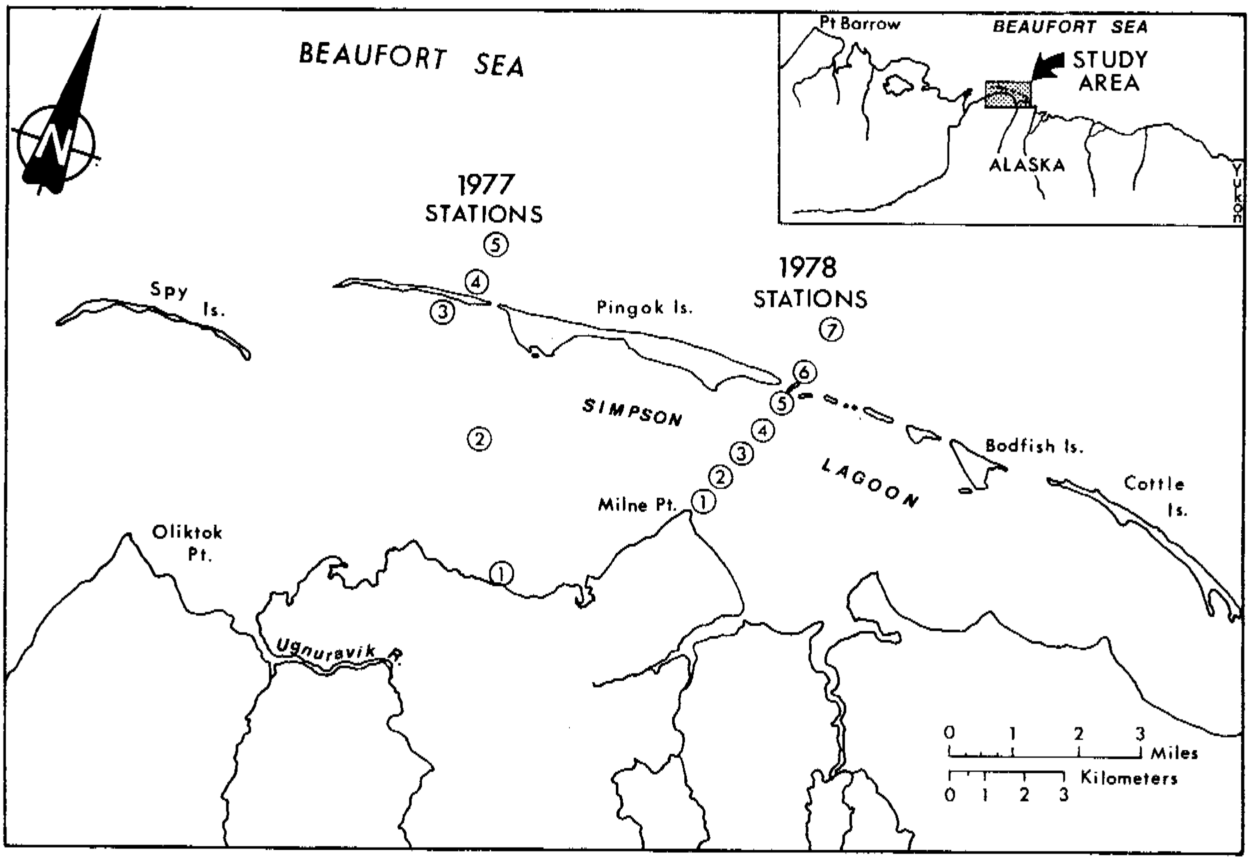

Figure 1. Map of Simpson Lagoon Area in Alaska, showing Locations of Sampling Stations in 1977 and 1978.

Island and Oliktok Point, (2) the large gap between Spy and Leavitt islands, and (3) the far eastern entrance between Cottle Island and Beechey Point. In addition, there are several small and shallow channels between the various islands. Flushing rates of lagoon waters are estimated at 10 - 20% exchange per day under normal conditions and up to 100% exchange per day during exceptionally strong winds (65 km/h) (Mungall 1978).

Although 14 small tundra creeks flow directly into Simpson Lagoon, water exchange in the lagoon during the open-water season is dominated by coastal currents of the Beaufort Sea. For much of that season, the waters flowing through the lagoon originate partly from North Slope rivers lying to the east of the study area. Because of prevailing easterly winds and westward-flowing currents, river waters discharged into the nearshore Beaufort Sea generally flow from east to west and remain in the nearshore zone. Thus, Alaska's largest North Slope river, the Colville, which empties into Harrison Bay immediately west of Simpson Lagoon, has surprisingly little direct hydrological influence on the lagoon despite the closeness of its discharge. During spring breakup in 1977 and 1978, overflow from the Colville did not enter the lagoon, and for the remainder of the season prevailing westward-flowing currents tended to carry the Colville's discharge to the west rather than through Simpson Lagoon. A reversal in the prevailing direction of nearshore currents occassionally occurs during the summer when storm winds blow from the west.

Simpson Lagoon is a shallow-water basin with an average depth of only 2 m and a maximum depth of 3 m. Outside Simpson Lagoon on the seaward side of Pingok Island, ocean depths drop to 2 m within 50 m of the shoreline and to 10 - 15 m within 1 km.

The lagoon floor is uniformly flat and almost featureless. In most areas, a layer of detritus covers substrates of mud and sand. The detrital layer, which varies in thickness up to 2 cm, is not consolidated, but consists of a flocculent, amorphous mass above which mysids and amphipods move about. Numerous small holes in the detritus are further signs of animal activity.

Some topographic relief on the lagoon floor is provided by shallow ice gouge marks in the central portion of the lagoon and occasional tundra clumps and piles of stones throughout. These stones, which measure approximately 2.5 cm in width, serve as a base for attached algae.

The Annual Cycle

The ice-free period in Simpson Lagoon is short, lasting about 3 months. Initial stages of spring breakup consist of flooding from the Kuparuk and Ugnuravik rivers in early June, and the formation of open water leads along mainland and island shorelines in mid-June. By late June and early July, the shorelead is 10 - 100 m wide with cold (0 - 4.5°C), clear and almost fresh waters (2.1 - 6.0 ppt). Most nearshore ice soon melts or is moved away by winds and currents, and the lagoon is 90% ice-free by mid-July.

Ocean ice may hold fast against the outside of the barrier islands until mid- or late July, at which time the ice is moved about 10 km offshore by winds. Thereafter, ice floes occasionally are blown back to the islands by wind, but the lagoon itself remains ice-free for the duration of the summer.

Freeze-up begins in the lagoon in late September, when slush ice forms in shallow, calm waters. Lagoon waters were open on 1 October 1978, although ice cover probably developed over the entire lagoon during the next two weeks.

During winter months, surface ice steadily increases in thickness. In November, the ice is 50 cm thick and maximum thicknesses of about 2 m are reached in late winter (April). At this time, approximately 90% of the lagoon volume is frozen solid and the only unfrozen water is located in the lagoon center where under-ice depths are 0.3 - 1.0 m.

Temperature and Salinity

Dramatic seasonal changes in the physical environment present stringent conditions for life in Simpson Lagoon. Water temperatures range from summer highs to 10-13°C to winter lows of -2°C. Summer salinities run the gamut from fresh to saline water, and in winter the water may become hypersaline (up to 68 ppt, Crane and Cooney 1975). A generalized seasonal pattern for these physical characteristics is as follows:

> Spring (late June - early July): waters cold (0-5°C) and nearly fresh (1-10 ppt) because of melting ice and river flooding.
>
> Summer (mid-July - mid-August): waters relatively warm (7-10°C) and brackish (18-25 ppt).
>
> Fall (late August - September): rapid cooling (0-6°C), waters brackish (18-25 ppt).
>
> Winter (mid-October - early June): water cold (0 to -2°C) and initially brackish (25-30) ppt), becoming saline or hypersaline (35-60 ppt) by winter's end.

Because coastal circulation patterns tend to hold discharge from North Slope rivers near the coastline, waters become progressively more saline with increasing distance from shore. Lagoon waters are generally warmer and less saline than waters outside the barrier islands; furthermore, temperatures decreases and salinity increases with distance from the mainland shore (Figs. 2 and 3). An exception to this pattern was observed on one occasion in 1977 when an apparent upwelling brought cold marine water against the outside of the barrier islands.

Little vertical stratification of temperature or salinity occurs in the lagoon. Bottom conditions were generally within 1°C and 3 ppt salinity of surface conditions. In the deep channel (3-4 m) between Spy and Leavitt islands, however, a tongue of cold hypersaline water was recorded (C. Mungall, pers. comm.). Similar hypersaline pockets of water were recorded in deep (4 m) pools in Kaktovik Lagoon in summer (Griffiths *et al.* 1977).

1977

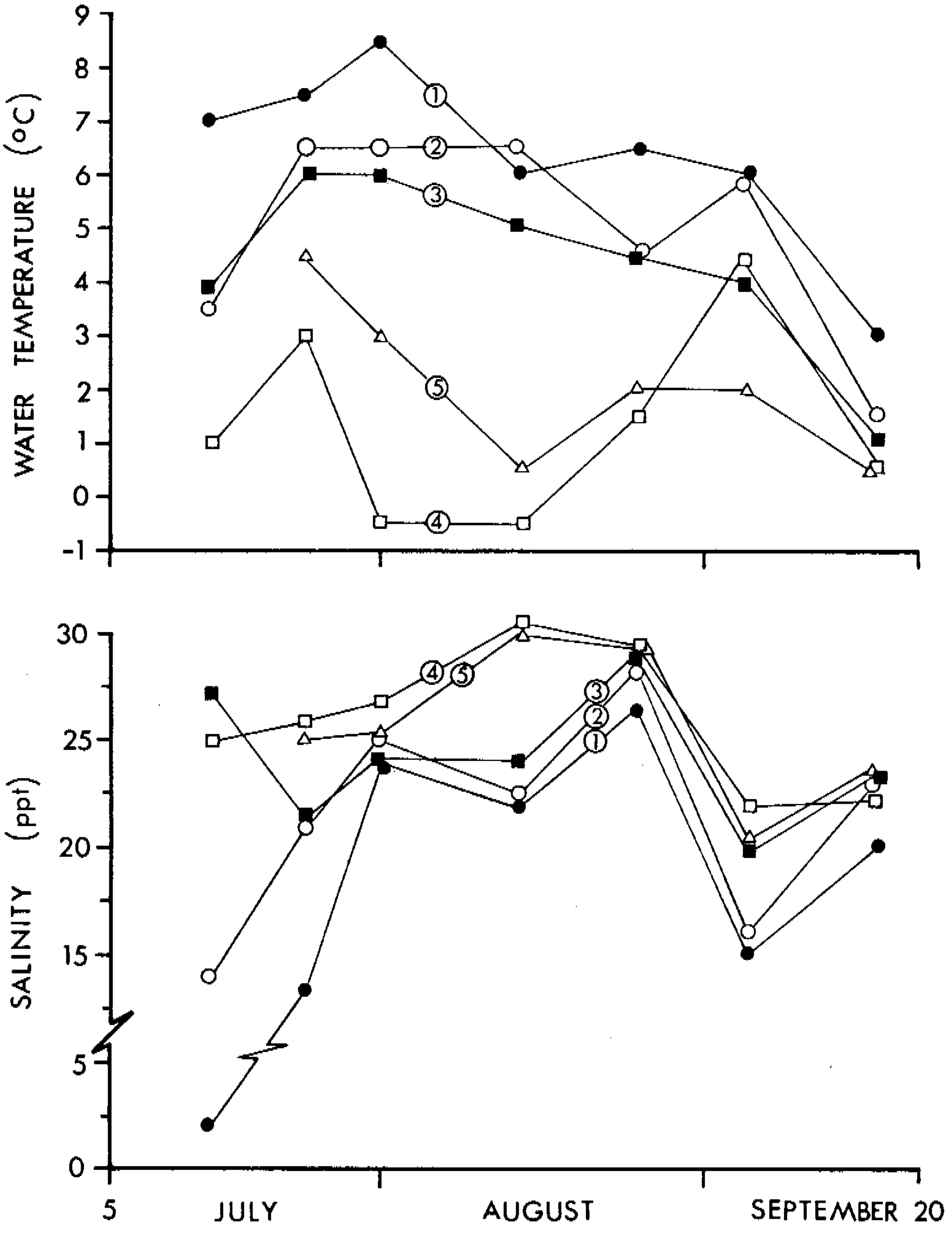

Figure 2. Temperatures and Salinity at Stations 1-5, 1977.

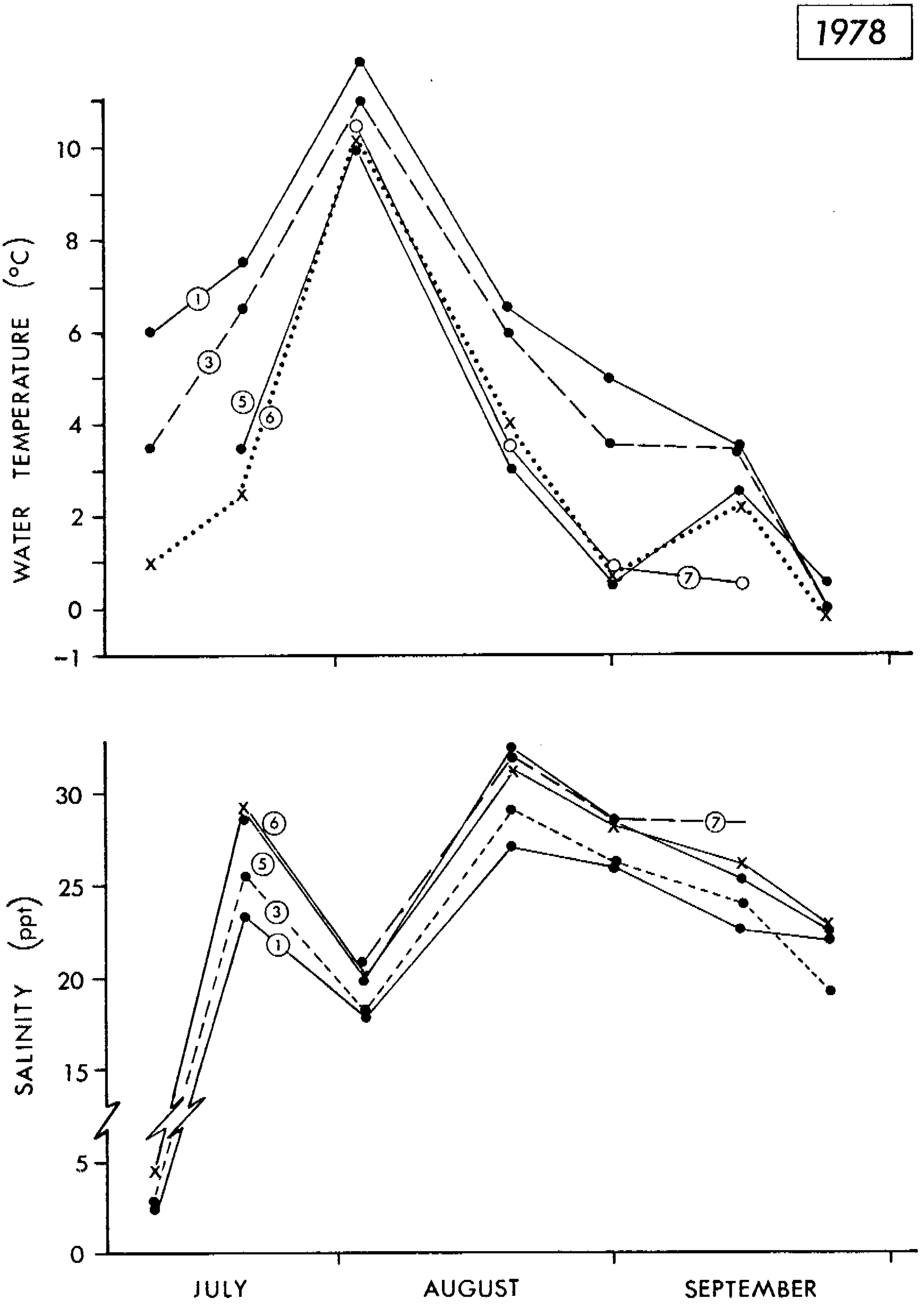

Figure 3. Temperatures and Salinity during 1978 at Stations 1, 3, 5, 6 and 7.

Turbidity

Lagoon waters are turbid to varying degrees for almost the entire open-water period. Because of variations in wind-generated turbulence, nearshore turbidity readings fluctuated widely (1-146 NTU recorded 80 m from shore) from day to day. Wave-washed waters around the lagoon edges are generally more turbid than waters elsewhere; there is often a band of murky water along the shoreline (Fig. 4). Maximum turbidities occurred during and after periods of high winds; the correlation between turbidity (measured 80 m from the shoreline) and wind speed was highly significant (correlation coefficient $r=0.629$, $P<0.001$, $n=56$). After winds slacken, turbidity readings fall rapidly as the sediments quickly settle out.

Simpson Lagoon, despite its shallow nature, is not a homogeneous mixture of wind-churned water. SCUBA divers observed that a vertical stratification of water currents occurred in the lagoon center even though the water depth was only 2 m. Currents were slower at the bottom and thus the flocculant detrital layer often remained in place despite relatively high velocities of overlying water.

Dissolved Oxygen

Dissolved oxygen concentrations remained high at all stations during the open-water period. The average summer value was 9.8 m/l (range 7.0-12.0 ml/l).

METHODS AND RATIONALE OF DATA COLLECTION

The fisheries program consisted of both summer and winter field studies in Simpson Lagoon and nearby waters. Sampling was most intensive during three periods: the open-water seasons of 1977 and 1978 and the winter of 1978-1979.

In order to document fish use of Simpson Lagoon and identify important areas for fish, the 1977 field program was designed to

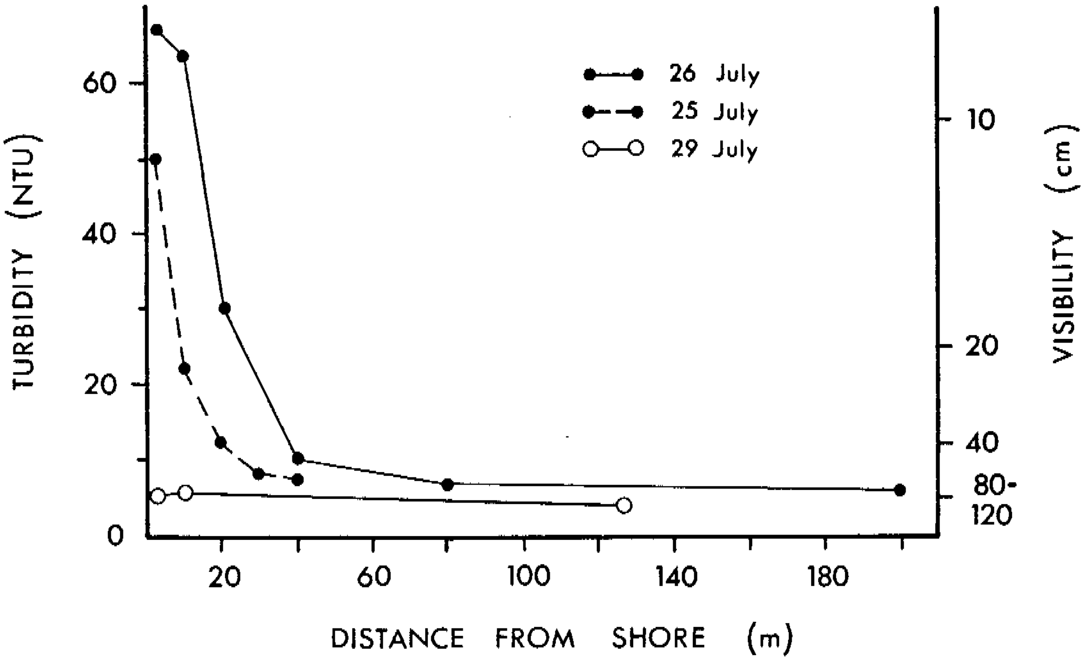

Figure 4. Turbidity Profiles at Milne Point (East), 1978. Water depths were shallow: 0.9 m deep at 20 m offshore; 1.4 m deep at 200 m offshore.

sample representative nearshore habitats in time and space during the open-water season. Five habitat (Fig. 1) were sampled on a regular basis:

Station No. (1977)	Habitat Type	Water Depth (m)
1	mainland shoreline	0-1.2
2	lagoon center	2-2.5
3	island shoreline (lagoon)	0-1.2
4	island shoreline (ocean)	0-1.2
5	offshore ocean	8-10

The temporal sampling scheme during 1977 consisted of (1) a spring breakup period (16 June-5 July) when sampling was restricted to open water leads around Pingok and Leavitt islands, and (2) a summer period when samples were taken at approximately 10-day intervals at all Stations. Sampling ended 23 September, when lagoon waters were beginning to freeze. During each sampling period and at each location, the water column was sampled by a variety of techniques to insure adequate collection of fish present.

In 1978, the field camp was moved from the west end of Pingok Island to Milne Point for ease of logistic support, and the locations of the 1978 sampling program reflect this change (Fig. 1). Most fisheries studies were conducted at Station 1 or at other locations along the mainland shoreline; the remainder of the stations served primarily as collection sites for invertebrates (Griffiths and Dillinger 1979) although ichthyoplankton samples were taken at each. As in the previous year, the 1978 summer sampling program (19 June-24 September) spanned the open-water season.

Summer Methodology

A diagrammatic comparison of principal sampling gear used during the 1977 and 1978 open-water seasons is shown in Figure 5; gear dimensions are listed in Table 1.

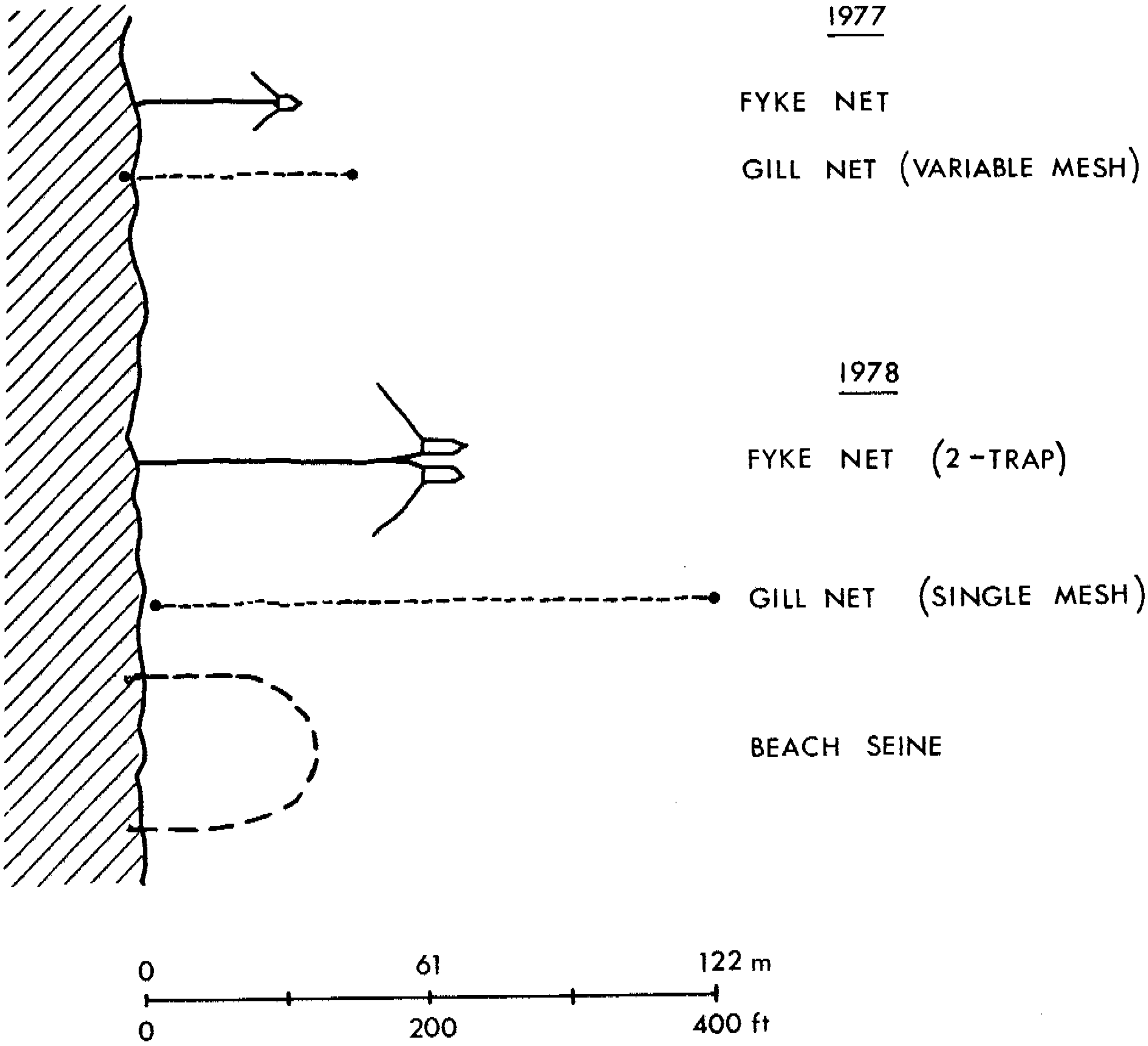

Figure 5. Fish Sampling Gear used During Open-Water Studies.

TABLE 1. Descriptions of Sampling Gear.

Net Type	Major Dimensions	Mesh Size (stretched)	Material, Comments
Gill Net #1	400' x 6' (single panel)	2"	Monofilament
Gill Net #2	150' x 6' (2 75' panels)	75' x ¾", 75' x 1"	#210/2 multi filament
Gill Net #3	150' x 6' (3 50' panels)	50' x 1", 50' x 1½" 50' x 2"	#69 Monofilament
Gill Net #4	150' x 6' (4 37.5' panels)	37.5'x1", 37.5'x1½" 37.5'x2", 37.5'x2½"	1", 1½", 2" #69 Monofilament 2½" #104 Monofilament
Gill Net #5	150' x 6' (5 30' panels)	30' x 1", 30' x 1½" 30' x 2", 30' x 2½" 30' x 3½"	Monofilament
Trammel Net	150' x 6' (triple panel)	Outer walls - 3" Inner walls - ¾"	3" - #139 Monofilament ¾" - #210/2 Multifilament
Fyke Net 1977	Lead net 100' x 4' Wing nets 25' x 4' Trap - 4' x 4' x 15' (2 throats)	1" lead & wing nets ½" trap	#44/5 Green nylon
Fyke Net 1978	Lead net 200' x 4' Wing nets 50' x 4' Mouth - 6' x 4' Trap - 12' x 3' x 3' (2 - 6"x10" throats)	1" lead & wing nets ½" trap	Lead & wings #63 knotless nylon, dark grey Trap - #147 knotless Nylon - dark grey
Fyke Net Under ice	Four leads 90' x 6' Trap - 6' x 6' x 6' (4 mouths) (4" diameter throat)	½"	Ace knotless nylon
Faber Net	0.5 m Diameter Mouth 3 m long	1.024 mm.	
Beach Seine	300' x 6'	2½"	Equipped with mud rollers
Minnow/ Amphipod Trap	40 cm diameter 1 m long One mouth each end	1/8"	Knotless nylon
Box Trap	4' x 4' x 4' 4 mouths 1.5' diameter	1/32"	Nylon mesh

Gill Nets

Gill net #5 (Table 1) was used in 1977. In shallow waters at Stations 1-4, this net sampled the entire water column; both sinking and floating gill nets were used in deeper (10 m) waters at Station 5. Stations were first sampled soon after the ice melted and thereafter at approximately 5-12 day intervals. Gill net sets were usually 24 h in duration but sometimes varied (from 10-120 h) because ice and weather conditions interrupted the normal routine. Total number of sets and days fished between 24 June and 18 September 1977 are listed below.

	1977 Seasonal Totals	
Station (1977)	Gill Net Sets	Days Fished
1	10	10
2	10	19
3	10	10
4	7	10
5	7	10.5

A longer gill net (#1 (Table 1) was used in 1978 to determine the micro-distribution of fish relative to the shoreline. The 2 in mesh size used on this net is particularly effective in catching char and ciscos in coastal waters (Griffiths *et al.* 1975). The net was marked at 2-m intervals so that the locations of captured fish along the net could be recorded. The net was set perpendicular to the shoreline with a 2- to 3-m gap between the net and shore. The rationale for leaving this gap was to ensure that fish trying to avoid the net would be able to swim around both ends and thus not bias our estimates of their distribution by being funneled into the net at the shoreward end. Water depths were typically 0.3 m at the landward end of the net and 1.5 m at the seaward end. The gill net was set for short time periods (usually 1-3 hr) because of the effectiveness of the net at catching fish and to minimize the possibility that fish would avoid areas where many fish were already caught. In some cases, a transect longer than 122 m was sampled by sequentially resetting the net at increasing distances of 122 m farther offshore for equal time intervals.

Fyke Nets

Fyke nets proved to be useful and efficient in sampling fish, including juveniles too small to be caught by gill nets. The style of net as well as the location and manner operating the net differed between the two summers of operation (Fig. 5, Table 1).

During spring breakup of 1977, fyke nets were operated in open-water leads along Pingok and Leavitt islands, but catches were small. Permanent fyke net stations were established at Stations 1 and 3 on 25-27 July 1977 and operated almost daily until 22 September 1977. The fyke trap was generally situated in 1 m of water so that the top of the trap was 20 cm out of the water. Nets were checked daily, weather permitting. Fish were emptied from the cod end of the trap into a holding pen attached to a boat. Specimens were identified and measured; those large enough were also tagged.

In 1978, the design of the fyke net was improved in several respects: (1) lead and wing nets were doubled in length, (2) the trap was enlarged, (3) the net color was changed to grey, and (4) two traps were used simultaneously so that the direction of fish movement could be determined (Fig. 5). This net appeared to be more efficient than the 1977 version; more fish and a wider size range of fish were caught. On one memorable occasion, a single trap held over 25,000 cod (60 - 140 mm in length) with no observable fish mortality.

Because of the large number of fish caught during 1978, only sub-samples were measured. All fish caught were counted, with the exception that during peak catches of arctic cod, numbers of this species were estimated. Estimates were obtained by counting the number of cod in a dip net filled to a given level, repeating this for several additional samples, and then applying the mean number per net-full to the total number of net-fulls in the trap.

The Milne Point region was sampled by the two-trap fyke net in 1978. Because wave action on the east side of the point interfered with the operation of the net, and because a submerged gravel bar extended westward from Milne Point, the fyke net was located on the west side of the point approximately 500 m from the tip. The net operated almost the full length of the open-water season (30 June - 24 September 1978). Fish caught in this fyke net were assumed to be traveling east or west and parallel to shoreline. However, the submerged gravel bar off Milne Point may have deflected some of the westward-swimming fish, causing them to miss the trap and thus biasing our judgements of the proportion of fish swimming in each direction.

Faber Net

A modified Faber net (Faber 1968) was used to catch planktonic fish (Table 1). Each tow filtered approximately 82 m^3 of surface water (i.e., a 5-min tow at 1.4 m/sec). Each value presented is the average of two replicate tows at a sampling site.

Beach Seine

In 1978, a 91.4 m (300 ft) beach seine was used to estimate numbers of fish in the usually turbid shoreline waters. The net was set with the aid of a Boston Whaler powered by a 50 hp motor. While one end of the net was held onshore, the seine was set in a curve, returning to shore approximately 35 m down the beach from the starting point. Water depth on the deep side of the net was generally 1.2 m. The net was then pulled onto shore. Captured fish were counted, measured and released; large fish were also tagged.

The area swept by the seine was estimated in order to calculate fish densities. The enclosed sampling area was bound by a shoreline length of 35 m (± 3 m) and a 91 m length of net. Using these dimensions, the area seined was 980 m^2 if rectangular in shape or 1019 m^2 if elliptical in shape. The average of these two values, 1000 m^2, will be used in this report. The sampling error for densities of fish derived in this manner is at least 5% (e.g.,if the shoreline distance is 32 m rather than 35 m, then the rectangle area is 944 m^2 and the elliptical area is 947 m^2); other more significant sources of error include habitat selectivity (shallow areas could not be sampled) and avoidance by the fish due to boat disturbance.

A variety of coastal areas were sampled by beach seine during the summer period, 26 July - 1 September (Fig. 6). Three general habitats were seined: mainland shoreline (n=44 seine hauls), lagoonside island shorelines (n=11), and oceanside island shorelines (n=8).

Other Methods

Other methods were also used to sample fish or otherwise obtain information but none was as successful as any of the previously described gear. Brief descriptions of other sampling efforts which proved unsuitable may be of interest.

1. SCUBA diving. In both 1977 and 1978, divers swam underwater transects about every two weeks at most sampling stations (Fig. 1). Although we had hoped to study fish distribution and behavior in this manner, few fish were sighted. In 65 20-min dives, a total of four fourhorn sculpins and one arctic flounder were observed. Poor visibility (often <1 m), low fish densities, and avoidance behavior of fish probably account for the dearth of sightings.

2. Aerial surveys. Some observers report sighting fish in arctic coastal waters from aircraft; however, fisheries biologists who looked for fish during five aerial surveys flown at 30 m ASL over the study area saw none. These were fixed-wing surveys flown over nearshore and offshore areas between Harrison Bay and Flaxman Island. Turbid lagoon waters often obscured visibility, although waters were clear in offshore areas and in shore leads during early summer.

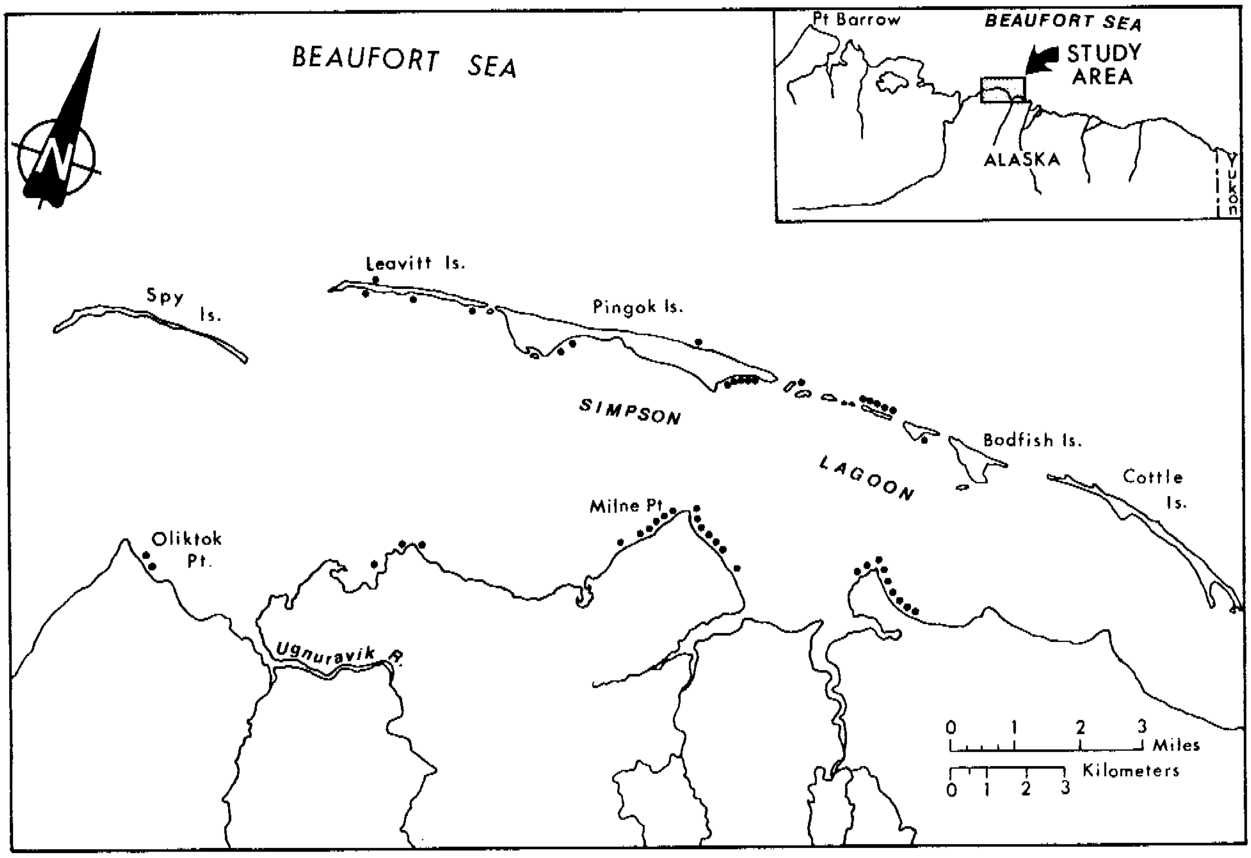

Figure 6. Sites Sampled with a 91.4 m Beach Seine, 26 July - 1 September 1978. Symbols represent one or more sampling efforts at Milne and Kavearak Points.

3. Otter trawl. A 4.9-m otter trawl was used in 1977 to sample invertebrates. Only 10 fish were caught in 79 tows. Low catches probably resulted from slow trawling speeds and boat disturbance in shallow (1- to 2-m) waters.

4. Purse seine. A large purse seine (3.7 x 183 m) was tested in open lagoon waters. Four men set the net in calm water at Station 3 on 29 July 1978, but no fish were caught. It quickly became apparent that it was not practical to work a net this size with the boats available (17' Boston Whaler, 15' Zodiac).

Winter Methodology

A winter fish sampling program was conducted in 1978-1979 at several locations from Prudhoe Bay to the Colville Delta. In April and May of 1978, gill nets were set in the Kupigruak and East Channels of the Colville Delta (Stations A and B, Fig. 7). During November 1978 and February 1979, four nearshore habitats were sampled (Fig. 8).

Because of the difficulties in collecting fish in ice-covered areas, a variety of nets were used during winter studies. Details of net types and time fished are presented in Table 2. Under-ice water temperatures during sampling operations were -1.0 to -3.0°C and salinities were 17.9 - 36.0 ppt (Table 3).

Estimation of Daily Ration

To determine the effect of fish predation on epibenthic food resources, it is first necessary to estimate the amount of food ingested by fish each day (daily ration). In this study, the daily ration of arctic cod was calculated by determining the proportion of the day that the cod spend feeding, the amount of food in their stomachs, and the rate at which food is passed through their stomachs (evacuation rate).

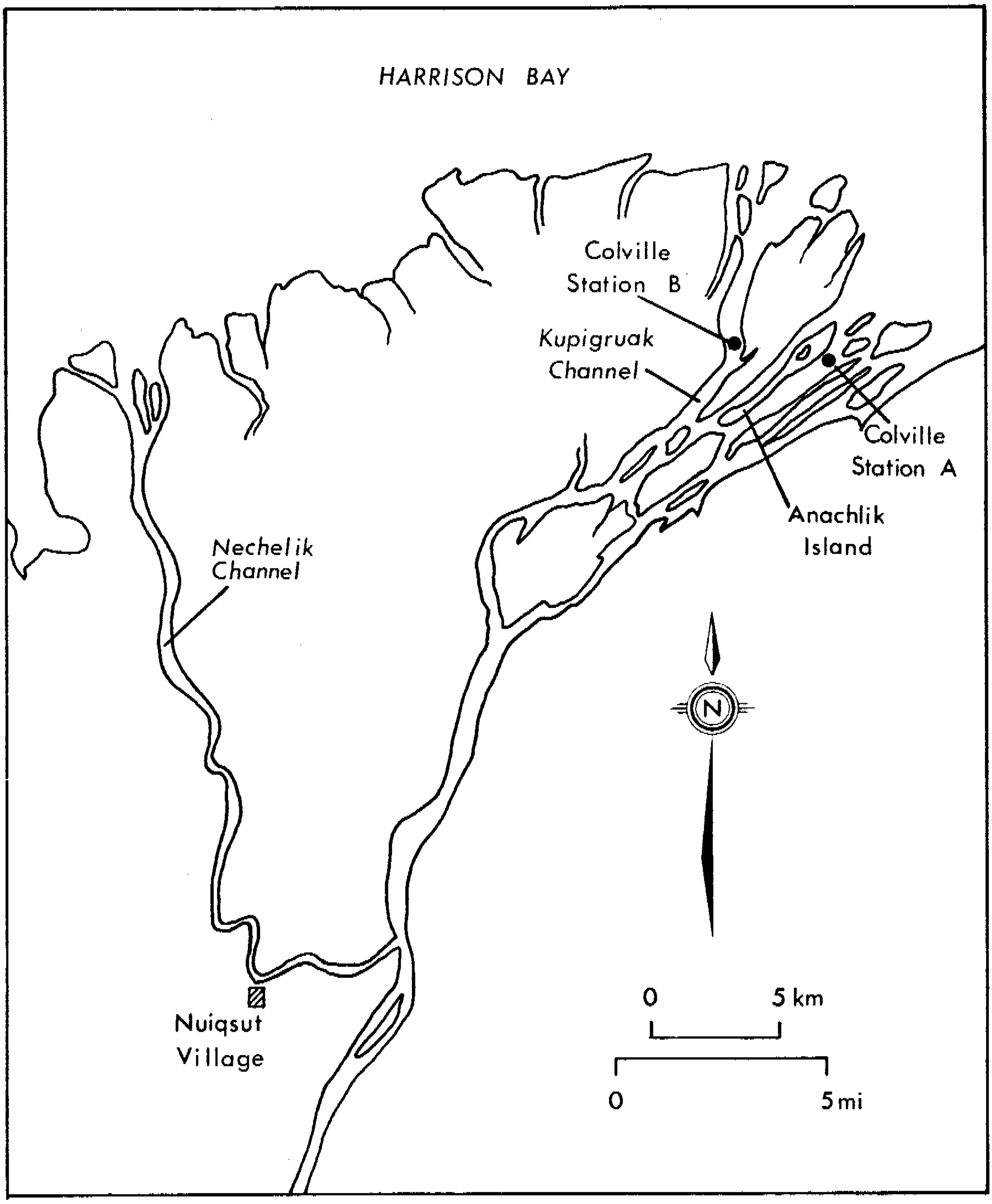

Figure 7. Locations of Winter Gill Net Samples (Stations A and B) in the Colville Delta. Also shown are Nuiqsut Village where subsistence fishing occurs and Anachlik Island where a commercial fishery (Helmericks) operates. Many tagged fish from Simpson Lagoon were recaptured in this fishery.

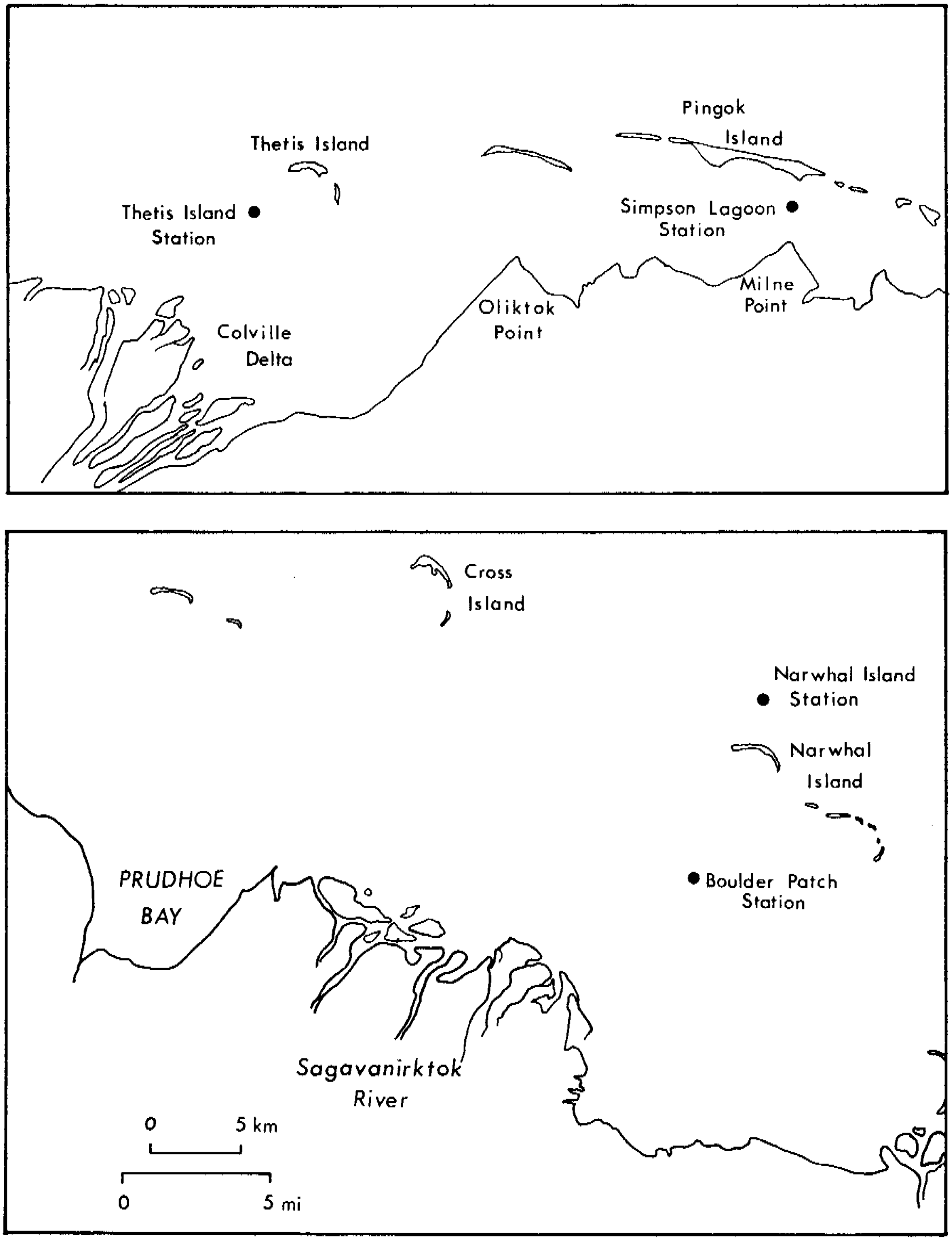

Figure 8. Winter Sampling Sites Between the Colville Delta and Narwhal Island.

TABLE 2. Sampling Dates and Gear Used during Winter Surveys. Descriptions of sampling gear are given in Table 1.

Sampling Period	Station (see Fig. 7, 8)	Net Used (Table 1)	Dates Fished	Total Days
April 1978	Colville A	Gill Net 5	8-20 April	13
	Colville B	Gill Net 5	9 April - 22 May	44
November 1978	Thetis Island	Gill Net 5	9-14 November	5
		Gill Net 2	9-16 November	7
	Simpson Lagoon	Gill Net 2	4-15 November	12
		Gill Net 3	4-15 November	12
	Boulder Patch	Gill Net 2	5-10 Nov., 12-16 Nov.	7
		Gill Net 3	5-16 November	11
	Narwhal Island	Box Trap	3-4 November	1
		Minnow/Amphipod Trap	4-5 November	1
February 1979	Thetis Island	Gill Net 5	18-26 February	8
		Gill Net 4	18-26 February	8
	Simpson Lagoon	Gill Net 5	11-14 February	3
		Gill Net 2	12-14 February	2
		Gill Net 4	24-26 February	2
	Boulder Patch	Gill Net 4	14-15 February	1
		Gill Net 5	14-15 February	1
		Under-Ice Fyke	15-27 February	12
	Narwhal Island	Gill Net 4	19-27 February	8
		Trammel Net	19-27 February	8

TABLE 3. Physical Conditions at Winter Sampling Stations (see Fig. 7 and 8 for locations).

Station	Date	Depth (m)		Water Temp. (°C)	Salinity (ppt)
		Ice	Water		
Colville A	5 Apr. 78	2	1.5-4.5	-1.0 to -1.3	18 - 25
Colville B	5 Apr. 78	2	10.7	-1.0 to -1.7	19 - 32
Thetis Island	11 Nov. 78	0.7	3.0	-1.0 to -1.2	24 - 28
	26 Feb. 79	1.6	2.1	-	28.0
Simpson Lagoon	11 Nov. 78	0.7	2.4	-1.5 to -2.0	24.0
	24 Feb. 79	1.6	1.2	3.0	36.0
Boulder Patch	11 Nov. 78	0.7	5.8	1.5	23.0
	27 Feb. 79	1.6	4.9	-	28.5
Narwhal Island	11 Nov. 78	0.7	12.1	-	-
	25 Feb. 79	1.6	10.6	-	28.0

Stomach Evacuation Rate

The evacuation rate of food from stomachs of arctic cod was determined by placing freshly-caught fish in a food-free environment and then withdrawing samples of these fish at timed intervals to see how much food remained in the stomachs. The sample of arctic cod was caught in the previously-described fyke net from 10:00 - 13:00 ADT on 20 August 1978. The fish were placed in a large, fine-mesh holding pen (2 x 2 x 1.2 m deep; 0.8 mm mesh) located in the lagoon at the fyke net site. Samples of 18 - 20 fish were taken 0, 2, 4, 7.5 and 20.5 h after removal from the fyke net and dissected within one hour. Stomachs were preserved in 10% formalin and contents were later weighed on a Mettler balance. The errors in weights of stomach contents resulting from formalin preservation and the time delay (6 wks) between collection and weighing are not known but are presumably consistent among samples since all samples were treated similarly. Lagoon water temperatures and salinities varied slightly during the course of this experiment (4.5 - 6.5°C, 24 - 26 ppt).

Feeding Periodicity

To determine whether arctic cod fed continuously or at particular times during the day or night, fish samples were collected from the lagoon at intervals over a 24-h period and their stomach contents inspected. The experiment was conducted at Milne Point where specimens were caught by beach seine or fyke net operating for short periods. On 23 - 24 August 1978, 10 - 15 arctic cod were collected at approximately 5-h intervals: 10:00, 15:00, 19:00 - 20:00, 24:00 - 01:00, 06:00 - 08:00 ADT. As the experiment progressed, the rate of catch decreased, presumably because few cod were in the area. Consequently, later in the sampling period more effort and time were required to catch at least 10 fish. The experiment ended when no cod were caught during the last sampling period at 11:00 - 13:00 on 24 August; presumably the cod had vacated the area. Therefore, data acquired on two earlier dates (20 August 1978 at 10:00 - 13:00 and 21 August 1978 at 10:00 h) were included to supplement the analysis of feeding periodicity. The 20 August data were the t = 0 h data from the food evacuation rate experiment; the 21 August data were from the first attempt at a feeding periodicity experiment, which was aborted when rough waters hindered sampling efforts. Stomach fullness data from all dates were obtained in a similar fashion. Lagoon water temperatures and salinities were similar during all sampling periods: 20 August (6.5°C, 25 ppt), 21 August (4.5°C, 25 ppt), 23 - 24 August (4.5 - 5.0°C, 25 - 26 ppt).

Physical and Chemical Measurements

Water temperature, salinity, dissolved oxygen and turbidity were measured daily at Station 1, where the fyke net was operated, and at approximately 10-day intervals at other stations during the open-water seasons. Sampling instruments used in 1977 included a YSI-33 Salinity/Conductivity Meter (salinity, temperature), Hach Model 2100A Turbiditimeter (turbidity) and Hach Portable Oxygen Determination Kit (dissolved oxygen). In 1978, equipment included a Hydro Lab Meter (temperature, conductivity) and DRT-15 Turbidimeter by H.F. Instruments.

RESULTS AND DISCUSSION

Fish Populations in Simpson Lagoon

Species Composition

During summer (1977-78) and winter (1978-79) sampling periods, a total of 21 fish species were caught in Simpson Lagoon and nearby coastal waters. These fishes are listed below according to their principal life-history pattern:

Anadromous Species

arctic char (*Salvelinus alpinus*)
arctic cisco (*Coregonus autumnalis*)
least cisco (*C. sardinella*)
Bering cisco (*C. laurettae*)
broad whitefish (*C. nasus*)
humpback whitefish (*C. pidschian*)
boreal smelt (*Osmerus eperlanus*)
ninespine stickleback (*Pungitius pungitius*)
pink salmon (*Oncorhynchus gorbusca*)
chum salmon (*O. keta*)
threespine stickleback (*Gasterosteus aculeatus*)

Marine Species

arctic cod (*Boreogadus saida*)
fourhorn sculpin (*Myoxocephalus quadricornis*)
arctic flounder (*Liopsetta glacialis*)
saffron cod (*Eleginus navaga*)
capelin (*Mallotus villosus*)
Pacific herring (*Clupea harengus*)
snailfish (*Liparus* sp.)
sculpin (*Myoxocephalus* sp.)
Pacific sand lance (*Ammodytes hexapterus*)

Freshwater Species

grayling (*Thymallus arcticus*)

Based on the variety of sampling methods used and the thorough sampling efforts in time and space (see METHODS), it is felt that the above species list represents virtually all fishes utilizing the lagoon during 1977 and 1978. Almost 200,000 fish were caught during the course of this study (all but subsamples were released alive). Totals of 10,807 fish were taken during the 1977 open-water season, 179,937 fish during the 1978 open-water season, and 759 fish during winter studies.

Relative Abundance

Although 21 fish species were caught in Simpson Lagoon, five species accounted for over 91 and 98% of all fish caught during the summers of 1977 and 1978, respectively. Two marine species (arctic cod, fourhorn sculpin) were the numerical dominants in the brackish water system, and three anadromous speices (arctic cisco, least cisco, arctic char) were the next most abundant. These species also characterize the fish fauna of nearshore waters along most of the Beaufort Sea coastline (Craig and McCart 1966; U.S. Dept. Commerce and Dept. Interior 1978).

The relative abundance of fishes taken in Simpson Lagoon varies according to method of capture (Table 4). Each type of gear commonly used to catch fish is strongly biased and catches a different portion of the population of each species. In 1977, for example, the Faber net collected ichthyoplankton, the fyke net caught primarily small and/or marine fish, and gillnets caught primarily large anadromous fish.

The fyke net data are of particular interest because the majority of fish caught by this method were small arctic cod, fourhorn sculpins and arctic ciscos. These data and the results of Bendock (1977) from Prudhoe Bay show that small fish are substantially more common in nearshore Beaufort Sea waters than indicated by earlier studies that relied on data obtained by gill nets (reviewed by Craig and McCart 1976).

Fish numbers and composition in Simpson Lagoon changed markedly between the two years of study. In 1978, eight additional fish species were encountered (Table 4; a lone sockeye salmon caught in the Colville River is not listed in this table). Three of these species are outside their reported ranges by several hundred kilometers; the threespine stickleback and sockeye salmon have not previously been recorded in Beaufort Sea waters, and the Pacific sand lance has apparently not been collected previously between the Chukchi Sea and Herschel Island, Yukon Territory (McAllister 1962; McPhail and Lindsey 1970; Hart 1973; Scott and Crossman 1973). There was also a small run of pink salmon in Simpson Lagoon during 1978, whereas during 1977 no salmon were caught.

TABLE 4. Relative Abundance of Fish Caught during the Open-water Season by Different Methods in Simpson Lagoon.

	1977			1978	
Fish species	GILL NET %	FYKE NET %	FABER NET %	BEACH SEINE %	FYKE NET %
Arctic cod	*	8	83	8	78
Fourhorn sculpin	9	70	0	21	18
Arctic cisco	56	15	0	17	*
Least cisco	12	2	0	48	1
Arctic char	14	4	0	4	*
Broad whitefish	4	*	0	1	*
Humpback whitefish	2	0	0	0	*
Arctic flounder	*	1	0	*	*
Boreal smelt	0	*	0	*	*
Saffron cod	0	0	0	0	*
Bering cisco	1	0	0	0	*
Capelin	1	*	0	0	*
Pink salmon	0	0	0	*	*
Ninespine stickleback	0	*	0	0	*
Pacific herring	0	0	0	0	*
Snailfish sp.	0	*	17	*	*
Grayling	0	0	0	0	*
Chum salmon	0	0	0	0	*
Sculpin sp.	0	0	*	*	0
Three-spine stickleback	0	0	0	0	*
Pacific sand lance	0	0	0	0	*
No. fish caught	781	10,026	366	450	179,487
% anadromous fish	89	21	0	70	3

* < 1%

The tremendous numbers of arctic cod (estimated in the millions) that entered Simpson Lagoon in mid-August of 1978 constituted the most important difference between years. The actual 1978 catch of 139,792 of these fish was approximately 13 times larger than the total number of all fish caught during the previous summer. In fact, on four separate occasions in 1978, the daily catch of arctic cod exceeded the total 1977 catch. Arctic cod were also present in the lagoon in 1977, but their numbers were low (n = 767 in the fyke net). Difference between years in sampling methods undoubtedly affected the size and species composition of the catch. However, the almost 200-fold increase in numbers of arctic cod caught in 1978, and their overwhelming dominance of the 1978 species composition in the lagoon (from 8% in 1977 to 78% in 1978), demonstrates that fish numbers and relative abundance in the lagoon-barrier island ecosystem may fluctuate dramatically from year to year.

If the numbers of arctic cod in 1978 are reduced to equal only 8% of the catch as occured in the previous year, and if only the data obtained from 25 July to 22 Sept. (the period that the 1977 fyke net operated) are considered, then the relative abundance of the major species becomes as follows:

	1977 %	1978 %
arctic cod	8	(8)
fourhorn sculpin	70	79
arctic cisco	15	2
least cisco	2	3
arctic char	4	2
total number fish caught	10,026	34,582

It appears that proportions of most major species other than arctic cod and arctic cisco were fairly similar in the two years. Catches in both years indicate that fourhorn sculpin are a major component of this nearshore ecosystem. Numbers of fish were much higher in

1978, but a direct comparison between years is questionable due to several differences in methodology (e.g., changes in fyke net location and improved efficiency in 1978 - see METHODS).

Biomass

When lagoon populations of fish are described in terms of biomass rather than numbers of individuals, the dominance of the system by marine species is less pronounced. The principal marine species, arctic cod and fourhorn sculpin, are small fish whose total biomass is much less impressive than their total numbers. For example, one average-sized arctic cisco is the weight equivalent of 66 average arctic cod.

To obtain biomass estimates for fish in Simpson Lagoon, it was first necessary to estimate the average weight of each species taken. Fyke net data were used to estimate mean weights because fish caught in beach seines were not weighed and gill nets selectively caught large fish. For arctic cod, a random sample of 108 individuals taken from the fyke net in 1978 were weighed to provide an average. For the remaining species, the average weight was estimated from sub-samples of the 1978 fyke catches; these specimens had been selected for life-history analysis rather than as an unbiased representation of fish sizes taken by fyke net, so the resultant average weight may be somewhat biased. The average weights obtained in this manner are listed below for species that comprised more than 1% of the total fish biomass.

	1978 fyke net
Species	Mean weight (g)
arctic cod	10
fourhorn sculpin	45
arctic cisco	280
least cisco	270
arctic char	760

Species	1978 fyke net Mean weight (g)
broad whitefish	700
humpback whitefish	700
arctic flounder	140
saffron cod	35
pink salmon	1010

The above means were multiplied by the number of each species caught during 1978 in fyke nets to provide an estimate of the relative biomass of each species.

Biomass calculations demonstrate that anadromous species are more important as consumers than might have been deduced based on their relative abundance (Fig. 9). During the open-water season of 1978, anadromous fish accounted for almost half (46%) the estimated total fish biomass but only 3% of the estimated total number. This large difference reflects the relatively large size and small numbers of anadromous fish and the small size and large numbers of marine fish. Three out of every four fish collected in the lagoon were arctic cod, but this species accounted for only 26% of the total fish biomass.

A similar situation existed during 1977, when anadromous fish comprised 46% of the total biomass and 21% of the numbers captured in the fyke net. In that year, the fourhorn sculpin was the most commonly captured species (70% of catch) but because of the small size of individuals, accounted for a lower proportion of the biomass (49% of total biomass).

Habitat Utilization

Two prominent trends in the spatial distribution of anadromous fish during the open-water season in the Simpson Lagoon study area

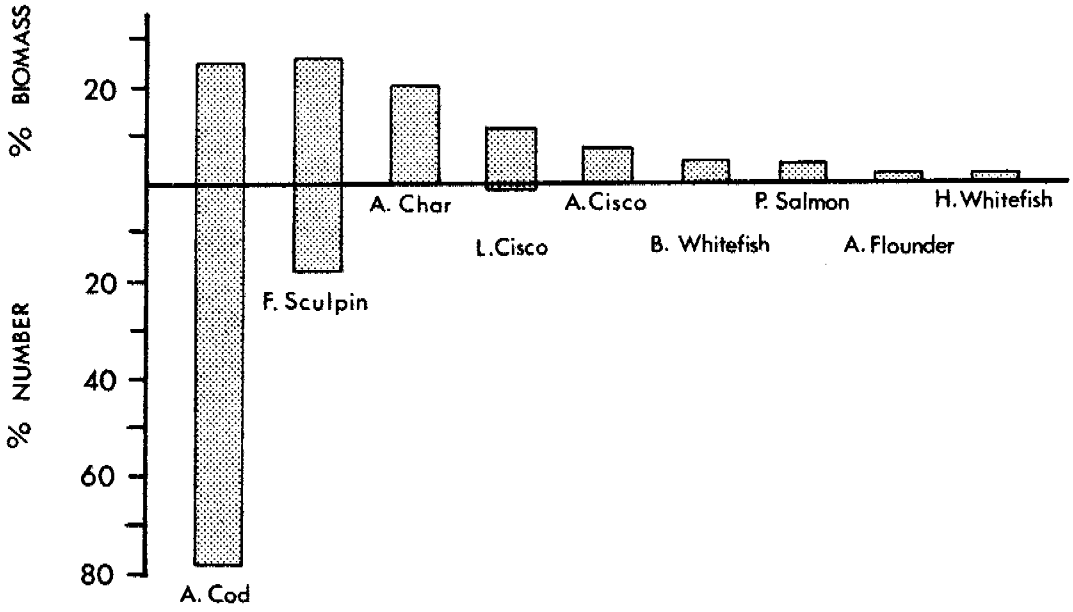

Figure 9. Comparison of Relative Abundance and Biomass for the 1978 Fyke Net Catch. Species comprising less than 1% of the total biomass are not included. For the nine species listed, the total number of fish caught was 178,353 and the estimated total biomass caught was 5405 kg.

were evident: (1) most fish were found in nearshore rather than offshore marine locations, and (2) fish numbers were highest along shoreline edges, particularly the mainland shoreline. These generalizations are not necessarily valid for marine fishes; the two most abundant--fourhorn sculpin and arctic cod--are not restricted in distribution to nearshore waters.

Nearshore Versus Offshore Distribution

During the 1977 gill net program far more fish were caught per unit effort in lagoon habitats than in marine habitats (Figure 10, Table 5). This difference is even more apparent if the seaward shoreline of the barrier islands is considered to be a nearshore habitat. This shoreline may be flooded by lagoon waters when west winds push the lagoon water mass out the gaps between the barrier islands. On a catch per unit effort basis, fish were 5-98 times more abundant at nearshore stations than at the one offshore station. Nearshore catches ranged from a high of 39.2 fish/24 h (species combined, seasonal average) along the mainland shoreline to a low of 2.1 fish/24 h in the lagoon center. In contrast, the average catch in offshore gill nets was only 0.4 fish/24 h, and, significantly, no anadromous species were caught (Table 5).

In 1978, several tows with an otter trawl were made 5-10 km offshore and, again, marine species were the only fish caught. Other fisheries studies have also documented the absence or very low density of anadromous fish in offshore Beaufort Sea waters (McAllister 1962; Galbraith and Fraser 1974; Griffiths *et al.* 1975, 1977; Frost *et al.* 1978). Arctic anadromous fish remain in nearshore habitats, foregoing the impressive oceanic migrations of some non-arctic salmonids.

Numbers of fish collected in plankton trawls in 1977 were also greater inside the lagoon than offshore. Table 6 shows that arctic cod young-of-the-year, which comprised 83% of the Faber net catches

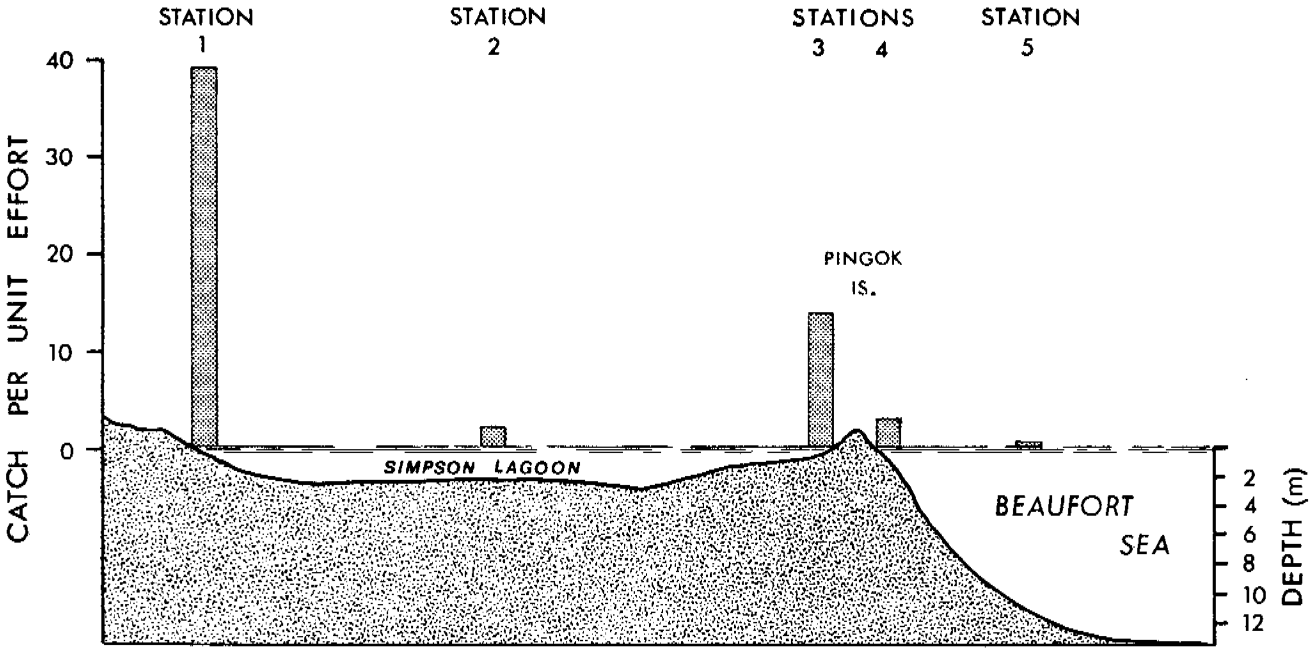

Figure 10. Cross-Section of Simpson Lagoon Study Area Showing Relative Numbers of Fish Caught at 5 Sampling Stations, 1977. Numbers of fish represent a seasonal average for combined species caught in a standardized 24 hr gill net set.

TABLE 5. Comparisons of Gill Net Data at Five Sampling Locations During the Open Water Season, 1977. (See Fig. 10 for locations.)

Fish Species	Seasonal Averages of Fish Caught Per 24-Hour Gill Net Set at Stations 1	2	3	4	5
Arctic cisco	17	1.1	9	0.1	0
Least cisco	8.1	0	0.7	0	0
Arctic char	5.9	0.4	3	2.1	0
Fourhorn sculpin	3.4	0.5	0.8	1	0.1
Broad whitefish	3	0	0	0	0
Humpback whitefish	1.6	0	0	0	0
Arctic flounder	0.2	0	0	0	0
Capelin	0	0.1	0.8	0.1	0
Snailfish	0	0	0.1	0	0.2
Arctic cod	0	0	0	0	0.1
Totals	39.2	2.1	14.4	3.3	0.4
No. days fished	10	19	10	10	10.5

TABLE 6. Seasonal Densities of Young-of-the-Year Arctic Cod Collected by Faber Net during 1977.[1]

	No. Arctic Cod/1000 m^3 at Stations			
Sampling Dates	1	2	3	5
11 July	-	6	0	-
22 July	-	50	0	0
31 July	-	0	31	0
14 August	-	855	694	0
25 August	0	0	0	0
5 September	0	0	6	0
14 September	0	0	99	62
Means	0	130	119	10

[1] Paired t-test on averaged data for stations 2 and 3 vs. station 5 gave $t = 1.05$, $n = 5$, $P>0.1$.

(Table 4), were more abundant at Stations 2 and 3 (130 and 119 fish/1000 m^3; seasonal averages) than at Station 5 (10 fish/1000 m^3). However, the extreme variability in catch records indicate the need for a more extensive sampling program before the general significance of lagoon habitats for these fish is known.

For comparative purposes, densities of arctic cod young-of-the-year at other locations were as follows: 28 fish/1000 m^3, Chukchi Sea (Quast 1974); 10-60 fish/1000 m^3, Barter Island area (Griffiths *et al.* 1977); and 4-130 fish/1000 m^3, Canadian High Arctic (Bain *et al.* 1977; LGL, unpublished data).

The "Edge Effect"

Within the nearshore region, it is apparent that fish are not uniformly distributed but are far more abundant along mainland and island shorelines than in the lagoon center (Fig. 10). Seasonal averaged catches along the mainland shoreline were 19 times greater than in the lagoon center. This finding is similar to that obtained in Kaktovik Lagoon where three shoreline gillnets caught 30 times more fish than three mid-lagoon sets (Griffiths *et al.* 1977).

Although fish catches along all shorelines in the Simpson Lagoon study area were higher than in open-water areas, the mainland shoreline was used more extensively and by more species of fish than were island shorelines (Fig. 10, Table 5). Data obtained in 1978 by different sampling gear (91.4 m beach seine) followed the same pattern shown in Figure 10. Fish densities along the mainland shoreline (0.0095 fish/m^2, species combined) were far greater than at other locations, averaging 3.6 and 24 times greater than densities along the lagoon and ocean side of the barrier islands, respectively (Table 7). The relative numbers of fish caught along the three shoreline habitats were very similar during the two years of study, especially if small fish (i.e. char and whitefish <200 mm, sculpin <100 mm) are excluded from the 1978 beach seine data (these size classes of small fish are not often caught by gill nets):

TABLE 7. Beach Seine Data for Mainland and Barrier Island Shorelines during the Open-Water Season, 1978.

	Seasonal Averages of Fish/Seine Haul		
	Mainland	Island lagoonside	Island oceanside
Least cisco	4.9	0.1	-
Fourhorn sculpin	2.0	0.4	0.1
Arctic cisco	1.4	1.2	-
Arctic cod	0.8	-	-
Arctic char	0.1	0.9	0.3
Broad whitefish	0.1	-	-
Boreal smelt	0.1	-	-
Arctic flounder	0.1	-	-
Pink salmon	0.02	-	-
Sculpin sp.	0.02	-	-
Liparid sp.	-	0.1	-
TOTALS	9.5	2.6	.4
DENSITY (Fish/m^2)	0.0095	0.0026	0.0004
No. Seine hauls	44	11	8

Method	Relative Number Caught island (oceanside)	 island (lagoonside)	 mainland shore
gillnet (1977)	1	4	12
beach seine (1978) ("large" fish only)	1	6	18
beach seine (1978) (all fish)	1	6.5	24

Data obtained by fyke nets (which tended to catch smaller fish than gill nets in 1977) corroborate the difference in fish catches between mainland and island shorelines (Table 8). In 1977, the average catches in 24 h were 160 fish at the mainland site and 104 fish at the island site (lagoon side of Pingok Island). If the omnipresent fourhorn sculpin is excluded from these comparisons, the difference in catches between sites is more apparent: 68 fish/day along the mainland versus 11 fish/day along the island.

Thus, catches of both large fish (gill net and seine catches) and small fish (fyke net and seine catches) are higher along the mainland shoreline than anywhere else in the study area. This may be a reflection of the fact that the mainland shoreline is, on the average, warmer and less saline than other nearshore habitats (Fig. 2 and 3). Some species apparently prefer such waters (described in Abundance of Fish vs Physical Factors).

Two notes of caution are necessary in regard to the above discussion. First, although fish are concentrated along the shoreline, the lagoon center probably accommodates as many fish because of its relatively large size. The following calculation illustrates this point. From Table 5, the average number of fish caught in each meter of gill net (all nets were 45.7 m long) can be determined for each station. These stations represent particular types of habitat (mainland edge, lagoon center, island edge), and the extent of each habitat can be estimated along a cross section of the lagoon from the mainland to Pingok Island. Using these sets of figures, the relative number of fish can be calculated for shoreline and lagoon center:

TABLE 8. Comparison of Fyke Net Data for Mainland and Island Sites, 8 August to 21 September 1977. During this period, nets were operated 36 days (mainland) and 30 days (island).

Fish	Mean Catch in Fyke Net/24 Hour	
	Mainland Shoreline (Station 1)	Island Shoreline (Station 3)
Fourhorn sculpin	92	94
Arctic cisco	36	6
Arctic cod	15	4
Arctic char	8	1
Least cisco	5	0.03
Arctic flounder	3	0.07
Smelt	0.6	0.07
Ninespine stickleback	0.4	0.07
Broad whitefish	0.3	0
Snailfish	0.1	0.03
Capelin	0	0.07
Total	160	105
Daily Range	(2-626)	(0-810)

1977 Station No.	Habitat Type	No. Fish per Meter of Gill Net	Estimated Width of Habitat Type Across Lagoon	Relative No. Fish in Habitat Type
1	mainland edge	0.86	100 m*	86
2	lagoon center	0.04	4500 m	180
3	island edge	0.33	100 m*	33

* estimated on basis of Figure 12.

Although these calculations are rough, they show that a theoretical gill net set across the whole lagoon would catch 119 fish in shoreline habitats and 180 fish in the lagoon center. It appears, then, that the total number of fish in the lagoon center may be similar to, or larger than, the total number of fish along the shoreline edges.

The second note of caution concerns the apparently greater importance of the mainland shoreline than the barrier island shoreline as a migration corridor. This difference may reflect the large (4-6 km) distance between the Pingok Island sampling site and the mainland coast. It is not known if densities of anadromous fish around Barrier islands are a function of the distance of these islands from the mainland.

Affinity for the mainland shoreline varied among species, as previously noted by Bendock (1977). Least cisco, broad whitefish and humpback whitefish in Simpson Lagoon were not commonly taken anywhere but in the relatively warm and brackish waters along the mainland (Tables 5, 7, 8). Arctic cisco and arctic char were distributed more widely and were commonly present along the lagoonside beaches of the barrier islands. Char were the most abundant anadromous fish along the seaward beaches of the barrier islands.

The fourhorn sculpin was distributed more evenly through the study area than were other species. Fyke net data (Table 8) showed sculpins to be equally abundant along mainland and barrier island (lagoonside) beaches, but beach seines showed them to be most abundant along the mainland. Other species were caught in numbers too low to suggest distribution patterns; many were recorded only at mainland sites but this may have been partly an artifact of the greater sampling efforts there.

The Shoreline Corridor

Many fish travel parallel to the shoreline along a surprisingly narrow corridor. It is a common observation that gill nets attached to the shoreline catch many fish while nets set only 100 m seaward of the shoreline catch few fish. On some occasions the fish may even swim within a few meters of the shore. Griffiths *et al.* (1975: 99) made the following observation at Nunaluk Lagoon, Yukon Territory (abridged and italics added from field notebook):

> On an unusually calm day in autumn (August 31, 1974), numerous schools of fish were observed moving eastward in shallow water (0.3 to 1.0 m) *about 1-5 m from the shoreline* adjacent to Nunaluk Spit. These schools were easily detected by small, V-shaped surface waves. At least 10 schools, all heading east, passed by in 30 min. Two of these schools were sampled by gillnet; each was composed of 10 to 20 Arctic cisco and Arctic char. *Two additional schools were observed that were not adjacent to the shoreline; one was moving eastward about 300 m offshore, another came perpendicular to shore and turned east.*

Furniss (1975:37) also noted that in Prudhoe Bay large numbers of arctic char sometimes migrated "very close to the shore in extremely shallow water".

In 1978, the distribution of fish relative to distances from shore was examined by recording the position of fish caught in a 122 m gill net placed perpendicular to the shoreline. The catch results show that, under certain circumstances, there is indeed a narrow band of fish adjacent to the shoreline. Although the specific factors involved are unknown, catches were greater close to shore under the following conditions: (1) the water was not exceptionally rough, and (2) the sampling location was at or near a prominent land projection into the lagoon (e.g., Milne Point or Kavearak Point), where water depths fell more rapidly than in embayments. Two examples are illustrated in Figure 11.

The most convincing evidence of fish traveling next to the shore was recorded at the tip of Kavearak Point on 24 July 1978 in fairly clear water (3.2 NTU, or roughly 1 m visibility). On this occasion 50% of the 32 fish caught in the gill net were within 30 m of the shoreline and all were within 80 m. Only anadromous species were caught in this 3-h net set: 13 least cisco, 13 arctic char, 4 arctic cisco, 1 broad whitefish, and 1 humpback whitefish.

A second but less distinct example was encountered at the Milne Point (East) site, which was located on the eastern side of the point, 0.6 km southward of the tip. Here 80% of the fish caught during a 4.5 h set on 29 July were within 61 m of the shoreline, but there were a few out to at least 120 m from shore. It seems likely in this case that, had the net been longer, at least some fish would have been caught more than 122 m offshore. Fishes caught in this set were as follows: 42 least cisco, 30 arctic cisco, 4 arctic char, 1 humpback whitefish and 7 fourhorn sculpin. The waters at Milne Point (East) were also clear (3.6-5.8 NTU). In neither of the cases illustrated in Fig. 11 did it appear that the concentration of fish near the shoreline was a response to any sharp gradient in water temperature or salinity.

In all, seven 122-m gill net sets were made off points of land in moderately calm weather:

Site	Date (1978)	Duration (h)	Total No. Fish
Kavearak Point	24 July	3	32
	8 Aug.	1.5	61
Milne Point	23 Aug.	1	19
	31 Aug.	1	14
	9 Sept.	7	17
Milne Pt. (east)	29 July	4.5	84
Pingok Island*	23 Aug.	1	13

* unnamed SE point in lagoon

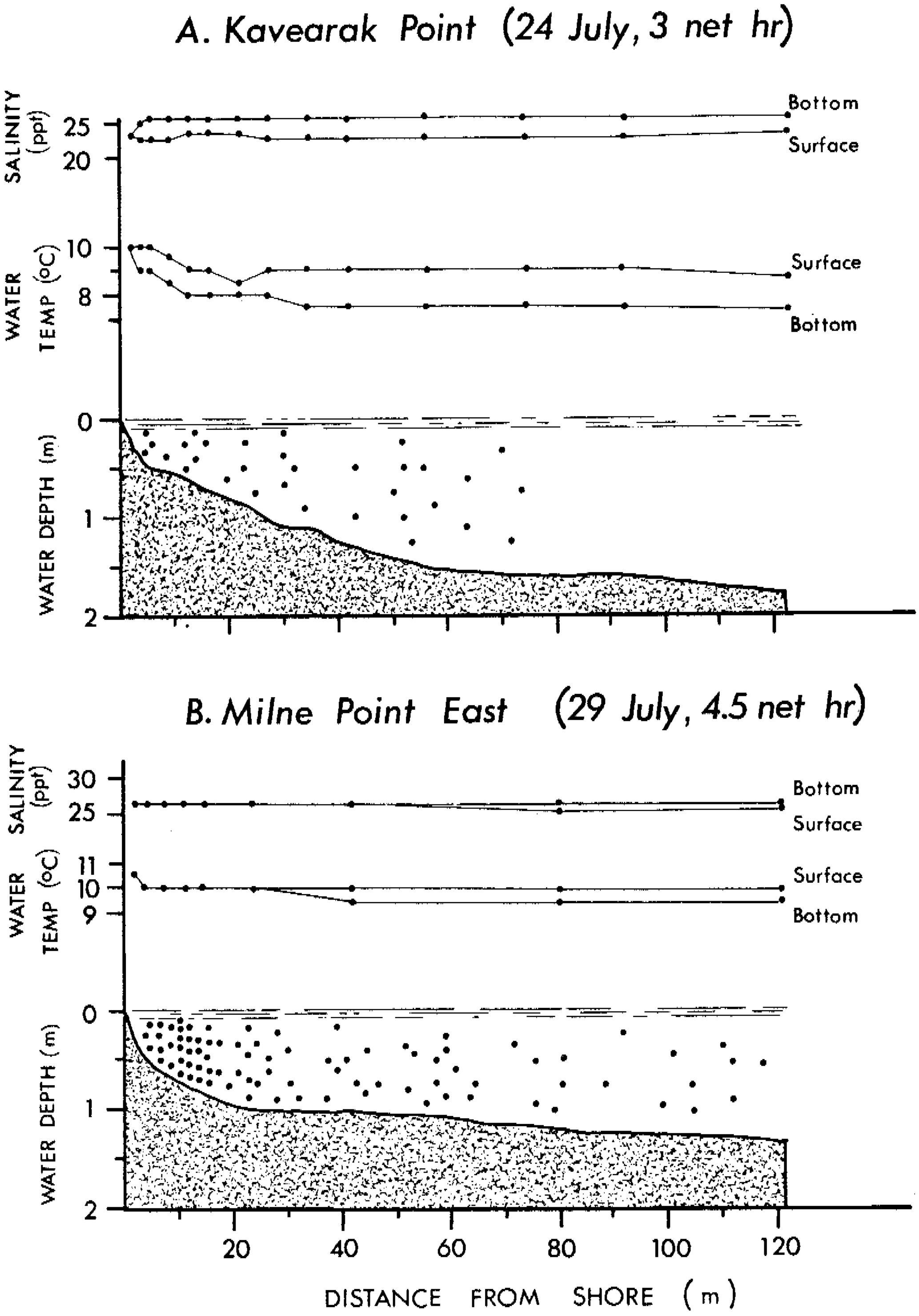

Figure 11. Shoreline Distribution of Fish at Two Sites. Actual distributions of fish (dots) are shown relative to the shoreline, but depths of fish in water column are schematic.

Total numbers of fish caught in these gill nets were 117 least cisco, 52 arctic char, 45 arctic cisco, 18 fourhorn sculpin, 4 broad whitefish, and 4 humpback whitefish. We combined the data from these seven gill net sets and found that distribution patterns were very different between anadromous and marine fish (Figure 12). The fourhorn sculpin, a marine species, was uniformly distributed but anadromous fish were most abundant near the shoreline. Approximately six times as many anadromous fish were caught in the first (landward) 40 m of net as were caught in the last (seaward) 40 m. The abundance of anadromous fish declined stadily with distance from shore out to about 100 m from shore, at which point numbers presumably levelled off. Data from 1977 (Fig. 10) suggested that low densities occurred across the center of the lagoon.

Among the anadromous species, there was a conspicuous absence of habitat partitioning within 122 m of shore (Fig. 13). This probably reflects the migratory nature of these species. Indeed, it has been observed that arctic cisco and arctic char may form mixed schools (Griffiths *et al.* 1975:99). More sedentary fish species often demonstrate spatial segregation along a shore-to-open-water transect (e.g., Werner *et al.* 1977).

It would be erroneous, however, to leave the impression that fish are always concentrated along Beaufort Sea shorelines. There are times and places where the shoreline concentration of fish does not occur. We encountered examples during 1978 (Figure 14). During stormy and rough waters on 9 August, most fish were caught several hundred meters offshore at Milne Point (East). Another transect in the embayment between Milne and Kavearak Points (10 August) caught no fish near the shoreline, but some fish were taken 1.6 km (1 mi) offshore during the same period (Fig. 14).

It appears, therefore, that anadromous fish commonly concentrate near shore along the Beaufort Sea coast, but the occurrence and width of this migration corridor are variable, depending on factors such as the configuration of the coast, underwater topography, weather, etc.

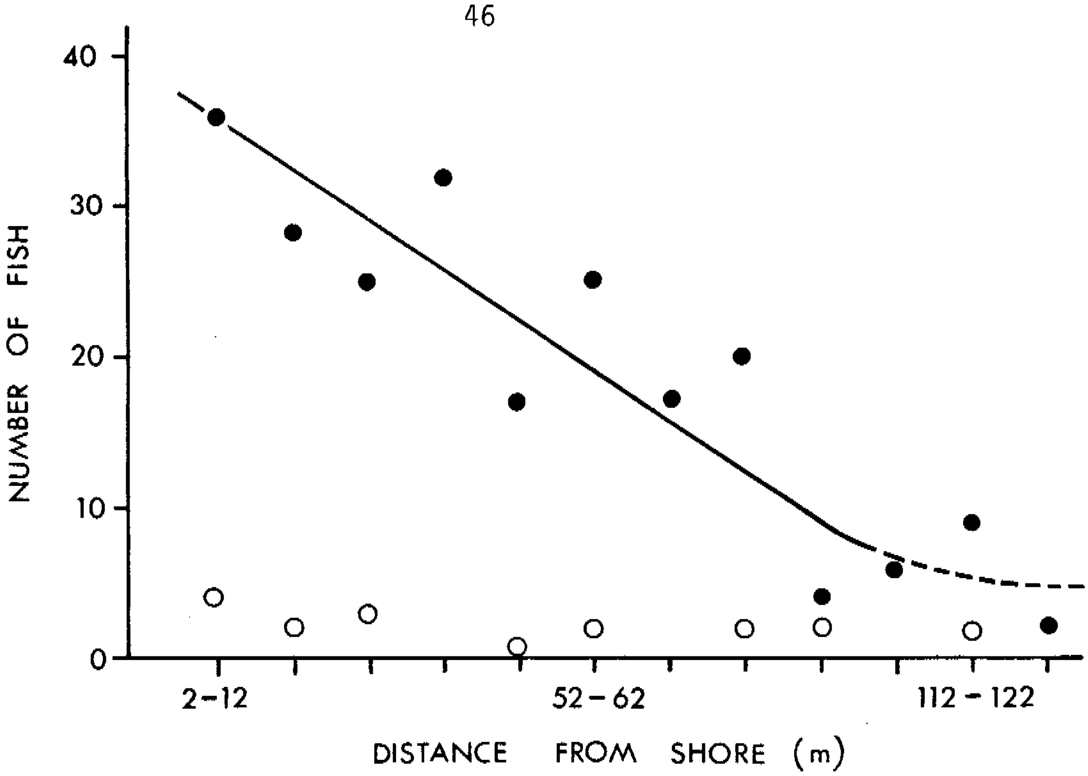

Figure 12. Distances of Fish from Shore off Points of Land on Seven Calm Days in 1978. Total numbers of anadromous fish (●) and fourhorn sculpins (○) caught in gill nets are plotted by 10 m interval. No gill net was set between 0-2 m (see METHODS).

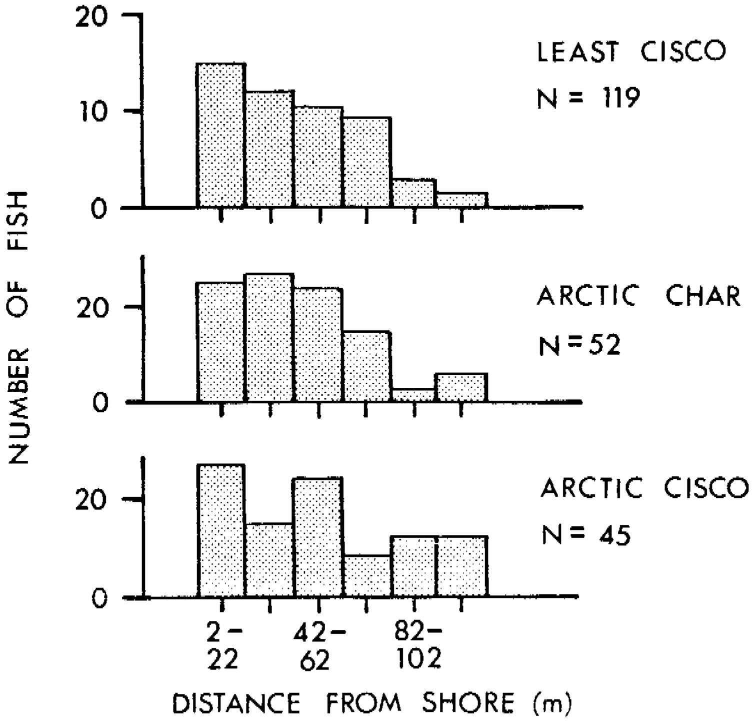

Figure 13. Distances of Three Anadromous Species of Fish from Shore off Points of Land on Seven Calm Days in 1978.

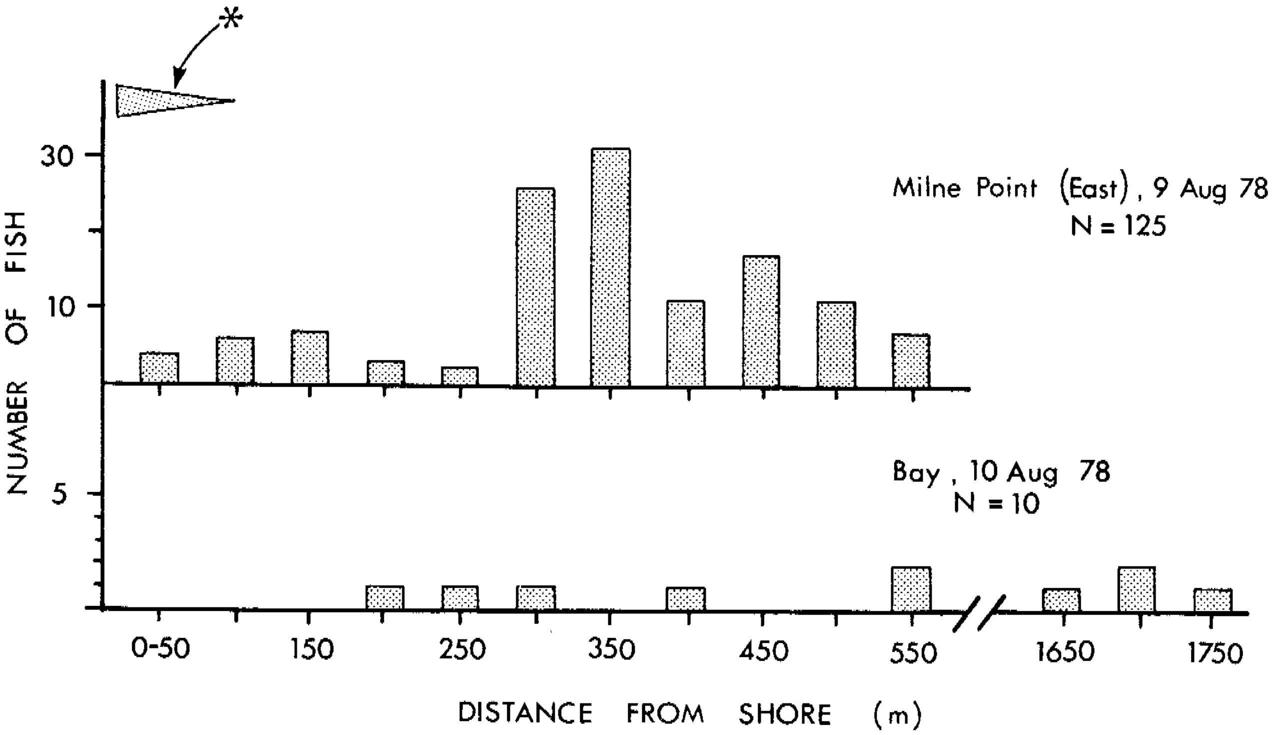

Figure 14. Dispersed Distribution of Anadromous Fish during Stormy, Rough-Water Conditions (top) and in a Relatively Shallow Bay between Milne and Kavearak Points (bottom; no nets were set between 550 and 1650 m). The usual location of the shoreline concentration of fish (see Fig. 12) is indicated by an asterisk.

Why fish concentrate along shorelines is not understood, but there are several possibilities:

1. Predator Avoidance - This is an improbable reason since predator densities are low (Craig and Griffiths 1978).
2. Food Abundance - This is not likely since available data indicate that food is more abundant in deeper waters away from the shoreline (Griffiths and Dillinger 1979).
3. Navigation Aid - perhaps shorelines are useful navigation aids since nearshore waters are often turbid; however, lagoon waters are frequently turbid along shorelines.
4. Habitat Preference - fish may prefer the slightly warmer and less saline waters that are generally found along shorelines; other relevant habitat factors may include water depth or angle of substrate.
5. Habitat "Constriction" Points - perhaps points of land that jut into Simpson Lagoon act as "diversion lines" for fish migrating east or west. A proportion of the fish crossing an embayment would encounter the landmark below its tip and follow its shoreline in order to get around the point. However, fish are also abundant along fairly straight stretches of the coast (e.g. see location and catches of Station 1 in 1977 - Figs. 1 and 10).

Summer Distribution

Figure 15 depicts general fish distribution during the open-water season. The figure represents a liberal extrapolation of point-sources of systematically-collected data combined with the practical and subjective experience we obtained while sampling for fish in Beaufort Sea coastal waters.

Four zones of fish density, graded from Zone 1 (highest density) to Zone 4 (lowest density), are proposed:

Zone 1. Highest densities of fish, occurring in a narrow band about 100 m wide along mainland shorelines, particularly around points of land but not in shallow embayments.

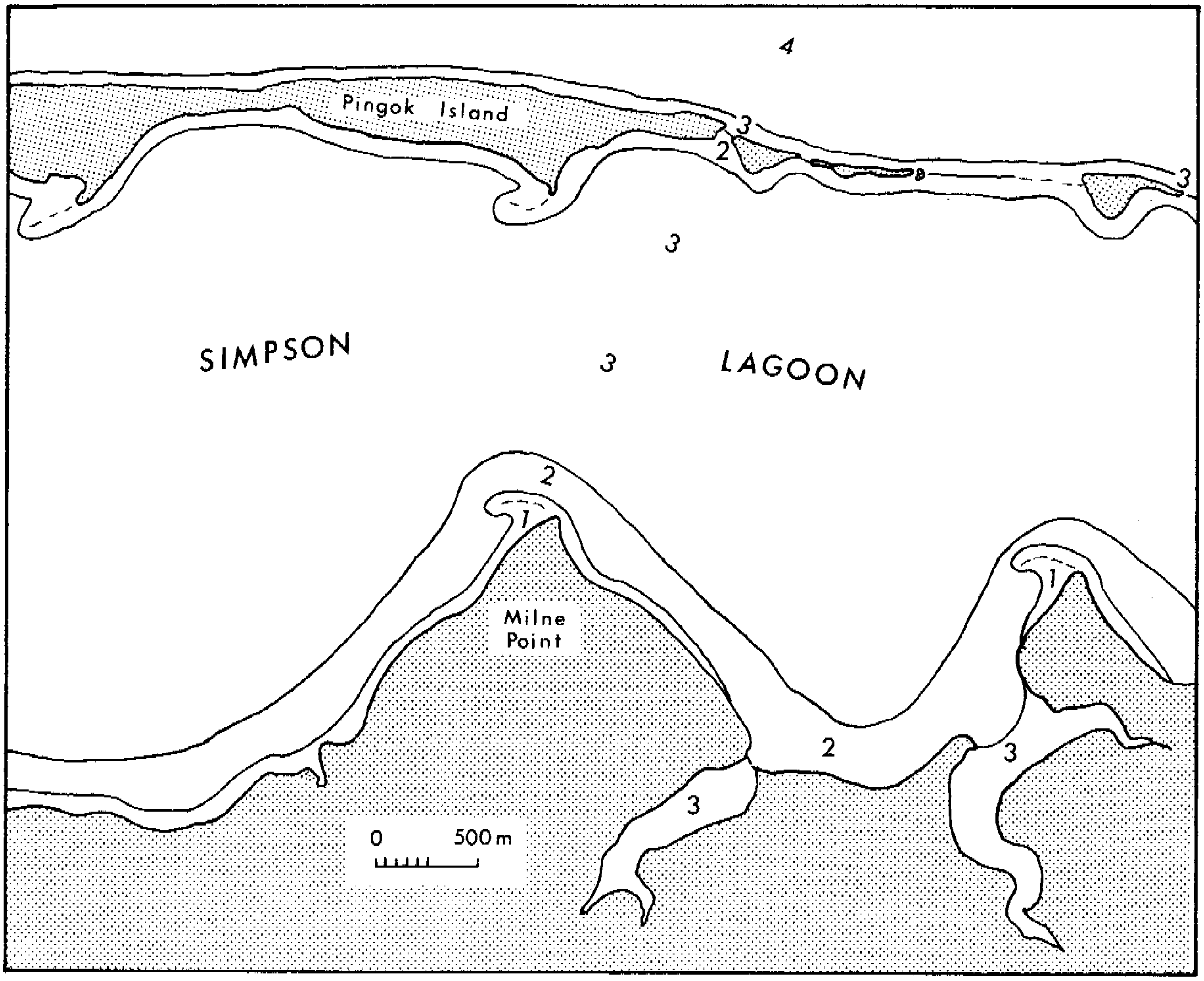

Figure 15. Hypothetical Density Distribution of Nearshore Fishes in the Study Area. Relative densities range from 1 (high) to 4 (low).

Zone 2. A band of medium density of fish around mainland and barrier island (lagoonside) shorelines, extending perhaps 500 m offshore or to the 1.5 m depth contour.

Zone 3. Generally lower densities of fish in the lagoon center and along a narrow band about 100 m wide on the ocean side of the barrier islands.

Zone 4. Lowest densities of fish (especially low densities of anadromous species) in the cold marine waters seaward of the barrier islands.

This picture may best describe the distribution of anadromous fish during the open-water season. The depicted density zones are, of course, generalized and could be refined by further studies.

Winter Distribution

Colville Delta. Both anadromous and marine species were found overwintering in the brackish (17.9-31.9 ppt) waters of the lower Colville Delta during the April and May, 1978, sampling period:

	Catch Per Unit Effort (No./day)	
Species	Station A	Station B
arctic cisco	1.8	1.0
least cisco	1.0	0.7
boreal smelt	0	0.4
fourhorn sculpin	0.5	0.2
Bering cisco	0.2	<0.1
saffron cod	0	<0.1
gill net days	13	44

These catches represent the first records of overwintering areas for anadromous ciscos in Alaskan Beaufort Sea drainages. The data also indicate that these fishes do not necessarily reside in freshwater habitats during the winter period; however, it is not known whether these species utilize other coastal regions for overwintering.

Data gathered during this phase of the winter studies will be analyzed in the final RU 467 report.

Coastal Areas. The abundance and distribution of the fish species utilizing nearshore habitats in the study area changes dramatically during the period of ice cover. This change is marked by the disappearance of all of the dominant anadromous species (cisco, whitefish, and char) that are common during the brief summer. In the November 1978 and February 1979 sampling periods five species of fish were caught. In order of decreasing numbers they are boreal smelt, fourhorn sculpin, arctic cod, saffron cod and snailfish. With the exception of the anadromous boreal smelt, all of these are marine species.

It appears that the boreal smelt and the four-horned sculpin are the dominant fish species in the nearshore waters of the study area during winter, and that they are concentrated in Harrison Bay near Thetis Island which is near the mouth of the Colville River (Table 9). The boreal smelt is a spring-spawning anadromous species (McPhail and Lindsey 1970), and it is assumed that its apparent concentration in Harrison Bay is a prelude to a spawning migration into the Colville River. This supposition is supported by the observation that the great majority of the boreal smelt captured were mature fish in pre-spawning condition. The apparent concentration of fourhorn sculpin, a marine species, near the mouth of the Colville River is not readily explained by any available information.

The data presented in Table 9 very likely provide a biased representation of the abundance and distribution of arctic cod. Arctic cod, because of their shape, are very difficult to catch in gill nets. In November, nearly all of the cod captured in gill nets had advanced gonadal development in addition to full stomachs. The resultant obese condition was likely responsible for their capture. In February 1979 all of the arctic cod had apparently finished spawning, and no captures were made in gill nets. During this sampling period, two new experimental fishing systems, an under-ice fyke net

TABLE 9. Summary of Winter Catch Data, 1978-79. See Fig. 8 for station locations and Table 2 for summary of sampling effort.

Fish	Thetis Island		Simpson Lagoon		Boulder Patch		Narwhal Island	
	Nov.	Feb.	Nov.	Feb.	Nov.	Feb.	Nov.	Feb.
Boreal smelt	182	333	12	0	0	0	0	0
Fourhorn sculpin	14	88	0	0	0	0	0	0
Arctic cod	6	0	21	0	13	51	2	3
Saffron cod	0	18	1	0	0	0	0	0
Snailfish	0	0	0	0	0	15	0	0

and a trammel net (Table 1), were responsible for the capture of all cod obtained. These new systems were each used at only one location; therefore geographic comparisons are not possible for arctic cod in February.

Saffron cod were also concentrated in the area of the Colville River mouth (Thetis Island station) in February. The appearance of mature fish in pre-spawning and spawned out condition suggests that this area is a spawning ground for this species.

Snailfish appeared in the under-ice fyke net catches at the Boulder Patch station in February 1979. Since this species is apparently vulnerable to capture only by this sampling method, we obtained no information about geographic or temporal patterns in its distribution or abundance. Snailfish were actively spawning in the area of the Boulder Patch station in February, as indicated by the attachment of their adhesive egg masses to under-ice sampling gear. The fact that they have demersal adhesive egg masses suggests that a solid substrate, as is common in the Boulder Patch area in the form of rocks and attached algae, may be a requirement for their spawning.

Abundance of Fish Versus Physical Factors

Due to large day-to-day variations in numbers of fish taken in fyke nets, comparisons were made between catch data and each of three features of the environment that fluctuated almost daily: salinity, water temperature and turbidity.

Correlation coefficients were calculated for data collected along the mainland shoreline during the period 30 July - 24 August 1977 (n=17-22 dates when measurements of each physical variable could be directly compared to daily fish catches). Since each day's catch covered a 24-h period, numbers of each species were compared separately to physical data collected both at the start and end of the corresponding 24-h period. In only one case was there a significant correlation between numbers of the five most abundant species and the physical factors monitored; least cisco catches were negatively correlated with water temperature (r = -0.461, P<0.05). This correlation appears biologically unreasonable because least cisco were most abundant along the mainland shoreline, where the warmest waters in the study area were found (Tables 5, 7, 8). Few of this species travelled along the barrier islands where water temperatures tended to be 2°C or more cooler (Fig. 2, 3). This particular correlation is most likely a spurious one and was not supported by data the following year.

A more extensive collection of data was possible in 1978 because of the extended time the fyke net operated. This provided more daily values (n=54-56) of fish numbers and physical factors during the period 10 July - 20 September. As in the previous year, there were no significant correlations of catches with turbidity, but several correlations between catches ans salinity and temperature emerged:

	Statistical correlation		
Species	Factor	Coefficient	P
fourhorn sculpin	salinity,	0.351	<0.01
	temperature	-0.265	<0.05
humpback whitefish	salinity	-0.451	<0.001
broad whitefish	salinity,	-0.367	<0.01
	temperature	0.281	<0.05
least cisco	temperature	0.427	<0.01
arctic flounder	temperature	0.302	<0.05

These correlations were derived from comparisons of fish numbers with physical conditions at the time the fish were counted (i.e., the end of the 24-h sampling period). If fish numbers are compared with physical conditions at the beginning of each sampling period, two of the above correlations (fourhorn sculpin vs temperature and broad whitefish vs temperature) are not significant.

The statistically significant correlations can be re-organized in the following fashion to illustrate relationships between fish numbers and relatively high or low salinities and water temperatures:

	LOW	HIGH
salinity	humpback whitefish broad whitefish	fourhorn sculpin
temperature	fourhorn sculpin	least cisco broad whitefish arctic flounder

The apparent preference for warm waters, low salinity waters or both exhibited by several species corresponds with their distribution patterns in Simpson Lagoon. Tables 5, 7 and 8 show that least cisco, humpback whitefish, and broad whitefish were all most abundant along the mainland shoreline where waters were warmer and less saline than in other nearshore habitats. In contrast, numbers of the fourhorn sculpin, a marine species, increased along the mainland shoreline when waters became more marine.

The above results must be treated with caution because seasonal trends in fish numbers, fish behavior and physical factors undoubtedly confound the relationships between daily catch and daily physical conditions. Data would have to be collected throughout several summer seasons in order to separate these interrelated factors.

To the extent that the above results are meaningful, it appears that there is a tendency for several species of anadromous fish to use shoreline habitats when waters are warm and brackish. A marine species tends to appear when conditions become more marine. The species that showed no correlation between numbers caught and temperature or salinity (arctic cisco, arctic char, arctic cod) are those with the widest distributions. We postulate that they are wide-ranging at least partly because they are more tolerant of fluctuating temperatures and salinities.

Fish Movements

General features of the temporal distribution of fish in the study area are that (1) most, but not all, fish use nearshore habitats only during the ice-free season, and (2) within this period, the fish are highly mobile and evaluations of their local abundance are complicated by day-to-day pulses of movement and larger scale movements over several-week periods.

During the brief arctic summer, both anadromous and marine fish invade the shallow water zone of the Beaufort Sea. Although nearshore ice may not completely disappear until early July, fish have by this time already been migrating and feeding under the ice and in leads for up to several weeks. The present study and others (Griffiths *et al.* 1975, 1977; Bendock 1977) show that fish enter nearshore waters almost as soon as there is enough unfrozen water in which to swim.

In Simpson Lagoon the first open water areas in spring were leads along mainland and island shorelines. When sampling programs began in the lagoon-side lead of Pingok Island on 19 June 1977 and along the mainland shore at Milne Point on 27 June 1978, fish were already present and actively feeding. First capture dates for major species are listed below; for most species, arrival dates were within one week of each other during the two years.

	1977	1978
fourhorn sculpin	19 June	28 June
arctic cisco	22 June	27 June
least cisco	30 June	29 June
broad whitefish	-*	29 June
humpback whitefish	-*	29 June
arctic char	3 July	6 July
arctic cod	12 July	7 July

* No broad or humpback whitefish were caught at Pingok Island in 1977.

Most anadromous fish appear to have returned to freshwater by the time ice-over. Marine species, on the other hand, are still present in the lagoon under the ice through November, but diminishing depths of unfrozen water probably force most if not all fish out of Simpson Lagoon and into deeper waters by mid-winter (see previous section). Because of the thickness of ice in late winter (about 2 m), all fish are excluded from the shallow shoreline habitats that are utilized so extensively during summer months.

Seasonal Movements

In the following sections, the movements of major fish species through Simpson Lagoon and adjacent regions are described. Information was derived from three sources: (1) a tagging program to document movements of individual fish, (2) fyke nets which operated daily during the open-water season, and (3) gill nets which were used to sample fish in summer and winter.

The tagging program was conducted to help study coastal movements of fish and their residency times in Simpson Lagoon. During the summers of 1977 and 1978, 5088 fish were tagged; 2146 large fish (generally >250 mm) were tagged with Floy dart tags and 2942 small fish (generally 100-250 mm) were tagged with metal opercular tags (Table 10). The recovery rate was low. Excluding fish recaptured the day after tagging (since they might have re-entered the fyke net upon release), only 1% of the small fish and 4% of the large fish were recovered. Most (82%) of the latter were caught in the Colville Delta commercial fishery. Additional movement information was obtained by the captures in Simpson Lagoon of 40 fish that had originally been tagged outside the study area by the Alaska Department of Fish and Game (ADF&G). All recapture data are listed in Appendix 1.

Data acquired as a consequence of the recapture of 138 fish during this study allows us to speculate about the movements of fish in coastal waters. However, any patterns inferred from these data should be viewed in the context of several factors:

TABLE 10. Summary of Fishes Tagged in Simpson Lagoon, 1977 and 1978.

Species	1977 Floy Dart Tag	1977 Opercular Tag	1978 Floy Dart Tag	1978 Opercular Tag	TOTAL
Fourhorn sculpin	0	2381	0	4	2385
Least cisco	126	46	893	5	1070
Arctic char	55	281	349	0	685
Arctic cisco	30	57	369	5	461
Broad whitefish	4	1	166	5	176
Arctic cod	0	110	0	0	110
Pink salmon	0	0	88	0	88
Humpback whitefish	1	0	64	0	65
Arctic flounder	0	47	0	0	47
Grayling	0	0	1	0	1
Total	216	2923	1930	19	5088

1. Recapture location. Locations of recaptures will be predictably clumped at the few coastal sites where fishing programs operate. Such operations occurred in Prudhoe Bay during summers of 1976 and 1977 (Bendock 1977; Doxey 1977), Simpson Lagoon during summers of 1977 and 1978 (this study), and the Colville Delta in early winter every year (Hemericks' commercial fishery). About 50,000 cisco and whitefish are harvested annually in the Colville commercial fishery which partially accounts for the large numbers of recaptures at this site.

2. Small Fish. Recaptures of small fish (marked with opercular tags) are not to be expected outside our study area because these fish are not sought by fishermen and small fish are generally not susceptible to capture by gill net or angling.

3. Direction of Movement. The net direction of movement between release and recapture sites depends on when as well as where fish were tagged. Anadromous fish tend to move away from rivers of origin in early summer and return in late summer.

4. Historical Perspective. Arctic char in the Sagavanirktok River were the object of an extended tagging program from 1970 to 1974. The probability of catching a tagged char from this drainage is greater than for other North Slope rivers.

Arctic Cisco. The arctic cisco was the first species caught in the study area each spring. During the early breakup period these fish were abundant in open-water leads around Pingok Island (Fig. 16). Individuals caught at this time were primarily mature spawners, which may have overwintered in the nearby Colville Delta (see Winter Distribution). It appears that spawners of the year leave their overwintering areas at the first opportunity, feed voraciously in Simpson Lagoon for about two weeks (all had stomachs full of amphipods and mysids), and then leave coastal waters.

Unlike the mature fish, which would spawn in fall, juvenile and mature non-spawning arctic cisco were abundant in nearshore

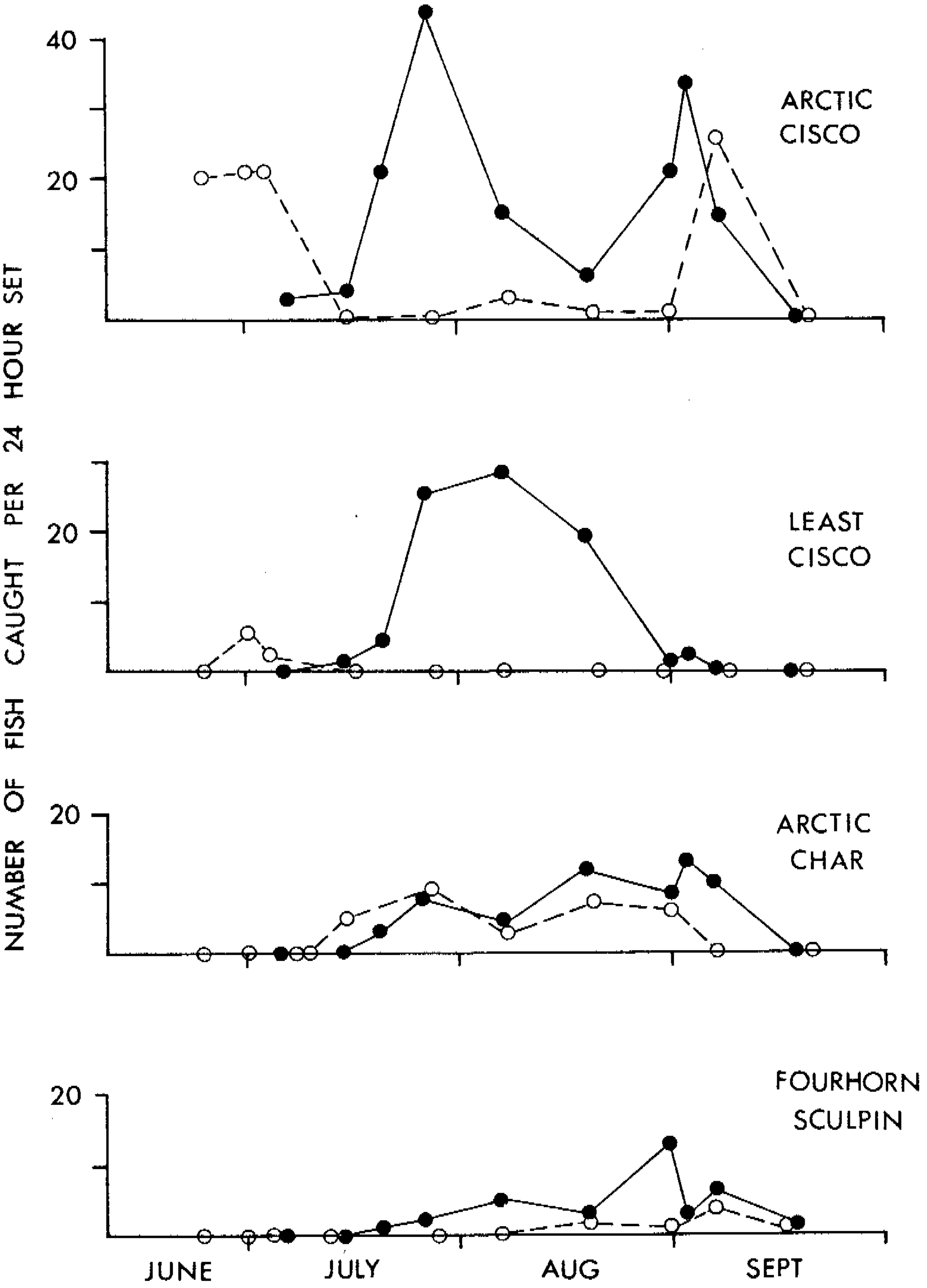

Figure 16. Seasonal Abundance of Fish Caught by Gill Net along Mainland (solid dots) and Pingok Island (open dots) Shoreline, 1977.

environments throughout the open-water season. Figure 16 shows two major periods of activity, which probably represent migrations from the Colville River in the latter half of July and back to the Colville in early September. This bimodal activity pattern was not observed for arctic cisco at locations more distant from the Colville: Kaktovik Lagoon (Griffiths *et al.* 1977); Prudhoe Bay (Bendock 1977).

Daily fyke net catches of arctic cisco (Fig. 17) indicate two points: (1) daily catches varied greatly, suggesting that fish were passing by in pulses or schools rather than in a large, even migration, and (2) temporal patterns varied substantially between years for this species. Most arctic cisco intercepted by the 1977 fyke net were small fish (92% of the arctic cisco caught were <200 mm); peak movements of these small fish occurred in late August and early September of 1977, perhaps indicating their return to the Colville River. The following year, these small fish were proportionally much less abundant in the fyke net (55% of total arctic cisco catch) and the autumn peaks of activity were absent. Analysis of directional movements showed that most Arctic cisco traveled eastward (away from the Colville) in early July 1978 and westward in mid-August 1978. These movements are in agreement with the contention that the Colville River is the source of arctic cisco in the study area. It is not known why these fish apparently returned to the vicinity of the Colville much sooner in 1978 than 1977.

Few arctic cisco were caught by gill or fyke nets in mid-September (Fig. 16, 17), and none were caught in the November or February winter sampling program. This indicates that individuals in the population had returned to the Colville Delta region by the end of September or October.

Of 31 arctic cisco tagged in Simpson Lagoon during summer and recaptured the same year, 30 were recaptured under the ice during the October - December period in the lower Colville Delta (Figure 18). One was recaptured at Milne Point, the site of tagging, 29 days after release.

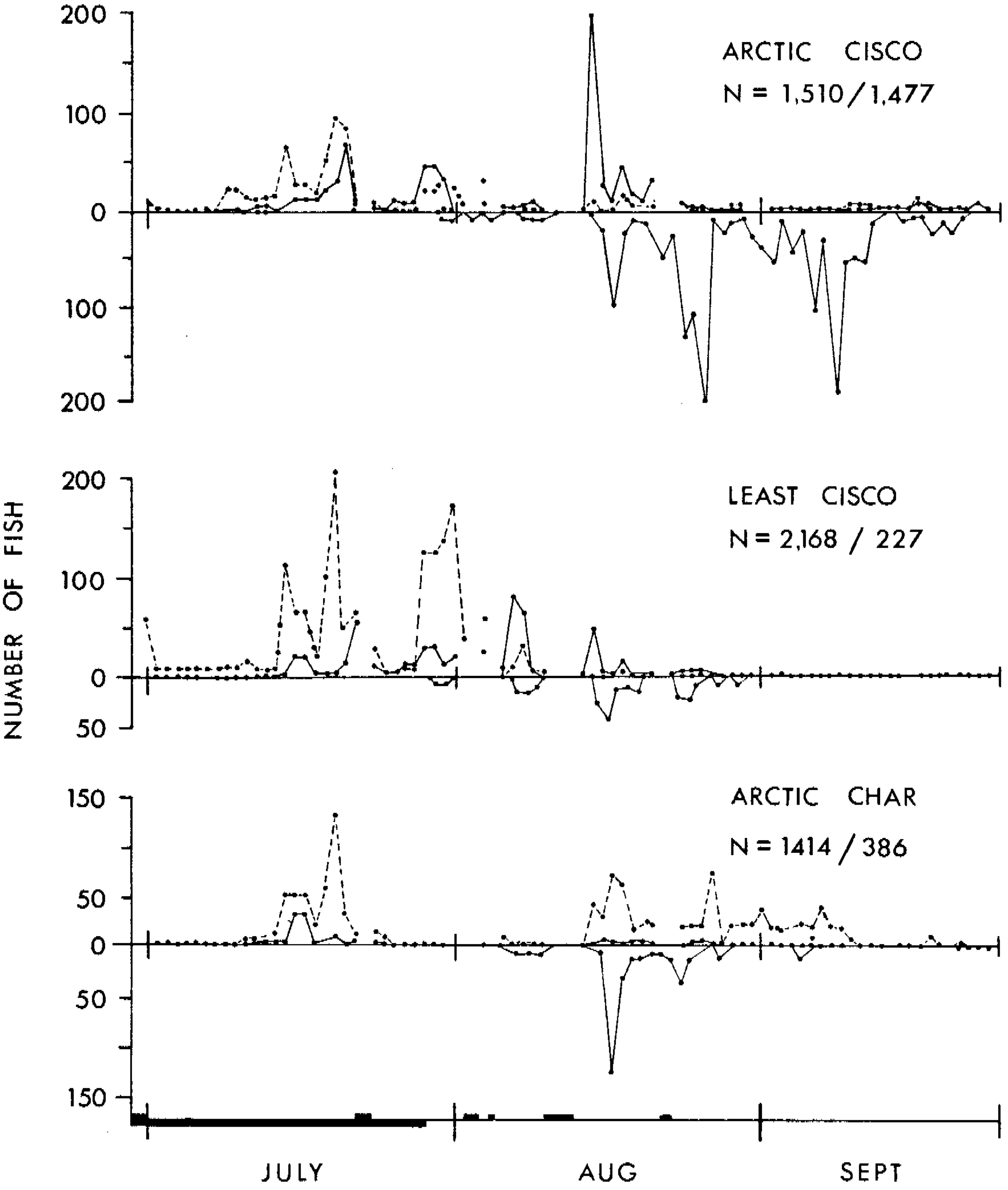

Figure 17. Comparison of Daily Fyke Net Catches along the Mainland Shoreline in 1977 and 1978. Nets were located at Milne Point in 1978 (upper graphs) and 6 km west of Milne Point in 1977 (lower graphs). Numbers of fish caught are indicated by year: 1978/1977. For 1978 catches, solid lines show fish moving westward; dashed lines show eastward movement. Dark bars along abscissa indicate periods when fyke nets were not in operation in 1977 and 1978.

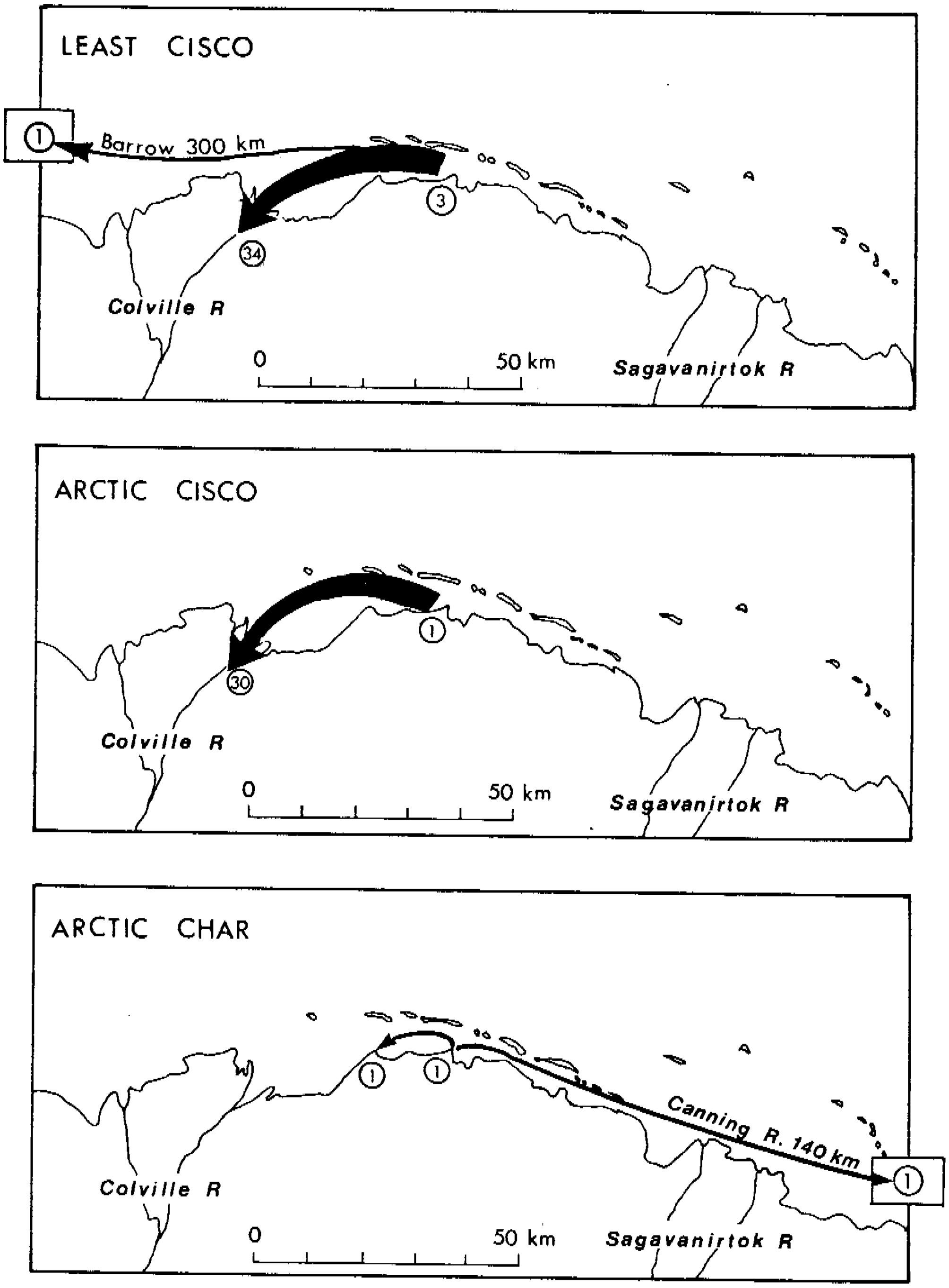

Figure 18. Coastal Movements of Tagged Fish during a Single Year. Fish were tagged at Milne Point, Simpson Lagoon. Numbers of recaptures at each site are indicated.

Three additional arctic cisco were recovered one year after release. One fish had visited Prudhoe Bay and Simpson Lagoon in consecutive summers. Two others travelled through Simpson Lagoon in August 1977 and were recaptured the following year in the Colville Delta (October 1978).

Least Cisco. In contrast to the arctic cisco described above, almost all least cisco in the system were large fish; 89% and 98% of all least cisco caught in fyke nets in 1977 and 1978, respectively, were >200 mm in length. This species was rare along barrier islands but was abundant along the mainland in mid-summer (Fig. 16). Fyke net catches showed that the predominant direction of movement was away from the Colville (east) in July and towards the Colville (west) in August (Fig. 17). The chronologies of the September catches were similar between the two years of study. By early winter, least ciscos apparently have moved towards their overwintering areas; none was caught in nearshore areas during November and February winter sampling efforts.

Recapture data are consistent with the view that the Colville River is the principal source of least cisco in coastal waters east of this river (Craig and McCart 1976; Bendock 1977; Doxey 1977). Most recaptures (89% of those recovered the same year that they were tagged) were taken in the Colville Delta commercial fishery (Fig. 18). These fish were tagged in Simpson Lagoon in the summer and recaptured under the ice of the Colville Delta during October - December. One other fish tagged by us was recaptured at a fishing camp near Barrow (specific location unknown) in the fall. Perhaps this least cisco originated in a stream to the west of the Colville.

Lease cisco were also recaptured in Simpson Lagoon 1-2 years after being tagged in Simpson Lagoon (n=1) by us or in Prudhoe Bay (n=26) by ADF&G. Ten of these were recaptured the first year after they were tagged; this indicates that some least cisco enter coastal waters on an annual basis.

Arctic Char. Char moving through the lagoon were generally large fish; 95% and 75% of all char caught in 1977 and 1978, respectively, were >200 mm in length. Their widespread distribution in the lagoon and around the barrier islands (Tables 5, 7) suggests that they are more tolerant of marine waters than are most other anadromous species. Similar abundance patterns for this species are evident along mainland and Pingok shorelines (Fig. 16). Char were common in nearshore waters for most of the open-water period, and fyke net catches showed that they remained in the lagoon about 2 weeks longer in 1978 than in 1977 (Fig. 17).

The direction of char movements, as indicated by the 1978 fyke net data, was predominantly from west to east. However, in this case the location of the fyke net may have biased catch statistics. It is possible that the submerged gravel bar off Milne Point influenced the movements of some fish so that they would not be proportionally represented in east and west traps of the fyke net (see METHODS). Char caught in gill nets did not exhibit the same directional movements. In 11 mainland gill net sets, 15 July - 9 September, field crews recorded the side that fish struck the net as an indicator of the direction of movement. The results did not show a predominant direction of movement (n=163 char, 51% caught on east side of net and 49% on west side). It is therefore concluded that the fyke net data do not accurately reflect the direction of movement of arctic char. (Other species do not lend themselves to a similar analysis because of apparent reversals in movement and the timing of gill net sets in relation to the timing of peak movements of fish.)

Recaptures of marked arctic char, though few in number, indicate that a large proportion of the individuals using Simpson Lagoon originate from the nearby Sagavanirktok River. Seven char that were recaptured in the lagoon had been tagged 4-7 years earlier in the Sagavanirktok drainage. An additional two fish had been tagged 1-2 years earlier in Prudhoe Bay.

Only three char were tagged at Milne Point and recovered the same year. One was caught at Milne Point 25 days later, the second at Oliktok Point, and the third in the Canning River approximately 140 km to the east (Fig. 18).

Arctic Cod. This species provided the most dramatic example of annual variability recorded during this study (Fig. 19). Based on our 1977 findings in Simpson Lagoon and Bendock's (1977) observations the previous year in Prudhoe Bay, a modest increase in cod numbers was expected as freeze-up approached, but we did not anticipate the massive school of cod that swept through the lagoon in mid-August of 1978. During a nine-day period (14-22 August), an estimated 124,200 arctic cod were caught in the Milne Point fyke net. The fish were highly mobile as indicated by erratic daily catches; for example, approximate daily catches during the period 18 to 22 August were 17,000, 42,000, 6,000, 40,000 and 15. There was no clear pattern of directional movements at this time (Fig. 19). These were generally small and young fish (60-160 mm, which would be ages 1-3 according to data given by Craig and Griffiths 1978:66).

The cod run was not restricted to Simpson Lagoon, but was also observed elsewhere along the Beaufort Sea coastline. Very large numbers of this species were reported in August in Prudhoe Bay on the west side of the ARCO causeway (C. Broad, pers. comm.). The tendency of arctic cod to travel in large schools has been observed in other high arctic areas (Bain and Sekerak 1978).

Arctic cod continued to occur throughout the nearshore area in November, and were found at the boulder patch and Narwhal Island sites in February 1979 (Fig. 8, Table 9).

Fourhorn Sculpin. Large fourhorn sculpins, generally 140-240 mm, were present in low numbers through most of the season (Fig. 16). Although gill net and beach seine data show that these large sculpins

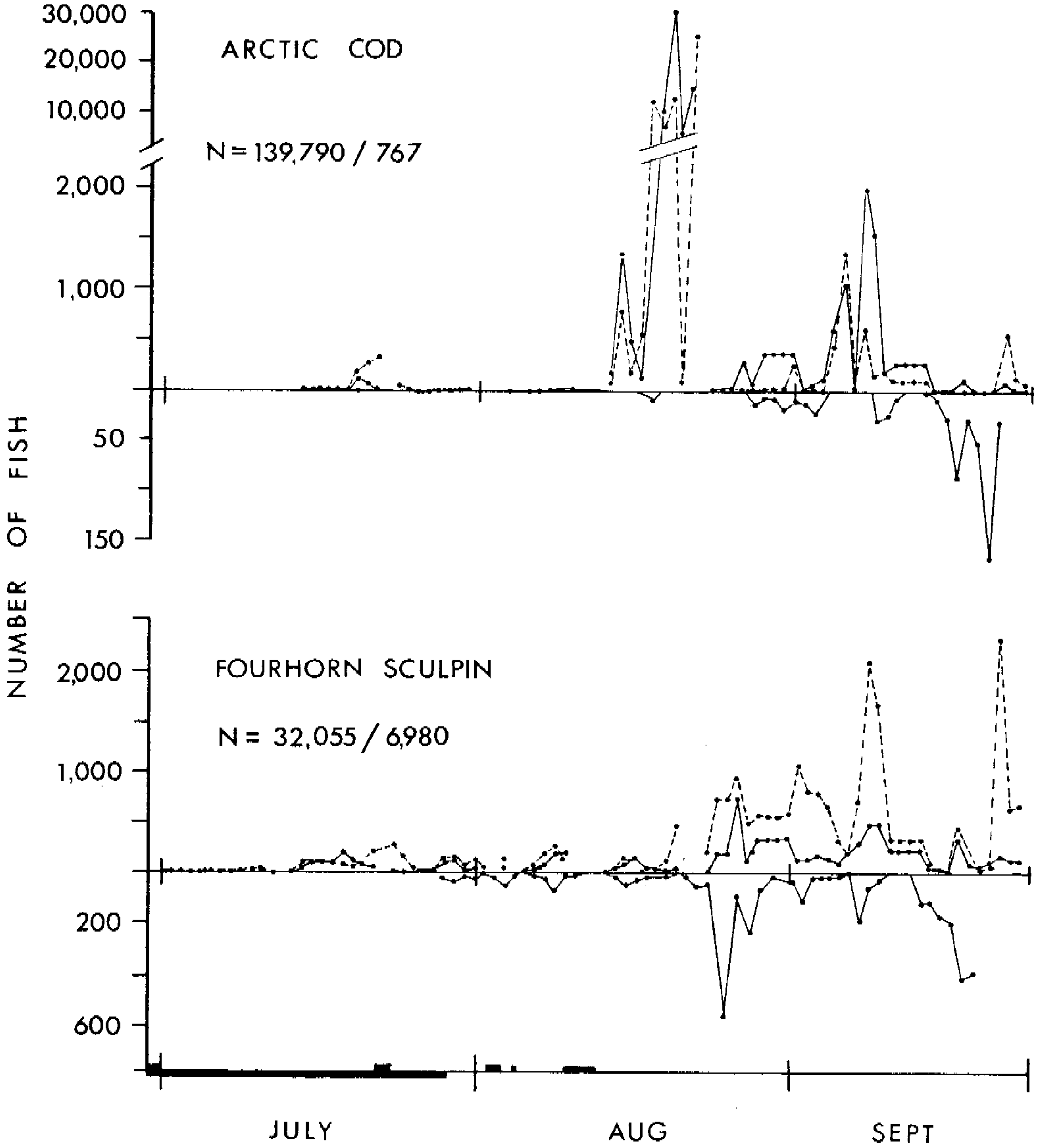

Figure 19. Comparisons of Daily Fyke Net Catches along the Mainland Shoreline in 1977 (lower graphs) and 1978 (upper graphs). See Figure 17 for explanation of symbols.

were more abundant along the mainland shoreline than near the barrier islands (Tables 5 and 7), fyke nets caught almost equal numbers of small sculpins at both locations (Table 8). Numbers of this species increased in both years as the open-water season progressed (Fig. 19), but winter data suggest that most of these fish leave the lagoon again in winter. It appears they then move to deeper waters such as those around Thetis Island (Table 9). The presence of spawned-out sculpin in February at the Thetis Island site suggests that they may spawn in that area. The 17 recaptures of marked fourhorn sculpin were described in the next section (Residency Time in Simpson Lagoon; see also Table 11).

Boreal Smelt. Although these fish occurred sporadically in Simpson Lagoon during summer, winter data indicated that they move into nearshore areas when these areas are covered by ice. A concentration of boreal smelt was found at the Thetis Island site during November and February; these smelt were presumably gathering for a spring spawning run into the Colville River.

Broad and Humpback Whitefish. Populations of broad and humpback whitefish enter coastal waters from the Colville and Sagavanirktok rivers, but little is known about their movements. One broad whitefish was recaptured at the Milne Point tagging site after 37 days, and another travelled from Milne Point to Oliktok Point in early September.

One broad whitefish and three humpback whitefish were tagged in Prudhoe Bay and recaptured 1-2 summers later in Simpson Lagoon.

Pink Salmon. A small run of pink salmon passed through Simpson Lagoon in 1978. One fish was tagged in the lagoon on 6 August and recovered the next month in a subsistence net at Barrier Island, about 250 km to the east.

Residency Time in Simpson Lagoon

Although it is difficult to determine the time that fish spend in an area, there are two basic reasons why this information is desirable:

1. An implicit assumption in this project has been that estuarine environments, such as Simpson Lagoon, are biologically special habitats in the arctic, just as they are in temperate latitudes. Does Simpson Lagoon provide essential habitat for some fishes? Do fish spend more time in lagoon habitats than in non-lagoon segments of the Beaufort Sea coastline?
2. If oil or a toxic chemical accidently spilled into a lagoon, would only those fish already present be affected, or would fish continually move into the contaminated area from surrounding waters?

It was not feasible to obtain precise information about residency time, but we obtained some useful information about this topic by examining (1) the pattern of tag recaptures, and (2) the mean rates of longshore movement of tagged fish.

Pattern of Recaptures. Although numbers of fish that were both tagged and recaptured in Simpson Lagoon were low, these data provide some indication of residency time of the fish.

For large anadromous fish (mainly arctic cisco, least cisco, and arctic char), the paucity of recaptures suggests that these fish do not linger in the lagoon. Despite a continued program of fyke and gill netting, only 9 of the 2146 large fish marked in the lagoon were recaptured in the lagoon during this two year study. Of these, one was marked in 1977 and recaptured in 1978, and 8 were both marked and recaptured in 1978. Excluding one least cisco that was caught a year after being tagged, the days elapsed between tagging and recapture were

least cisco	2, 2, 2, 28
arctic cisco	29
arctic char	24
broad whitefish	2, 38

Four of these fish were recaptured at the same site after two days; the remaining individuals, all recaptured about 1 month after tagging, may well have migrated out of Simpson Lagoon and back again.

The significant point is that these eight fish represent only 0.4% of all tagged large fish. Thus, a large portion of these fish either moved quickly out of the sampling area or avoided recapture.

Tag recaptures of small fish also provide some information on the movements of these fish and their residency times in Simpson Lagoon. In 1977, 2923 small fish were tagged and 15 were recaptured: 13 fourhorn sculpins, one arctic flounder, and one arctic cod. The arctic flounder was recaptured 21 days later at the same site (Milne Point); the arctic cod two days later at the same site (also Milne Point). The following numbers of days elapsed between tagging and recapture of the fourhorn sculpin: 2 days (n=5 fish), 3(1), 5(3), 16(1), 19(1), 21(1), 24(1). Eleven fourhorn sculpins were recaptured at the site where they were originally tagged (Table 11); the other two crossed the lagoon from the mainland and were recaptured 19 and 21 days later at Pingok Island. Four of the 2381 fourhorn sculpins tagged in 1977 were recaptured in 1978; three of these were recaptured about 5 km from their tagging site.

Tagging data for the fourhorn sculpin, coupled with what is known about the species, suggest that these marine fish may reside in a particular region for one or more summers. Andriyashev (1954) comments that this species "lives permanently near the coast without accomplishing any considerable migrations". In addition, males of this species are known to establish territories during their reproductive period in fall and winter (Westin 1969). Some sculpins apparently leave Simpson Lagoon in winter, and certainly must abandon the shallow, nearshore area of the lagoon in winter. The recapture of four individuals in the lagoon one summer after marking suggests that at least some individuals return to that area after having spent the winter elsewhere.

TABLE 11. Tagging and Recapture Distribution of Fourhorn Sculpin in Simpson Lagoon, 1977 and 1978.

	Tagged		
	1977		1978
Recaptured	Mainland (n=1217)	Pingok Island (n=1164)	Mainland (n=4)
1977			
Mainland	7	0	-
Pingok Island	2	4	-
1978			
Mainland	3	1	0

Net Rate of Movement. As fish travel along the coastline, their net rate of movement is a complex function of the frequency, duration and nature of feeding, resting, turning, migrating, etc. Recapture data can provide information about the net rate of movement. From this net rate, we can estimate the time that an average fish might spend while traveling the length of Simpson Lagoon.

An estimate of net movement rates was obtained by using all available mark and recapture data for anadromous fish in Beaufort Sea waters. Only the fish both marked and recaptured along the coast in a single year were useful. Sources of these data are the present study and another conducted by the Alaska Department of Fish and Game (Bendock 1977; Doxey 1977). ADF&G maintained several fyke nets in Prudhoe Bay and tagged nearly 5000 anadromous fish in 1976 and 1977. Suitable tag data (i.e., complete details of tag and recapture dates and locations, or reasonally complete data from which time and distances could be inferred) were available for 78 fish in the ADF&G studies and 4 fish from Simpson Lagoon. These fish had travelled net coastal distances of 0-241 km in 1-21 days (typically 1-20 km in 1-10 days). In all cases, a correction factor of 0.25 days was subtracted from the elapsed time between release and recapture to allow for the average time that recaptured fish spent in the ADF&G fyke net (fyke nets were checked twice daily, weather permitting). Data on fish that migrated from coastal waters to spawning sites in North Slope rivers were not included in these calculations.

The average net rate of travel of the 82 tagged fish (species combined) was 3.2 km/day (range=0-23 km/day, S.D.=4.3). At this rate of longshore movement, the mean residency time in Simpson Lagoon (37 km shoreline length) for an anadromous fish would be 12 days, assuming that the fish maintained the same net direction of travel throughout its period of residency in the lagoon. For those fish that characteristically travel eastward in early summer and return in late summer, total residency time for the summer would be 24 days.

At a rate of 3.2 km/day, an anadromous fish that entered coastal waters for 2 months would be able to travel about 100 km from its stream of origin before having to turn around. It is not known how realistic this range estimate is, but various tagging studies in the Beaufort Sea area each provide a few recaptures of anadromous fish that travelled 2 or 3 times this distance in coastal waters during a single summer (Furniss 1975; Griffiths *et al.* 1975; Bendock 1977; Doxey 1977; Craig and Griffiths 1978).

Migrating cisco and char are capable of much faster swimming speeds than is indicated by the above calculations for net movement. Measured speeds of 0.9 m/sec or 78 km/day have been recorded in coastal waters for fish apparently returning to fresh water in the fall (re-calculated from data of Griffiths *et al.* 1975). If fish entered coastal waters and proceeded outward at the slower rate (3.2 km/day), but then returned to their North Slope rivers at a rapid rate (50-75 km/day), their coastal range would be extended to almost 200 km.

It is interesting to note that these rough calculations would account for the observed scarcity of least cisco in the Barter Island region of the Beaufort Sea coast (Craig and McCart 1976; Griffiths *et al.* 1977). Barter Island is about 250-300 km from each of the two rivers (the Colville and Mackenzie rivers) that support major stocks of this species. Perhaps this distance is too great for most least cisco in the time available. These two rivers are also the principal sources of arctic cisco; however, there is no similar hiatus in their distribution in the area mid-way between these rivers.

Fish Densities

Population Size and Structure of Arctic and Least Cisco

The tagging program conducted in Simpson Lagoon during 1978 for arctic and least cisco provides the basis for estimates of the sizes of the Colville River populations of these important anadromous species. The operation of a commercial gill net fishery for arctic and least cisco in the Colville River delta during the period from

October through December 1978 provided recaptures of fish that were originally caught by fyke net and beach seine in Simpson Lagoon. The size of the tagged fish (>275 mm) was such that they should have been vulnerable to the commercial fishery. All available evidence, including the winter sampling in November 1978 and February 1979, indicates that all of these fish enter the Colville Delta by early winter. There is no reason to suspect that random mixing of marked and unmarked fish has not occurred by the onset of commercial fishing in October.

The conditions discussed above result in an excellent opportunity to estimate the numbers of catchable fish of these species. The characteristics of this system fit the requirements of the Petersen single-census procedure for estimating population size (Ricker 1975). The necessary data and results are given in Table 12. The direct estimate tends to overestimate the true population size, whereas the unbiased estimate (derived by Ricker's 1975 method and based on the method of Chapman 1951) more correctly estimate the true population. Population sizes are thus estimated at about 250,000 arctic cisco and 590,000 least cisco. These estimates of population size include only the fish vulnerable to the commercial fishery, which are non-spawning individuals over 275 mm in length.

Data available from an Alaska Department of Fish and Game tagging program conducted in 1976 provide an earlier estimate of population size for Colville River populations of arctic and least cisco, based on the same criteria and procedures used in the 1978 estimate. In that case the fish were tagged in Prudhoe Bay during the 1976 open water season, and were recaptured in the 1976 Colville River commercial fishery. The data used and resulting estimates are also given in Table 12. These estimates require the same assumptions and involve the same restrictions as the 1978 estimates. Also, for these estimates to be valid it must be assumed that all of the fish tagged in Prudhoe Bay returned to the Colville River delta in the fall of that year.

Comparison of the figures from 1976 and 1978 suggests that numbers of least cisco have increased somewhat, whereas numbers of arctic

TABLE 12. Estimates of the Catchable Populations of Arctic Cisco and Least Cisco in the Colville River Seagoing Population during 1976 and 1978.

	Arctic Cisco		Least Cisco	
	1978*	1976†	1978*	1976†
# tagged	369	628	893	3,185
# in commercial catch	18,115	31,659	21,681	34,620
# recaptured	26	19	32	269
Exploitation rate	0.07	0.03	0.04	0.08
Direct population estimate	257,094	1,046,413	605,035	409,906
Unbiased population estimate	248,256	992,541	587,385	408,528

*Fish tagged during this study in Simpson Lagoon.

†Fish tagged by ADF & G in Prudhoe Bay.

cisco have undergone a dramatic decrease from nearly one million to 250,000 catchable non-spawning fish.

As part of the study of cisco populations utilizing the nearshore area, subsamples of the commercial fish catch were analyzed to determine size, age, sex and reproductive condition. Samples of the arctic cisco catch from 1977 and 1978 and of the least cisco catch from 1978 were analyzed. Although the analysis is not yet complete, the length-frequency distributions of the 1977 and 1978 samples are available for arctic cisco (Figure 20). The size distribution of the arctic cisco catch apparently changed considerably from 1977 to 1978, and this change was accompanied by decrease in both the commercial catch and the population estimate.

All of the available indicators (population size estimates, size distribution of the commercial catch, and number of fish caught commercially) suggest that recent changes have occurred in the Colville River arctic cisco population. Possible causes of such changes are not easily identifiable, in part due to a lack of information about this species. For example, the spawning grounds for the Colville River arctic cisco population has not been identified.

Estimated Densities of Combined Species

In order to compare the available supply of invertebrate food resources in Simpson Lagoon with the total food requirements of all fish using the lagoon (see Griffiths and Dillinger 1979), we must (1) estimate how many fish are in the lagoon system and (2) find out how much food each fish consumes. In this section, total fish numbers are estimated; food requirements are described later (see Trophic Relationships section).

Seasonal estimates of fish densities in Simpson Lagoon are based on several sources of information acquired in the field and presented in this report. Steps in the derivation of these sometimes rough estimates are as follows:

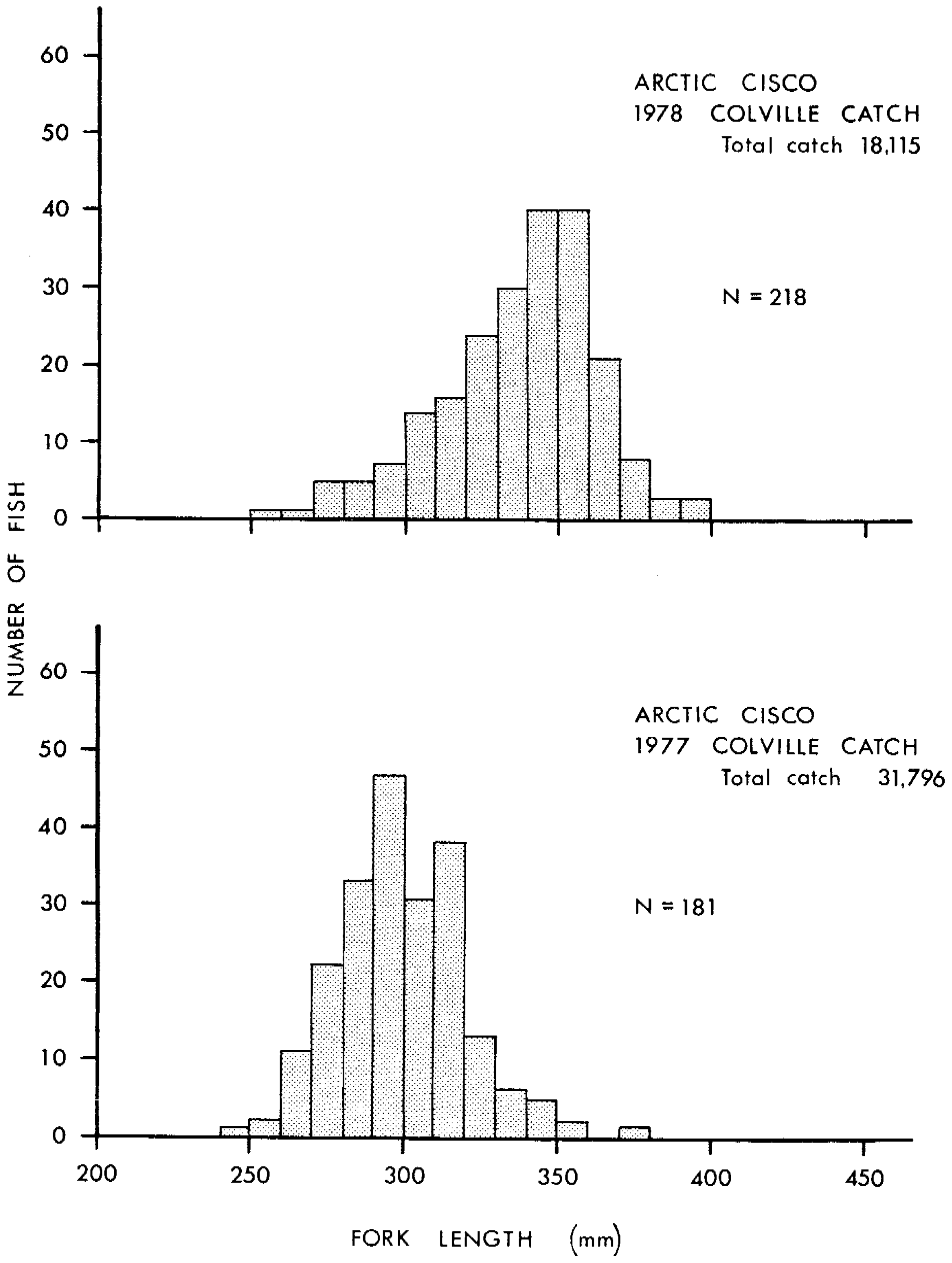

Figure 20. Size Distributions of Subsamples of Arctic Cisco Caught in the 1977 and 1978 Commercial Fishery, Colville Delta.

1. Fish were divided into "large fish" and "small fish" categories because of obvious differences in the amount of food consumed by each size range and the suspected difference in food consumed per unit weight. Based on a preliminary review of life-history data, individuals in each size category were assigned a mean weight which is later used in the INVERTEBRATE section to calculate daily food intake: 470 g for large anadromous fishes (species combined: arctic cisco, least cisco, arctic char, broad and humpback whitefish); 15 g for small anadromous fish and marine species (species combined: fourhorn sculpin, arctic cod, arctic cisco, etc.).

2. For calculation of fish densities, the lagoon was stratified by habitat, a 100 m wide edge of the lagoon (7 km^2) and a lagoon-center habitat (153 km^2). We did this because fish concentrations were generally high along shoreline edges and low in the center portion (Figs. 10 and 12). The average abundance of large fish along mainland and lagoonside shoreline of the barrier islands was about 10 times greater than in the lagoon center (Table 5).

3. The density estimates for large anadromous fish were derived from beach seine data (Table 7). Density estimates were 0.006 large fish/m^2 along mainland shorelines and 0.002 large fish/m^2 along inside island shorelines. The average of these values, 0.004 large fish/m^2, was then assigned to edge habitats during the mid-summer period when fish were most abundant in the lagoon (see Fig. 16); 1/10 these values were used for central lagoon habitats (Table 13).

   Beach seine data appeared to underestimate densities of small fish because our fyke net data showed that small fish were many times more numerous than large fish. Therefore, densities of small fish were assumed to be 5-6 times greater (as indicated by fyke net catches) than densities of large fish (estimated from Table 4). Since our fyke net catch records showed that numbers of small fish, particularly the numerically dominant arctic cod and fourhorn sculpin, increased during the latter half of the summer (see Fig. 19), we have correspondingly changed our density estimates for small fish in Table 13. Densities are assumed to be lowest in early summer, increasing thereafter.

   Numbers of arctic cod inhabiting the lagoon during their approximate 9-day run in mid-August were estimated by using the mark/recapture data for arctic and least cisco (see previous section) in the following

TABLE 13. Estimated Densities of Small Fish (15 g assumed weight) & Large Fish (470 g assumed weight) in Two Habitats in Simpson Lagoon, 1978.

Date		Small Fish (No./m^2x10^{-4})		Large Fish (No./m^2x10^{-4})	
		Edge*	Center**	Edge*	Center**
July	1-10	5	0.5	5	0.5
	11-20	20	2	20	1.5
	21-30	50	5	40	4
Aug.	1-10	50	5	40	4
	11-20	1450	1400	40	4
	21-30	70	7	40	4
Sept.	1-10	100	10	40	4
	11-20	100	10	10	1
	21-30	100	10	5	0.5

* 100m wide band along shoreline edges (from Fig. 12).

**All of lagoon except edges.

> way. In 1978, the total population of large arctic cisco centering coastal waters was estimated to be 248,256 fish. If we assume that one half of these fish went eastward from the Colville River and the other half went westward, (and there are no data to indicate this would be unreasonable) then 124,128 large arctic cisco passed through Simpson Lagoon in 1978. Of these, approximately 650 (0.5%) were caught in the fyke net. By similar calculations, we estimate that 0.6% of all least cisco were caught in the fyke net. If we assume that the fyke net caught a roughly equivalent portion of the arctic cod that passed through the lagoon (n=124,200 cod caught in fyke net), then about 23 million cod were in the lagoon. Cod densities would then be 23 million cod/160 km^2 (0.14 cod/m^2) if the fish were equally dispersed through the lagoon. The mean weight of arctic cod was 8 g during this run.

It is clear that many of these assumptions and calculations are rough, and so Table 13 must be interpreted accordingly. This exercise does, however, allow us to estimate the total amount of food consumed by fish and birds (Johnson 1979) in the lagoon. An analysis of food resources in relation to predation is presented by Griffiths and Dillinger (1979).

Trophic Relationships

Analyses of stomach contents of fish caught in Simpson Lagoon during the summer of 1977 indicated that mysids and/or amphipods dominated the diets of all common species of fish (Table 14). These taxa are also the primary foods of the large numbers of oldsquaw ducks that utilize Simpson Lagoon in late summer (Johnson 1978, 1979). Thus, it is important to determine the relationships between availability of invertebrates and cropping of these animals by vertebrate consumers. To accomplish this, the next step after identifying the important components of the diets of the major consumers is to determine the quantity of food consumed. This section addresses the food requirements of one dominant fish species in Simpson Lagoon, the arctic cod.

TABLE 14. Major Food Groups Eaten by Five Fish Species, Simpson Lagoon, 1977 (from Craig and Griffiths 1978).

	% Composition (Volume Basis)				
Food Item	Arctic Cisco	Least Cisco	Arctic Char	Fourhorn Sculpin	Arctic Cod
Mysid	66	61	32	33	71
Amphipod	24	16	55	43	3
Copepod	8	14	3	0	2
Isopod	1	0	0.3	12	4
Fish	0.1	0	5	10	0
Euphausiid	1	0	1	0	0.4
Cumacean	0	1	1	0	0
Unidentifiable	0	9	2	3	20
No. Stomachs Examined	57	30	30	35	30

The amount eaten each day (daily ration) by an average arctic cod was estimated using three types of information obtained under more or less natural field conditions during the summer of 1978. These types of information were (1) the proportion of the day that the fish spent feeding (feeding periodicity), (2) the rate at which food passed through their stomachs (gastric evacuation rate), and (3) the amount of food in their stomachs at various times of day. Experiments were conducted using sizes of juvenile arctic cod representative of those found in Simpson Lagoon. Size ranges and numbers of cod used for tests are shown below:

	Fork Length (mm)				Weight (g)		
Test Series	n	$\bar{X}$	(range)	S.D.	$\bar{X}$	(range)	S.D.
Feeding Periodicity	78	99	(60-127)	13.6	7.7	(1.5-17.9)	2.9
Evacuation Rate	96	104	(89-139)	10.2	8.7	(4.8-20.3)	2.6

These lengths of fish correspond to arctic cod in age classes 1 - 2 (see Table 15).

Feeding Periodicity

Most feeding occurred during morning and early afternoon, tapering off by late afternoon and early night (Fig. 21A). Stomach contents averaged 2.2% of the body weight of the fish at mid-morning (10:00-11:30 ADT), and increased to 4.8% of body weight by early afternoon (15:00). Thereafter, it appears that feeding diminished or ceased since stomach fullness steadily decreased until late evening or early morning. Some feeding resumed during early morning hours since stomach contents were not further depleted. This feeding pattern, particularly the decline in feeding at night, was somewhat unexpected since arctic cod are known to feed during the prolonged "nighttime" of the arctic winter except during spawning (Moskalenko 1964).

TABLE 15. Age-Length Relationship and Age-Specific Maturity of Arctic Cod in Simpson Lagoon, 1977 (from Craig and Griffiths 1978).

	Fork Length (mm)				Maturity			
					Males		Females	
Age	n	mean	(range)	SD	n	% Mature	n	% Mature
1	136	82	(54-129)	13	19	0	40	0
2	33	134	(106-171)	19	9	22	21	0
3	23	169	(150-193)	13	2	100	21	38
4	5	169	(138-195)	22	1	100	4	25
5	1	221	-	-	0	-	1	0
6	1	251	-	-	0	-	1	100
TOTALS	199				31	16%	88	11%

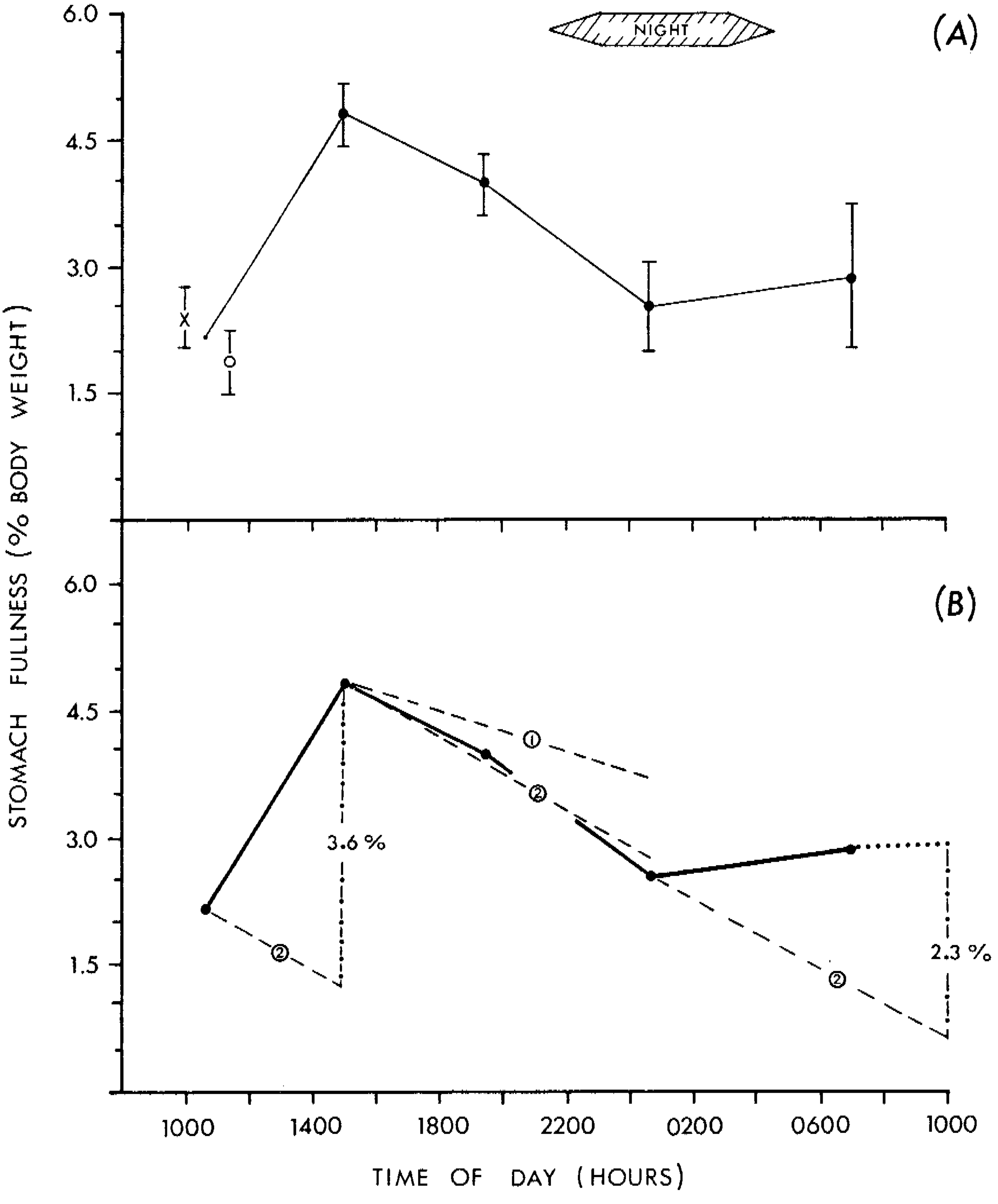

Figure 21. Feeding Periodicity and Daily Ration of Juvenile Arctic Cod in Simpson Lagoon. (A) Sample means (n=10-20) and standard error bars are indicated for collections on 20 August 1978 (open circle), 21 August 1978 (x) and 23-24 August 1978 (closed circles). (B) Diagrammatic method used to calculate daily ration of arctic cod where two digestion rates (①, ②) are indicated (see text for explanation).

The observed diel pattern of stomach fullness appears to be a reasonable reflection of feeding behavior despite the complication that all data were not gathered during a single 24-hr period (see METHODS). The morning data gathered on the three dates (20, 21 and 24 August) did not differ significantly among each other (Student's t Test, $P>0.1$), but the pooled morning data differed significantly from the 15:00 ADT data ($P<0.05$). Therefore, these observations will be assumed to represent the diel feeding pattern of cod during their late-summer incursion into Simpson Lagoon.

Gastric Evacuation Rate

Freshly-caught arctic cod were held under field conditions (4.5-6.5°C, salinity 24-26 ppt) to monitor the depletion of natural foods (mysids, amphipods and copepods) from their stomachs. An approximate evacuation rate of 0.1% of total body weight/h was estimated from the data presented in Fig. 22A. However, this value is almost certainly an underestimate of the actual mean evacuation rate. Although the experiment was conducted when cod stomachs appeared reasonably full, later laboratory measurements showed that stomach contents of these fish at the time they were captured averaged only 1.9% of body weight, a low value compared to the peak of 4.8% of body weight recorded at 15:00 during the feeding periodicity experiment (Fig. 21A). It appears, then, that due to the feeding periodicity of the fish, or other unknown factors, the evacuation experiment began when the cod stomachs were only half full. The significance of this point is that food does not pass through a fish's stomach at a constant rate--the rate varies according to the fullness of the stomach (e.g. Magnuson 1969; Tyler 1970; Windell *et al.* 1976). The rate is fastest when the stomach is full, slowing down as the stomach empties. Thus, most gastric evacuation occurs during the initial hours following a meal, and consequently, calculation of the evacuation rate with less than full stomachs, as occurred in the present study, underestimates

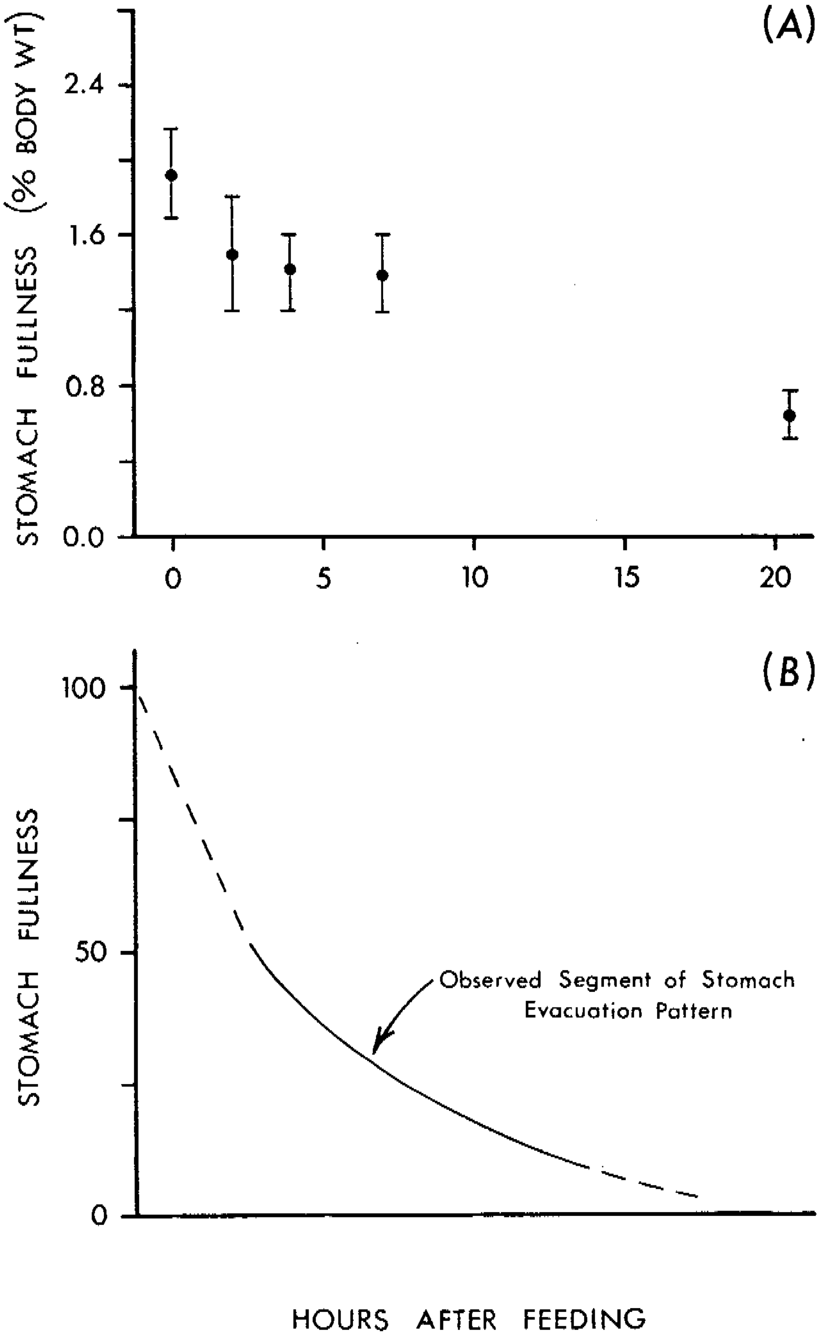

Figure 22. Evacuation of Food from Stomachs of Juvenile Arctic Cod. (A) Means and standard errors for samples of fish (n=18-20) held in a food-free pen in Simpson Lagoon, 20-21 August 1978. (B) Evacuation rate as a function of stomach fullness, based on results from other studies of other species (see text).

the rate at which most evacuation actually occurs. This point is illustrated on a schematic diagram of an evacuation pattern observed in other fishes (Fig. 22B).

Evidence that the observed rate of 0.1% of body weight/h is unrealistically low is shown in Fig. 21B where this evacuation rate (indicated by the symbol ① in Fig. 21B) is applied to the daily pattern of stomach fullness. It is apparent that, during the period 15:00-00:30 ADT, stomach contents were depleted at a rate that considerably exceeded the estimated evacuation rate.

A more realistic evacuation rate can be estimated in two ways:

1. Data from various studies (e.g., Tyler 1970; Windell *et al.* 1976) show that the rate of gastric evacuation is approximately twice as fast during the first half of the evacuation process (from full to half full stomach) than during the second half (half full to empty). Using this rough conversion factor, the initial evacuation rate for arctic cod then becomes 0.2% of body weight/h.

2. Data gathered to assess the feeding periodicity of arctic cod also provide a minimum estimate of the evacuation rate. During the period 15:00 to 00:30, the average stomach fullness declined almost 50% in a seemingly linear fashion (Fig. 21B). This decline, which is 0.2% of body weight/h, represents a minimum estimate of the evacuation rate because the actual rate must have been higher if the fish were feeding during this interval.

Both of these methods provide a similar estimate of evacuation rate, and this rate of 0.2% of body weight/h is used in subsequent calculations.

Calculation of Daily Ration

Calculation of the daily ration of arctic cod is based on the changing amount of food in their stomachs over a 24 h period and the rate of evacuation of this food from the stomach (Fig. 21B). As described below, the daily ration is calculated as the sum, over a 24 h period, of differences between the observed quantity of food in the stomachs versus the quantity that would have remained if the fish had digested what was present in the stomachs previously but eaten no additional food.

At the start of the feeding periodicity experiment, the stomach contents averaged 2.2% of the body weight of the fish (Fig. 21B). If no additional food had been ingested before the next sampling period, the stomach contents would have diminished at the rate of gastric evacuation, 0.2% body weight/h (indicated by symbol ② in Fig. 21B), to approximately 1.2% body weight. Instead, the stomach fullness rose to 4.8% body weight, representing an actual increase of 3.6% body weight for this period. During the next two time periods, between 15:00 and 00:30 ADT, the decline in stomach fullness matches the estimated gastric evacuation rate--primarily because the evacuation rate was determined, in part, from these data and the assumption that no feeding occurred in this interval. The next major period of feeding occurred in the morning hours, sometime after 00:30. During this period, it is estimated that an additional 2.3% body weight was consumed (note that Fig. 21B is extrapolated to 10:00 on 24 August in order to complete a 24 h period). Summing these calculations, the amount of food eaten per day is 3.6% of body weight + 2.3% of body weight = about 6% of body weight.

In view of the assumptions and potential sources of error associated with each stage of the calculation of daily ration, it is clear that the value determined during this exercise is an approximation. On the other hand, this is the only known estimate for any species of fish in the North American Arctic. Furthermore, these arctic cod data are particularly relevant since the experiments were conducted in field conditions using natural foods.

Daily rations of species like arctic cisco, arctic char and fourhorn sculpin are unknown, but estimates are necessary to compare the food requirements of consumers with available food supplies in Simpson Lagoon (see Griffiths and Dillinger 1979). It is therefore necessary to assign values for daily ration; the arctic cod data of 6% body weight will be used for all small fish (generally 100-250 mm in length). Large fish (generally 250-500 mm) and relatively sedentary sculpins presumably require less food and so will arbitrarily be assigned 5% body weight/day as a daily ration.

Using these values for daily food requirements of fish and the estimated densities of large and small fish in Simpson Lagoon (see Estimated Densities of Combined Species), Griffiths and Dillinger (1979) calculate that the total food requirements of fish in Simpson Lagoon were about two orders of magnitude lower than the available food supply in 1978. The tremendous numbers of arctic cod that entered Simpson Lagoon in mid-August may have contributed to the decline in mysid biomass described by Griffiths and Dillinger (1979).

CONCLUSIONS

1. Nearshore Fish Populations: Although 21 fish species were caught in Simpson Lagoon, five species accounted for over 90% of all fish caught during the summer of 1977 and 1978. These include two marine species (arctic cod, fourhorn sculpin) and three anadromous species (arctic cisco, least cisco, arctic char).

   Fish numbers and species composition changed markedly between the two summers. Our catch in 1978 included all species caught in 1977 plus eight additional species, among which a number of pink salmon. Massive numbers of arctic cod, many times more than were encountered in 1977, swept through the lagoon system during a nine-day period in mid-August of 1978.

   In winter, most anadromous fish appeared to depart Simpson Lagoon, but several marine species and one anadromous species (boreal smelt) used the deeper nearshore areas under the ice for feeding and/or spawning.

2. Habitat Use: Anadromous and marine fishes rapidly repopulated previously frozen regions of Simpson Lagoon during each of the two summers. Large numbers of fish originating from both fresh and marine waters invaded these shallow shoreline regions. Fish were most abundant in summer along the mainland shoreline where waters were relatively warm and brackish, and highest concentrations generally occurred within 100 m

of the shoreline. Fish were less abundant along barrier island shorelines and in the central part of the lagoon. In winter this pattern is reversed; as the ice thickness increases, fish are eventually excluded from shallow areas.

3. Movements and Migration: During the brief arctic summer, the distribution of juvenile and adult fish constantly changes because of day-to-day pulses of movement and large-scale population movements over periods of several weeks. This study provided evidence that some anadromous species (least cisco, broad and humpback whitefish) use shoreline habitats when waters are brackish and/or warm, and that one marine species (fourhorn sculpin) tends to approach the mainland shore when conditions there become colder and more saline. Other species were not detectably influenced by daily changes in water temperature and salinity.

   Interpretation of tagging data indicated that the summer residency times for individuals of anadromous species in Simpson Lagoon probably averaged about 24 days if fishes travelled through the lagoon during movements from and back to their rivers of origin. On the other hand the fourhorn sculpin, a marine species, are relatively sedentary and individuals may reside in the same general area for a year or more.

4. Trophic relations: The daily food ration of arctic cod was estimated under field conditions to be 6% of body weight per day. At this rate, it is possible that the large numbers of this species that entered Simpson Lagoon in 1978 may have contributed to the decline in mysid biomass described by Griffiths and Dillinger (1979). These authors also calculated that total requirements of fish in Simpson Lagoon were about two orders of magnitude lower than the available invertebrate food supply in the lagoon.

5. Cisco Population Sizes: Estimation of arctic and least cisco populations were made, based on a Petersen single-census mark and recapture procedure. The results indicate that during 1978 the Colville River supported seagoing populations of about 600,000 large least cisco and about 250,000 large arctic cisco. These estimates include only the individuals that were of a size (>275 mm) vulnerable to the commercial fishing in the Colville River delta. They do not include the spawning position of the arctic cisco population. A previous study, conducted by ADF&G indicated that in 1976 the same populations of arctic

and least cisco were composed of about 1,000,000 and 400,000 individuals, respectively. Reasons for the apparent decline in the arctic cisco population are not known.

RECOMMENDED FURTHER RESEARCH

Although analyses of the 1978 data are still in progress, needs for particular kinds of fisheries information are becoming apparent. Several topics requiring further research are briefly described below:

1. Critical habitats. Major gaps exist in our understanding of the life-histories of several key fish species that may be affected by industrial developments in the arctic. We cannot at this time identify where some of these species spawn or overwinter.

   The arctic cisco is especially poorly known. The Colville River is the major (only?) source of arctic cisco along the Alaskan Beaufort Sea coastline, yet we do not know where these fish spawn. No spawners were found by us during a reconnaissance of potential spawning areas. Similarly, little is known about where this species overwinters except that coastal areas near the Colville River may be used. Our studies also indicate that the population size of this important species has declined markedly over the past two years. The implications of this reduction, in view of the annual harvest by subsistence and commercial fisheries, must be examined.

   Spawning and overwintering areas are also poorly known for two other key species, the least cisco and arctic cod.

2. Habitat requirements. The importance of nearshore waters to anadromous fish populations is documented. These fish apparently do not stray far from the relatively warm and brackish waters along the coastline. These nearshore temperature and salinity regimes may be affected by industrial developments, such as causeways, which alter nearshore current patterns. It is important, therefore, to determine how fish will be affected by changes in these physical factors. Experimental assessments of the temperature and salinity preferences and tolerances of selected anadromous fishes are needed.

3. Regional data gaps. Fish use of two Beaufort Sea regions is poorly documented. The first of these regions includes all offshore waters, especially those in the 3-20 m depth zone. Virtually all fisheries studies to data have emphasized fishes, particularly the anadromous species, inhabiting shallow nearshore waters--typically less than 3 m deep. Although industrial developments will take place in the 3-20 m zone, little is known about the importance of this region to fish populations. Arctic cod spawn and overwinter in these waters, but specific important areas are not well known.

   The second region requiring investigation is the coast between the Colville River and Barrow. This region lies "downstream" of the proposed lease area due to prevailing nearshore currents of the Beaufort Sea. Preliminary evidence indicates that the species composition of fish in this area may differ from that between the Colville and Mackenzie rivers. Streams draining into the former region support important anadromous whitefish and least cisco populations, whereas in the latter region streams support arctic char populations. This regional difference in fish usage largely reflects hydrological differences between the two areas. It is thought that char are absent from streams between Barrow and the Colville River because these coastal drainages generally lack the perennial springs that are associated with the spawning grounds of char. Given these differences between drainages and fish populations in these two regions, it is difficult to extrapolate coastal data from one region to the other. We therefore recommend that the coastal region between Barrow and the Colville River be examined.

4. Fish versus nearshore obstructions. Concern has been raised that causeways which jut into coastal waters may affect arctic fish populations in several ways. By altering prevailing nearshore currents, causeways may affect temperature and salinity regimes in areas where fish concentrations are highest (addressed above), or disrupt the rate at which the food organism of fishes (mysids, amphipods) disperse into nearshore areas (addressed in Griffiths and Dillinger 1979). Causeways may also affect migrations of anadromous species. Although a summary report regarding this concern was prepared by the Alaska Department of Fish and Game, the problem requires review and complete data analysis before this issue will be resolved. Further field experimentation may be required.

SUMMARY OF 4th QUARTER OPERATIONS

Fourth quarter operations consisted of data analysis and preparation of the Annual Report.

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APPENDIX 1. Tag and recapture data for fish recovered during this study, Simpson Lagoon 1977-8.

1. LEAST CISCO

F.L.†	Tag		Recapture	
	Site	Date	Site	Date
345	MP	15- 8-77	MP	17- 8-78
295	MP	7- 8-78	MP	9- 8-78
295	MP	7- 8-78	MP	9- 8-78
310	MP	17- 7-78	MP	15- 8-78
280	MP	15- 7-78	CD	13-10-78
315	MP	22- 7-78	CD	14-10-78
340	MP	19- 7-78	CD	14-10-78
290	MP	7- 8-78	CD	14-10-78
330	MP	17- 7-78	CD	16-10-78
355	MP	19- 7-78	CD	16-10-78
320	MP	22- 7-78	CD	19-10-78
330	MP	15- 7-78	CD	19-10-78
310	MP	10- 7-78	CD	19-10-78
-	MP	7-78	CD	21-10-78
325	KP	8- 8-78	CD	23-10-78
315	MP	8- 7-78	CD	23-10-78
325	KP	8- 8-78	CD	23-10-78
255	MP	4- 8-78	CD	25-10-78
360	MP	8- 7-78	CD	26-10-78
320	MP	17- 7-78	CD	28-10-78
310	MP	17- 7-78	CD	30-10-78
315	MP	15- 7-78	CD	30-10-78
310	MP	15- 7-78	CD	1-11-78
335	MP	19- 7-78	CD	4-11-78
295	MP	22- 7-78	CD	6-11-78
330	MP	22- 7-78	CD	6-11-78
325	MP	7- 8-78	CD	7-11-78
330	MP	17- 7-78	CD	7-11-78
335	MP	11- 7-78	CD	7-11-78
290	MP	15- 7-78	CD	7-11-78
325	MP	17- 7-78	CD	11-11-78
320	MP	15- 7-78	CD	13-11-78
310	MP	11- 7-78	CD	16-11-78
320	MP	14- 7-78	CD	16-11-78
290	MP	22- 7-78	CD	18-11-78
315	MP	16- 8-77	CD	31-10-77
315	MP	15- 8-77	CD	31-10-77
300	MP	18- 8-77	CD	25-11-77
298	MP	15- 8-77	B	24-10-77
336	*PB	1- 8-76	MP	6- 8-77
319	*PB	1- 8-76	MP	23- 8-77
355	*PB	10- 8-76	MP	23- 8-77
330	*PB	31- 8-76	MP	1- 7-78
310	*PB	23- 7-76	MP	3- 7-78
330	*PB	23- 7-76	MP	8- 7-78
352	*PB	21- 7-76	MP	8- 7-78
345	*PB	31- 7-77	MP	15- 7-78
320	*PB	17- 8-76	MP	15- 7-78
350	*PB	15- 8-76	MP	15- 7-78
340	*PB	23- 7-76	MP	15- 7-78
-	*PB	31- 7-76	MP	17- 7-78
-	*PB	1- 8-76	MP	17- 7-78
343	*PB	13- 8-76	MP	19- 7-78
349	*PB	24- 7-77	MP	20- 7-78
323	*PB	25- 8-76	MP	21- 7-78
350	*PB	16- 8-76	MP	22- 7-78
335	*PB	3- 8-76	MP	1- 8-78
-	*PB	28- 7-77	MP	2- 8-78
320	*PB	19- 7-76	MP	7- 8-78
320	*PB	20- 7-76	KP	8- 8-78
-	*PB	10- 8-76	MP	15- 8-78
325	*PB	23- 7-77	MP	18- 8-78
-	*PB	31- 7-76	KP	15- 7-78
325	*PB	25- 7-77	MP	19- 8-78
-	*PB	7- 8-77	OP	5- 8-78

APPENDIX 1. (cont'd).

2. ARCTIC CISCO

F.L.†	Tag		Recapture	
	Site	Date	Site	Date
321	MP	16- 8-77	CD	31-10-77
298	MP	15- 8-77	CD	26-10-77
365	MP	15- 8-77	CD	10-11-77
308	MP	15- 8-77	CD	19-11-77
350	MP	10- 7-78	MP	9- 8-78
-	*PB	8- 8-77	MP	4- 7-78
-	MP	8-78	CD	13-10-78
340	MP	15- 7-78	CD	14-10-78
295	MP	14- 8-77	CD	16-10-78
277	MP	17- 8-77	CD	16-10-78
345	MP	22- 7-78	CD	16-10-78
310	MP	13- 7-78	CD	16-10-78
355	MP	17- 7-78	CD	17-10-78
320	MP	15- 7-78	CD	17-10-78
320	MP	20- 7-78	CD	20-10-78
315	MP	17- 7-78	CD	21-10-78
320	MP	19- 7-78	CD	25-10-78
345	MP	20- 7-78	CD	27-10-78
-	MP	8-78	CD	30-10-78
340	MP	17- 7-78	CD	30-10-78
-	MP	8-78	CD	1-11-78
330	MP	11- 7-78	CD	1-11-78
-	MP	8-78	CD	4-11-78
-	MP	8-78	CD	4-11-78
310	MP	19- 7-78	CD	8-11-78
-	MP	8-78	CD	10-11-78
-	MP	8-78	CD	13-11-78
325	MP	17- 7-78	CD	14-11-78
315	MP	20- 7-78	CD	16-11-78
340	MP	17- 7-78	CD	18-11-78
-	MP	8-78	CD	21-11-78
330	MP	15- 7-78	CD	21-11-78
310	MP	20- 7-78	CD	5-12-78
360	MP	14- 7-78	CD	15-12-78

3. ARCTIC CHAR

F.L.†	Tag		Recapture	
	Site	Date	Site	Date
252	MP	25- 7-78	MP	19- 8-78
360	MP	4- 9-78	OP	5- 9-78
380	MP	19- 7-78	CR	9-78
533	*IR	17- 9-72	LI	3- 8-77
649	*IR	9- 9-72	LI	26- 7-77
600	*IR	24- 8-72	MP	18- 8-78
680	*IR	14- 7-74	MP	26- 8-78
-	*IR	13- 9-72	KP	16- 8-78
555	*IR	19- 9-71	MP	19- 7-78
-	*PB	29- 7-77	P	8- 7-78
600	*PB	31- 7-76	MP	6- 8-78
620	*PB	8- 8-76	MP	18- 8-78
560	*SR	21- 8-71	MP	26- 8-78

4. BROAD WHITEFISH

F.L.†	Tag Site	Tag Date	Recapture Site	Recapture Date
434	*PB	9- 8-76	MP	30- 6-78
380	MP	1- 7-78	MP	7- 8-78
403	MP	3- 9-78	OP	5- 9-78

5. HUMPBACK WHITEFISH

F.L.†	Tag Site	Tag Date	Recapture Site	Recapture Date
400	*PB	16- 7-76	MP	25- 7-77
408	*PB	19- 7-76	MP	5- 8-77
402	*PB	2- 9-76	MP	1- 7-78

6. FOURHORN SCULPIN

F.L.†	Tag Site	Tag Date	Recapture Site	Recapture Date
144	PI	24- 8-77	PI	29- 8-77
207	PI	27- 8-77	PI	27- 8-77
129	MP	21- 8-77	MP	23- 8-77
134	PI	15- 8-77	PI	1- 9-77
212	MP	17- 8-77	PI	4- 9-77
160	MP	17- 8-77	PI	6- 9-77
168	MP	27- 8-77	MP	16- 9-77
114	MP	23- 8-77	MP	28- 8-77
160	MP	23- 8-77	MP	28- 8-77
162	PI	1- 9-77	PI	3- 9-77

APPENDIX 1. (cont'd).

F.L.†	Tag		Recapture	
	Site	Date	Site	Date
207	MP	26- 8-77	MP	28- 8-77
197	MP	26- 8-77	MP	29- 8-77
190	MP	27- 8-77	MP	29- 8-77
135	MP	28- 8-77	MP	22- 7-78
240	PI	16- 8-77	MP	20- 8-78
214	MP	26- 8-77	MP	31- 8-78
195	MP	26- 8-77	MP	5- 9-78
7. <u>ARCTIC FLOUNDER</u>				
195	MP	30- 7-77	MP	21- 8-77
8. <u>ARCTIC COD</u>				
165	MP	19- 9-77	MP	21- 9-77
9. <u>PINK SALMON</u>				
430	MP	6- 8-78	BI	9-78

---

† F.L. Fork length (mm).

* Tagged by the Alaska Dept. Fish and Game.

<u>Sites</u>

B - near Barrow
CD - Colville Delta
CR - Canning River
IR - Ivishak River
KP - Kavearak Point
LI - Leavitt Island
MP - Milne Point
OP - Oliktok Point
P - Peat Island
PB - Prudhoe Bay
PI - Pingok Island
SR - Sagavanirktok River

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BEAUFORT SEA BARRIER ISLAND-LAGOON
ECOLOGICAL PROCESS STUDIES

ECOLOGY OF INVERTEBRATES IN SIMPSON LAGOON, BEAUFORT SEA, ALASKA

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and

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Edmonton, Alberta, Canada

1 April 1979

TABLE OF CONTENTS

Page

SUMMARY ix

ACKNOWLEDGEMENTS xi

INTRODUCTION 1

- Objectives 1
- Relevance to Problems of Development 2

CURRENT STATE OF KNOWLEDGE 3

STUDY AREA 5

METHODS AND RATIONALE OF DATA COLLECTION 5

- Faber Net 5
- Drop Net 9
- Drift Net 9
- Amphipod Trap 11
- Diver Operations 11
  - Visual Estimates of Epibenthic Invertebrates 11
  - Airlift Samples 12
  - Photographic Quadrats 12
- Laboratory Techniques 12
  - Sorting 12
  - Measuring 13
  - Biomass 14
- Limitations and Biases 14
  - Drop Net 17
  - Visual Estimates by Divers 17
  - Airlift Samples 17
  - Photographic Quadrats 18
  - Laboratory Techniques 18
- Comparison of Sampling Techniques 18

RESULTS 21

- Early Season Movements and Distribution of Epibenthic Invertebrates 21
- Open-Water Season Movements, Distributions and Abundances of Epibenthic Invertebrates 26

TABLE OF CONTENTS (cont'd)

Page

- Mysids 27
  - Mysids Near the Bottom 27
  - Mysids in the Water Column 35
- Amphipods 43
  - Amphipods Near the Bottom 43
  - Amphipods in the Water Column 54
- Summary 60
- Trophic Relationships 62
- Biology of Key Invertebrate Species 70
  - *Mysis litoralis* 71
    - Seasonal Growth Rate 71
    - Reproduction 75
    - Fecundity 76
  - *Mysis relicta* 76
    - Seasonal Growth Rate 78
    - Reproduction 82
    - Fecundity 83
  - *Onisimus glacialis* 83
    - Seasonal Growth Rates 86
    - Reproduction 86
    - Fecundity 87
  - Other Amphipod Species 89
    - *Apherusa glacialis* 89
    - *Pontoporeia affinis* 89
    - *Halirages mixtus* 89
    - *Gammarus setosus* 89
    - *Parathemisto libellula* 90
- CONCLUSIONS 90
- RECOMMENDED FURTHER RESEARCH 91
- SUMMARY OF 4TH QUARTER OPERATIONS 92
- LITERATURE CITED 93
- APPENDICES 100

LIST OF TABLES

Table		Page
1	Water Depth and Bottom Type at the Seven Principal Sampling Stations in the Simpson Lagoon Area, 1978 .	7
2	Invertebrate Sampling Schedules and Methodologies followed in Simpson Lagoon during the Open-Water Season of 1978	8
3	Equations and Comparisons Used to Determine Energy (K cal) Available to Birds and Fish in Simpson Lagoon, 1978	15
4	Statistical Comparisons of Density Estimates of Mysids and Amphipods Obtained with Various Sampling Techniques in Simpson Lagoon, 1978	20
5	Early-Season Distribution of Epibenthic Invertebrates in Simpson Lagoon, 5-7 June 1978	24
6	Diver Observations in Leads Inside and Outside Simpson Lagoon on 28 June 1978	25
7	Comparisons of Mysid Biomass Near the Bottom (mg ash-free dry weight/m^2), Among Lagoon Stations (1-5) and Among All (1-7) Using the Freidman Two-Way Analysis of Variance	30
8	Comparisons of Mysid Biomass Near the Bottom (mg ash-free dry weight/m^2) Among Sampling Periods for Lagoon Stations (1-5) and for Lagoon and Offshore Stations (1-7) Using the Freidman Two-Way Analysis of Variance	31
9	Comparisons of Mysid Biomass in the Water Column (mg ash-free dry weight/100 m^3) Among Lagoon Stations (2, 3, 4) and Among Lagoon and Offshore Stations (2, 3, 4, 6/7) Using the Friedman Two-Way Analysis of Variance	40
10	Comparisons of Mysid Biomass in the Water Column (mg ash-free dry weight/100 m^3) Among Sampling Periods for Lagoon and Offshore Stations	41
11	Comparisons of Biomass (mg ash-free dry weight/m^2) for Amphipods Near the Bottom Among Lagoon Stations (1-5) and Among Lagoon and Offshore Stations (1-7) Using the Friedman Two-Way Analysis of Variance	49

LIST OF TABLES (cont'd)

Table | Page

12 Comparisons of Biomass (mg ash-free dry weight/m^2) for Amphipods Near the Bottom Among Sampling Periods for Lagoon Stations (1-5) and for Lagoon and Offshore Stations (1-7) Using the Friedman Two-Way Analysis of Variance 50

13 Comparisons of Biomass (mg ash-free dry weight/100 m^3) for Amphipods in the Water Column Among Lagoon Stations and Among Lagoon and Offshore Stations Using the Friedman Two-Way Analysis of Variance 58

14 Comparisons of Biomass (mg ash-free dry weight/100 m^3) for Amphipods in the Water Column Among Sampling Periods for Lagoon Stations and for Lagoon Offshore Stations Using the Friedman Two-Way Analysis of Variance 59

15 Estimates of Daily Food Requirements (g ash-free dry wt/m^2) of Small and Large Fish in Simpson Lagoon in 1977 and 1978 63

16 Estimated Daily Food Requirements (mg ash-free dry weight/m^2) of Oldsquaw Ducks in Simpson Lagoon in 1977 and 1978 64

17 Estimates of Food Available (Mysids and Amphipods) (g/m^2 ash-free dry wt) in Simpson Lagoon 1977 and 1978 66

18 Major Species of Epibenthic Invertebrates and their Principal Foods 69

19 Growth (Total Length and Wet Weight) of *Mysis litoralis* Collected in Simpson Lagoon 8 July-23 September 1978 72

20 Fecundity of Selected Species of Arctic Marine Epibenthic Invertebrates 77

21 Growth Rate (Total Length and Wet Weight) for *Mysis relicta* Collected in Simpson Lagoon 8 July-23 September 1978 79

22 Growth Rate (Total Length and Wet Weight) for *Onisimus glacialis* Collected in Simpson Lagoon 8 July-23 September 1978 88

LIST OF FIGURES

Figure Page

1 Map of Simpson Lagoon Showing Principal Sampling Stations Where Invertebrates were Collected During the Open-Water Seasons of 1977 and 1978 6

2 Two Models of a Central-Pursing Drop Net (modified from the Clutter net) used for Collecting Epibenthic Invertebrates in Simpson Lagoon in 1978 10

3 Anatomical Features of Invertebrates that were Measured for Later Conversion (by equations) to Total Lengths 16

4 Map of Simpson Lagoon Early Season Invertebrate Sampling Sites, April-June 1978 22

5 Map of Simpson Lagoon Showing Approximate Extent of Area Available to Epibenthic Invertebrates During Winter 22

6 Biomass of Mysids Near the Bottom in Relation to Date and Sampling Station 28

7 Biomass of Mysids Near the Bottom at the Various Sampling Stations in 1977 and 1978 29

8 Biomass of Mysids Near the Bottom at Lagoon Stations in Simpson Lagoon in Relation to Date in 1977 and 1978 33

9 Biomass of Mysids Near the Bottom at Offshore Stations in Simpson Lagoon in Relation to Date in 1977 and 1978 34

10 Biomass of Mysids in the Water Column in Relation to Date and Sampling Station 36

11 Biomass of Mysids in the Water Column at Various Sampling Stations in Simpson Lagoon in 1977 and 1978 37

12 Biomass of Mysids in the Water Column at Lagoon Stations in Simpson Lagoon in Relation to Date in 1977 and 1978 38

LIST OF FIGURES (cont'd)

Figure		Page
13	Biomass of Mysids in the Water Column at Offshore Stations in Simpson Lagoon in Relation to Date in 1977 and 1978	39
14	Biomass of Amphipods Near the Bottom in Relation to Date and Sampling Station	44
15	Biomass of Amphipods Near the Bottom at Various Sampling Stations in 1977 and 1978	46
16	Biomass of Amphipods Near the Bottom at Lagoon Stations in Simpson Lagoon in Relation to Date in 1977 and 1978	47
17	Biomass of Amphipods Near the Bottom at Offshore Stations in Simpson Lagoon in Relation to Date in 1977 and 1978	48
18	Biomass of Amphipods in the Water Column in Relation to Date and Sampling Station	52
19	Biomass of Amphipods in the Water Column at Various Stations in Simpson Lagoon in 1977 and 1978	55
20	Biomass of Amphipods in the Water Column at Lagoon Stations in Simpson Lagoon in Relation to Date in 1977 and 1978	56
21	Biomass of Amphipods in the Water Column at Offshore Stations in Simpson Lagoon in Relation to Date in 1977 and 1978	57
22	Comparisons of Food Available (Mysids and Amphipods) and the Daily Food Requirements of Birds and Fish in Relation to Time in Simpson Lagoon During 1977 and 1978	67
23	Increase in Total Length of First- and Second-Year *Mysis litoralis* During the Open-Water Season in Simpson Lagoon	73
24	Length-Frequency of *Mysis litoralis* Collected by Drop-Nets in Lagoon and Offshore Stations During the Open-Water Season 1978	74

LIST OF FIGURES (cont'd)

Figure Page

25 Increase in Total Length of First- and Second-Year *Mysis relicta* During the Open-Water Season in Simpson Lagoon 80

26 Length-Frequency of *Mysis relicta* Collected by Drop-Nets at Lagoon and Offshore Stations During the Open-Water Season 1978 81

27 Increase in Total Length of First- and Second-Year *Onisimus glacialis* During the Open-Water Season in Simpson Lagoon 84

28 Length-Frequency of *Onisimus glacialis* Collected by Drop-Nets at Lagoon and Offshore Stations During the Open-Water Season 1978 85

LIST OF APPENDICES

Appendix		Page
1	Estimates of Total Length and Wet Weight for *Mysis litoralis* for Different Length Intervals ..	101
2	Estimates of Total Length and Wet Weight for *Mysis relicta* for Different Length Intervals	102
3	Estimates of Total Length and Wet Weight for *Onisimus glacialis* for Different Length Intervals	103
4	Estimates of Total Length and Wet Weight for *Pontoporeia affinis* for Different Length Intervals	104
5	Estimates of Total Length and Wet Weights for *Apherusa glacialis* and *Halirages mixtus* for Different Length Intervals	105
6	Estimates of Total Length and Wet Weights for *Gammarus setosus* for Different Length Intervals .	106
7	Estimated Total Length and Wet Weight for *Parathemisto* sp. for Different Length Intervals .	107
8	Relationship of Total Length to Body Weight and Body Dry Weight for *Cyrtodaria kurriana* of Different Length Intervals	108
9	Abundance and Biomass of Important Species of Epibenthic Invertebrates Collected in the Water Column in Faber Net Samples in Simpson Lagoon and Nearshore Areas, 10 July-23 September 1978	109
10	Abundance and Biomass of Important Species of Epibenthic Invertebrates Collected Near the Bottom in Drop Net Samples in Simpson Lagoon and Nearshore Areas, 8 July-23 September 1978	113

SUMMARY

Invertebrate investigations in the Simpson Lagoon area on the Alaskan Beaufort Sea Coast in 1977 and 1978 concentrated on those organisms identified as important food items to higher trophic levels (fish and birds). The main objectives of the research were to study the seasonal and habitat distributions, abundances and biomasses, and life histories of these important organisms.

Results of 1977 and 1978 studies showed that mysids and amphipods were the most abundant invertebrate groups in Simpson Lagoon in terms of numbers and biomass and, as well, were the most common foods of key bird and fish species. In both years amphipod and mysid densities and biomasses varied widely in space and time during the open-water season. The total biomass of these invertebrates was an order of magnitude lower in 1978 than it was in 1977. Extensive current-assisted movements of amphipods and mysids into, out of and within the lagoon appeared to occur during the open-water season. Divers observed that large numbers of amphipods and mysids were associated with the detritus layer that covered most of the bottom of the lagoon. This detritus (derived from tundra erosion) may have provided these organisms with a direct or indirect source of food.

Amphipods, but not mysids, were found in Simpson Lagoon in high-salinity waters under the ice in April 1978. In November 1978, both amphipods and mysids were found under the ice in the lagoon, in abundances similar to those of summer. To what extent these organisms remained in the lagoon through the winter and spring of 1978-79 is not yet known.

Mysis litoralis and *Mysis relicta* grew at a rate of about 2.4 mm/30 days during the open-water season but the only abundant amphipod (*Onisimus glacialis*) grew much more slowly, about 0.8 mm/30 days. This growth in mysids and amphipods contributes to the increase in biomass of the invertebrate population, and therefore in providing energy for fish and birds. Most of the growth occurs during summer in the warm, brackish nearshore environments.

Results showed that individuals of the two species of mysid and the one abundant species of amphipod live up to three years, which is longer than heretofore suspected. The major breeding season for these species was late fall-early winter and the young of all three species were released from brood pouches in late spring.

A potential cause of adverse impacts to epibenthic invertebrates is the construction of causeways or other structures that would block important movements of these invertebrates. The movements that appear important to some of the species include those between the lagoon and offshore. Another potential disturbance related to petroleum development on the continental shelf is contaminant (e.g., oil) introductions. Adverse impacts of oil on invertebrates might indirectly affect the fish and birds that depend on those invertebrates for food. Previous investigations have shown that responses of epibenthic invertebrates to oil are highly variable, but that adverse effects occur under some circumstances. In the nearshore environment, invertebrates could be affected by oil in the water column or (probably more critical to epibenthos) by oil on and in benthic substrates.

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We would like to take this opportunity to mention the unique contribution of Howard McElderry, who played an especially active and interested role in modifying and carrying out the field program. Ken Coyle of the University of Alaska and Hal Koch of Western Washington State University provided prompt assistance in confirming the identification of the epibenthic invertebrates. Benny Gallaway and Joe Margraff contributed fresh ideas and insight into the sampling design and the analysis of results. Joe Truett, John Richardson and Aaron Sekerak provided helpful criticism of the manuscript and editorial comments.

INTRODUCTION

The apparent inevitability of petroleum exploration and development activities along the Alaskan Beaufort continental shelf has heightened concern regarding the effects of these activities on the nearshore marine environment. The interdisciplinary study of which this report is a part (Beaufort Sea Barrier Island-Lagoon Program, RU 467) was initiated to examine nearshore trophic relationships and to define important biological processes in a barrier island-lagoon system as a strategy to assess the potential impacts of these activities. The first year of field research (1977) emphasized higher trophic levels (fish and birds), with the view that it would thereafter be possible to progress down the food web to develop an understanding of processes that supported the key vertebrates. Consequently our first Annual Report of research (LGL 1978) described the importance of the Alaskan Beaufort Sea coast and its nearshore barrier island-lagoon systems as summer breeding, rearing and feeding areas for birds, and as feeding and rearing areas for anadromous and marine fish. That report showed that epibenthic invertebrates were the primary source of food for the important vertebrate species in the barrier island-lagoon system, and indicated that these invertebrates were present in sufficient quantities to supply the energy requirements of the birds and fish utilizing the system. The objectives of the 1978 invertebrate program described here were to provide more detailed information on the biology and trophic relationships of the important invertebrate species.

Objectives

The specific objectives of the invertebrate investigations for 1978 were

1. to determine temporal and spatial variations in the abundance and biomass of important invertebrate groups;
2. to determine how biomass and productivity of important invertebrates are related to energetic needs of their consumers in Simpson Lagoon;

3. to gather seasonal life-history and growth information (length, weight, sex, breeding condition) for the important species of invertebrates; and
4. to investigate the movements of invertebrates into and out of the lagoon during the open-water season.

In this annual report, the results of the 1977 and 1978 field seasons are compared. A complete discussion of the biological significance of these results in regard to development in the nearshore Beaufort Sea will be presented in the final report after the completion of the winter sampling program.

Relevance to Problems of Development

Oil contamination of the Jones Islands-Simpson Lagoon barrier island-lagoon system might have serious effects, either direct or indirect, on the epibenthic community. If organisms came into physical contact with oil in the water, indications from previous studies are that they might succumb (e.g., Percy 1976; Busdosh and Atlas 1977; Foy 1978). Oil entering a shallow lagoon would also become mixed with bottom sediments and organic debris. Benthic invertebrates, including those that might repopulate lagoons from offshore areas (Feder *et al.* 1976) after water-column contamination has diminished would have to contend with oil-contaminated habitats and food sources. These effects of oil could result in drastically reduced densities of epibenthic organisms, the effects of which might be felt at higher trophic levels.

The results of this year's study showed transport of epibenthic invertebrates by nearshore currents to be an important factor in maintaining the standing crop of invertebrates in the lagoon. Alteration of land masses through development activities (e.g., causeway construction, building of artifical islands) could affect circulation patterns in the lagoon and other nearshore areas and thus disrupt the normal patterns of transport of invertebrates.

CURRENT STATE OF KNOWLEDGE

Prior to oil and gas development on the Alaskan coast of the Beaufort Sea, most arctic studies of benthic invertebrates were qualitative in nature and, because of logistics difficulties, were conducted primarily in the vicinity of the Naval Arctic Research Laboratory at Point Barrow. MacGinitie (1955) conducted extensive survey work in this area from 1948 to 1950, and documented the species composition of the invertebrate community. Several taxonomic studies have been reported for a variety of benthic organisms near Point Barrow: sponges (De Laubenfels 1953), polychaetes (Pettibone 1954), amphipods (Shoemaker 1955), molluscs (MacGinitie 1959), mysids (Holmquist 1963), and cumaceans (Given 1965). These taxonomic studies are relevant to this study since some of the same species of invertebrates are found along the Alaskan Beaufort Sea coast to Demarcation Point. An extensive review of existing literature and unpublished data on the distribution, abundances and life histories of benthic organisms, with emphasis on the Alaskan arctic coast, has been compiled by Carey (1977). In addition, Feder *et al.* (1976) have published an excellent annotated literature review of benthic invertebrates of arctic regions in Canada and Alaska.

With the discovery and development of oil and gas in or near both the Canadian and Alaskan parts of the Beaufort Sea, several quantitative studies of infaunal and epibenthic invertebrates were initiated. (Infaunal organisms live in bottom substrates, whereas epibenthic organisms live on or near the bottom.) Crane and Cooney (1974) investigated the invertebrate fauna of Simpson Lagoon during late summer. They found that crustaceans, molluscs and polychaetes were the dominant members of the nearshore invertebrate community, that biomass increased seaward of the lagoon, and that the seasonal distribution of infauna was strongly influenced by bottom-fast ice. However, as Feder *et al.* (1976) point out, the study was conducted over a short time period in August and it lacked information on seasonal variations of invertebrate distribution and biomass.

More extensive work conducted by Feder and Schamel (1976) in the nearshore areas of Prudhoe Bay indicated that benthic biomass was low in that area, although the number and diversity of organisms increased with distance from shore. This seaward increase suggests the existence of a marine stock of invertebrates that is available to repopulate nearshore ice-stressed areas each spring (Feder and Schamel 1976; Feder *et al.* 1976). Carey *et al.* (1974) sampled across the Alaskan Beaufort Sea continental shelf in depths ranging from 20 to > 2000 m. The results of that study also indicate that species diversity and biomass increase with depth and distance from shore, at least from the 20 m depth contour to the edge of the continental shelf (200 m) (Carey *et al.* 1974; Carey 1977). Wacasey (1975) reported similar findings in a study in the Canadian Beaufort Sea between Herschel Island and Cape Dalhousie, centered principally in nearshore waters of the Mackenzie Delta. Wacasey found low diversity (<20 species per station) and low biomass (2 g/m^2) in most nearshore areas. However, biomasses as high as 5 g/m^2 were found in protected bays and lagoons.

Awareness that specific groups of invertebrates are important to higher trophic levels has been steadily building. Numerous studies have shown that arctic epibenthic and pelagic invertebrates, principally mysids, amphipods, isopods and copepods, comprise major components of the diets of fish, birds and mammals (Griffiths *et al.* 1975, 1977; Kendel *et al.* 1975; Stirling *et al.* 1975; Bradstreet 1977; Bendock 1977; Fraker *et al.* 1977; Searing 1977; Bain and Sekerak 1978).

Our 1977 results (Griffiths and Craig 1978; Craig and Griffiths 1978; Johnson 1978) showed that mysids and amphipods were the most abundant invertebrates in Simpson Lagoon, both in numbers and biomass, and were also the major food items of fish and birds. Four species of mysids and 17 species of amphipods were collected during the 1977 field season. Amphipod and mysid density and biomass varied widely among sampling localities and collection periods, indicating that these invertebrates were distributed unevenly. Large-scale movements of amphipods and mysids into, out of and within the lagoon appeared to occur during the open-water season. Most amphipods and mysids were associated with the detritus layer that covered most of the lagoon bottom.

STUDY AREA

A description of the study area and sampling stations is provided in Craig and Haldorson (1979). Figure 1 shows the locations of principal sampling locations in the Simpson Lagoon study area for 1977 and 1978. Table 1 shows the water depths and substrate characteristics at the 1978 stations.

METHODS AND RATIONALE OF DATA COLLECTION

Results from the first year of study in 1977 showed that epibenthic mysids and amphipods and, to a lesser degree, infaunal molluscs were the predominant food items of birds and fish. Therefore, these organisms were selected as the focal point of the 1978 invertebrate program. An analysis of the 1977 sampling techniques illustrated that traditional invertebrate sampling methods (trawls and nets) did not collect reliable quantitative data; consequently,in 1978 invertebrates were sampled using a variety of improved techniques (Table 2).

All invertebrate samples were preserved in 10% formalin and shipped to the laboratory for analysis. Descriptions of sampling techniques follow.

Faber Net

A modified Faber net (0.5 m diameter; 1.024 mm mesh) (Faber 1968) was used to collect samples of invertebrates and ichthyoplankton in the water column in Simpson Lagoon. The net was towed 30 m directly astern a Boston Whaler for 5 min. The volume of water

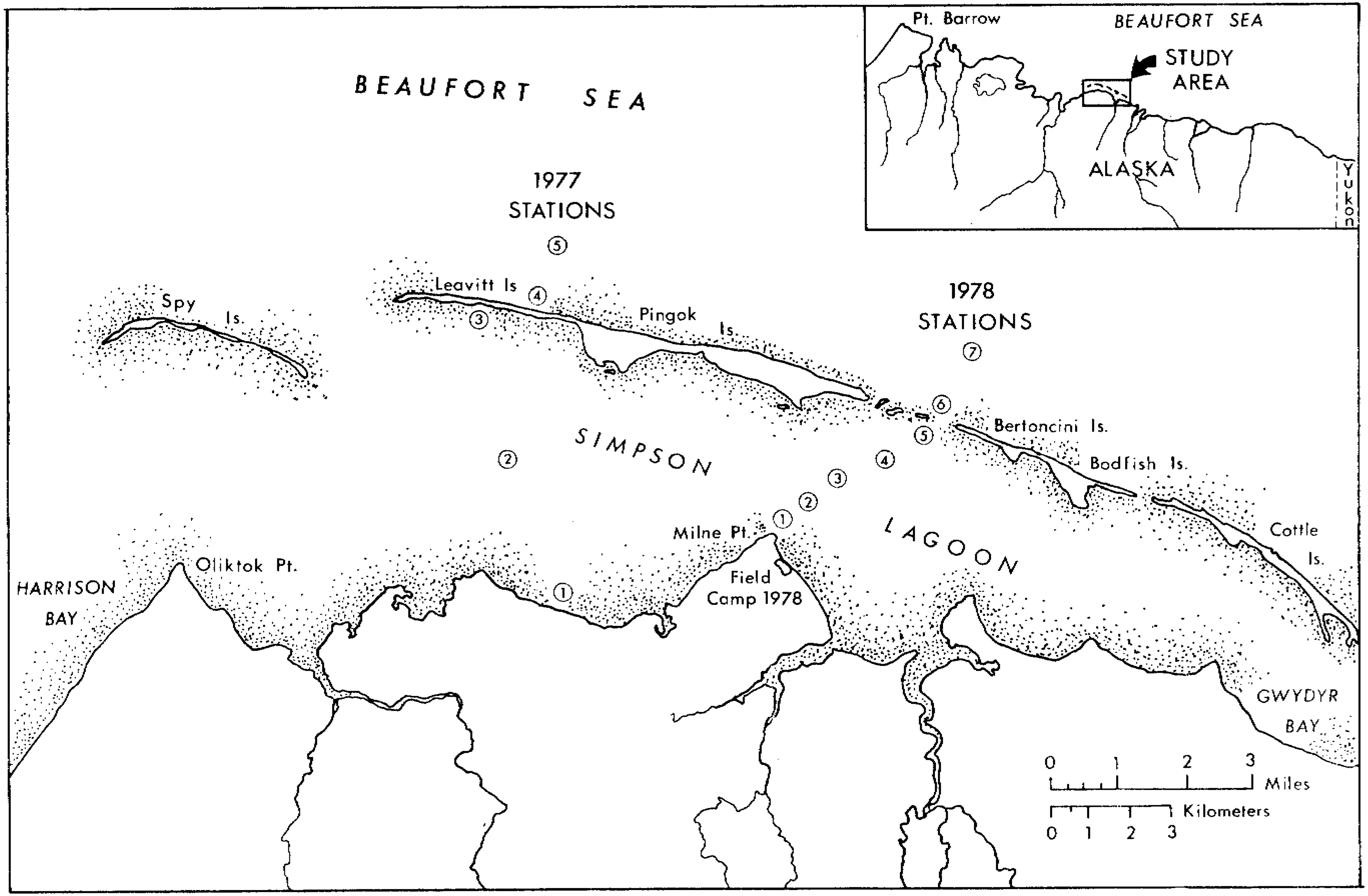

Figure 1. Map of Simpson Lagoon Showing Principal Sampling Stations Where Invertebrates were Collected During the Open Water Seasons of 1977 and 1978.

Table 1. Water Depth and Bottom Type at the Seven Principal Sampling Stations in the Simpson Lagoon Area, 1978.

Station	Water Depth (m)	Bottom Type
1	1.8	- Sand; occasionally some soft sediment on the sand
2	2.5	- Mud/detritus
3	2.5	- Mud/detritus
4	2.5	- Mud/detritus
5	1.0	- Sand ridges; detritus in ridges
6	1.5	- Sand ridges; detritus in ridges
7	7.5	- Very light flocculent detritus/mud

Table 2. Invertebrate Sampling Schedules and Methodologies followed in Simpson Lagoon during the Open-Water Season of 1978.

Sampling Technique	Stations Sampled	No. of Samples/Station	Approximate Sampling Periodicity	Data Requirements
Faber Net	2,3,4,6/7[†]	3	14 Days	Temporal and spatial variations of invertebrates in the water column.
Drop net	1-7	5	14 Days	Temporal and spatial variations of epibenthic invertebrates.
Drift net	Gaps in islands	2-10	Weekly	Movements into and out of the lagoon by epibenthic invertebrates.
Under ice baited amphipod traps	1-7	1	Daily from 4-7 June	Early season presence of invertebrates in the lagoon.
Observations by divers	1-7	10	Five dates (see text)	Provision of density estimates to compare with estimates from drop net samples.
Air lift	1-7	6	Three dates (see text)	Bivalve biomass
Photographic quadrats	1-7	2	Five dates (see text)	Density estimates of invertebrates; evaluation of substrate characteristics.

[†] Ice prevented sampling at Station 7 early in the season.

filtered was calculated using time and a digital readout flowmeter (General Oceanics, Inc. model 2030).

Drop Net

Two models of a central-pursing drop net (Fig. 2) were designed specifically for this project by modifying an epibenthic invertebrate sampler developed by R. Clutter (1965).

1. A shallow-water version equipped with a pole handle.
2. A deep-water version with a heavy metal frame (10 kg).

All net screening was 1.0 mm nitex, and the purse collar was nylon ballistics cloth with 0.65 cm sq atlas netting around the margin.

The drop net used in shallow water was operated by first folding the purse collar back over the metal frame so that the metal rings on the collar encircled the bottom edge of the frame. With both the top and bottom of the net open, it was thrust to the bottom and held in place by the pole. Both purse lines were immediately pulled enclosing the sample in the net. The sample was then washed down the sleeve into a collecting bucket and the net was inspected to ensure that all organisms had been removed.

The drop net used in deep water was prepared and operated as above, except that the net was dropped rather than thrust to the bottom. The heavy weight of the frame caused the net to drop rapidly, and then held the net on bottom substrates while the pursing lines were drawn.

Drift Net

A 2.8-m-long tapering drift net (1.024 mm mesh size) was used to measure the movements of current-borne invertebrates in and out of the lagoon through the gaps between the barrier islands. The net was attached to a 1.0 m x 0.2 m metal frame and was set with its long axis vertical. Thus the net extended from the bottom to the top of the water column. The sample trap was emptied every

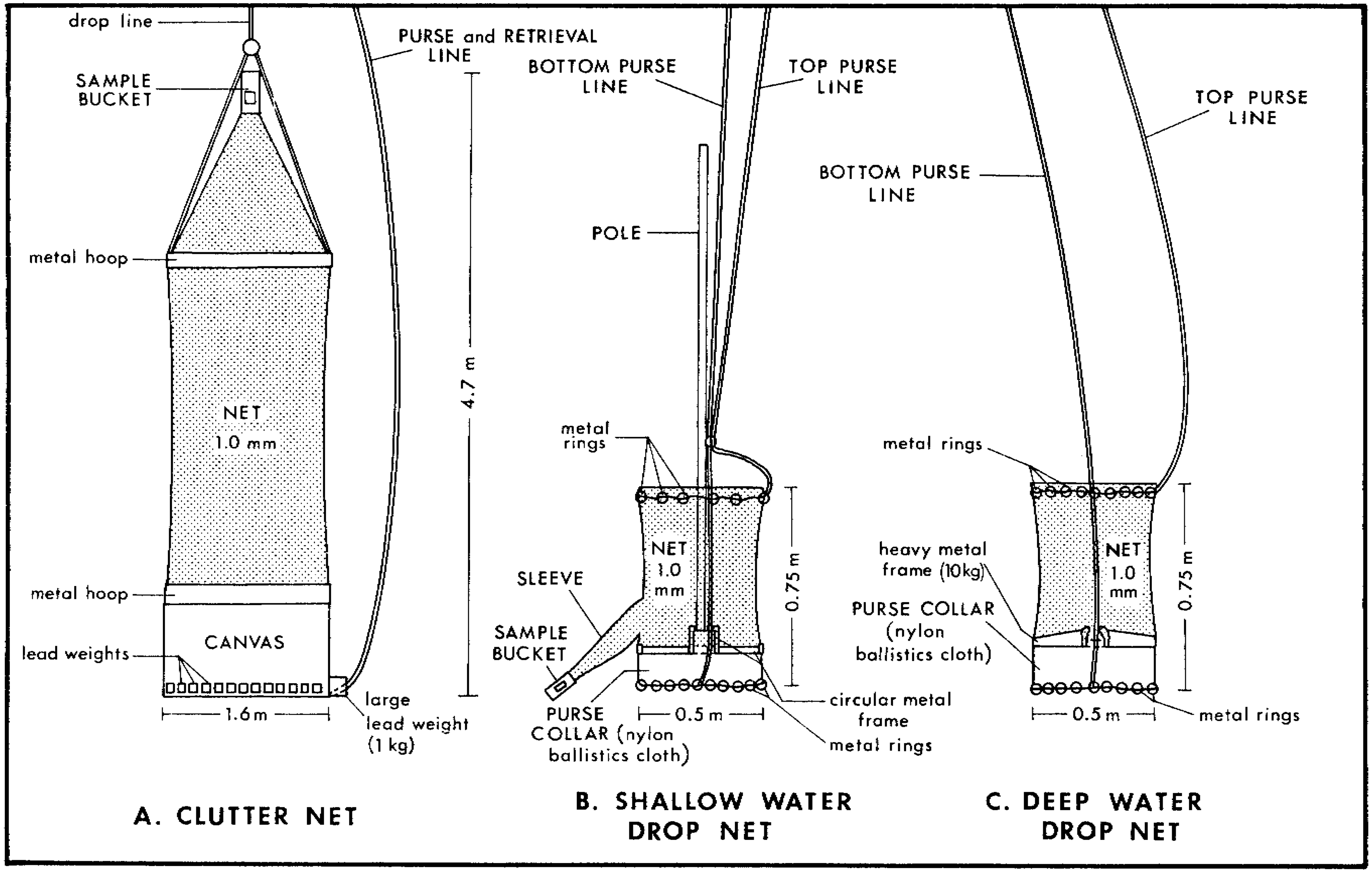

Figure 2. Two Models of a Central-Pursing Drop Net (modified from the Clutter net) used for Collecting Epibenthic Invertebrates in Simpson Lagoon in 1978.

hour and replaced by a new trap. The volume of water filtered was calculated using time and a digital readout flow meter (General Oceanics, Inc. model 2030).

Amphipod Trap

During the preliminary stages of spring breakup (5-7 June 1978) amphipod traps baited with meat were placed on bottom substrates under the ice at six locations (Fig. 4) across the lagoon and at one site on the ocean side of the barrier islands. The traps were cylindrical and measured 25 cm in length, 7 mm in diameter and were constructed of 1 mm wire mesh.

Diver Operations

SCUBA dives were conducted in Simpson Lagoon on five dates during the open-water season: 21, 25 and 31 July; 19 and 29 August. Stations 1-5 were sampled on all these dates; stations 6 and 7 were sampled on the last two dates only. Three divers were used on each occasion; two conducted the sampling and the third acted as a safety diver. Divers used the following sampling techniques:

Visual Estimates of Epibenthic Invertebrates

Each diver carried a 20 x 20 cm (0.04 m^2) quadrat frame and on five occasions during each dive recorded the number of mysids and amphipods by holding the frame approximately 10 cm off the bottom and estimating the number of organisms encompassed by the quadrat. This method was discontinued for amphipods and used only for mysids because divers noted that large numbers of amphipods burrowed into bottom substrates and could not be counted.

Airlift Samples

Two airlift samples were collected from each station during each of the last three dives. Divers emplanted a circular frame (15 cm in height and 40 cm in diameter; area 0.125 m^2) into the substrate and vacuumed out all material to a depth of about 2 cm. The airlift was a 1.5 m length of PVC pipe (10 cm in diameter) with a net (mesh size=1.0 mm) on the top. When the compressed air inlet near the bottom of the pipe was activated, material was drawn up the pipe and filtered through the net. Samples were later sieved (0.5 mm mesh size) and preserved.

Photographic Quadrats

Divers attempted to take color photographs of benthic invertebrates by using a Nikonos camera equipped with a wide angle lens and a strobe light system. An area of 50 x 25 cm (0.125 m^2) was photographed using a fixed-focus frame that ideally would allow measurements and counts to be made from the photographs. Six photographs of the bottom were taken at each station during each dive period. However, because of the turbidity of the water and back scattering of light, mysids and amphipods were not visible in the photographs.

Laboratory Techniques

Sorting

Samples were sieved through a 1.024 mm mesh nylon screen, washed with water, and examined under a low-power binocular microscope. All whole or partial organisms were separated into major taxonomic groups (amphipods, mysids, etc.) and counted. Techniques for counting fragmented organisms were as follows:

1. Copepods: The total number of copepods was assumed to be the number of whole organisms plus the number of separate cephalothoraxes present.
2. Amphipods: Amphipod specimens were often in two parts (head plus peraeon, abdomen plus telson) or three parts (head, peraeon, abdomen plus telson). The sum of the numbers of whole amphipods and separate 'abdomens plus telsons' constituted the total number.
3. Mysids: The total number of mysids equalled the number of whole organisms plus the number of separate telsons.
4. Polychaetes: Polychaetes were generally broken in half. The total number present was assumed to be the number of whole polychaetes plus the number of anterior parts.
5. Medusae: The number of whole medusae plus the number of bells constituted the total number in the sample; fragmented bells were counted if over one-half the bell was present.
6. Bivalves: Similarly, the number of whole bivalves plus the number of partial shells (>½ of whole shell) constituted the total number of bivalves in the sample. Half shells were presumed to be from non-living individuals and were not counted.

If large numbers of individuals were present, the sample was first scanned for large or rare organisms, and was sub-sampled with a Folsom Plankton Splitter (following the methods of McEwen *et al.* 1954). We found no significant differences between the number of specimens when pairs of chambers were compared (Wilcoxon matched-pairs signed-ranks test: n=10 pairs, $P<0.05$).

Only those taxonomic groups that comprised significant portions of the drop net samples or the diets of higher trophic level organisms were identified to species. These major taxa were amphipods, mysids, copepods and bivalves.

Measuring

Two techniques were used to obtain total lengths of dominant invertebrate species.

1. Because broken organisms sometimes precluded measurements of total lengths of organisms (especially those in fish and bird stomachs) specific anatomical structures (referred to as "partial lengths") were measured (Table 3 and Fig. 3). These measurements were converted to total lengths by using best-fit equations for the relationship between the partial length and total length. These equations are presented in Appendicies 1 to 8. Because of the relative ease in measuring partial lengths, all samples were analyzed in this fashion and later converted to total lengths. On the basis of total lengths, organisms were assigned to a 2-mm length interval.

2. Bivalve and copepod total lengths were measured directly because of the difficulty of establishing precise relationships between partial and total lengths.

Biomass

For each important invertebrate species, we measured and weighed approximately 50 organisms from each length interval and developed best-fit equations for the relationship between total length and wet weight (Appendicies 1 to 8).

Wet weight was converted to ash-free dry weight and then to Kcal energy content by using data from microbomb calorimeter studies carried out by Dr. Donald Pattie of the Northern Alberta Institute of Technology (Table 3). These data were used to calculate the amount of energy available (per m^2) to consumers in Simpson Lagoon.

Limitations and Biases

The inherent errors of some sampling techniques for invertebrates were discussed in a previous report (Griffiths and Craig 1978). Limitations and biases of new techniques that were utilized in 1978 are discussed below.

Table 3. Equations and Comparisons Used to Determine Energy (K cal) Available to Birds and Fish in Simpson Lagoon, 1978.

Organism	Partial Length:Total Length Conversion	Total Length:Wet Weight Conversion	Percent of Wet Weight to Equal Ash-Free Dry Weight	K calories/g Ash-Free Dry Weight
Mysis litoralis	Total length = 6.4739(Partial length)$^{+}$0.8442	Wet Weight = 0.0294(Total length)$^{2.4476}$	11.5[1]	5.47[1]
Mysis relicta	Total length = 6.5982(Partial length)$^{+}$0.6512	Wet Weight = 0.0442(Total length)$^{2.3087}$	11.5[1]	5.47[1]
Onisimus glacialis	Total length = 2.2313(Partial length)$^{+}$0.5995	Wet Weight = 0.0544(Total length)$^{2.5597}$	19.7[1]	5.07[1]
Pontoperia affinis	Total length = 2.6674(Partial length)$^{+}$0.2652	Wet Weight = 0.6395(Total length)$^{1.2687}$	17.8[2]	5.39[1]
Apherusa glacialis	Total length = 5.0667(Partial length)$^{-}$0.0933	Wet Weight = 0.0832(Total length)$^{2.1070}$	13.7[3]	6.90[1]
Gammarus setosus	Total length = 5.1022(Partial length)$^{+}$0.6080	Wet Weight = 0.0497(Total length)$^{2.5045}$	11.1[3]	5.17[1]
Parathemisto spp.	Total length = 3.7535(Partial length)$^{+}$0.1765	Wet Weight = 0.0564(Total length)$^{2.4436}$	14.9[3]	6.23[1]
Mysid spp.	-[4]	-[4]	11.5[1]	5.47[1]
Amphipod spp.	-[4]	-[4]	15.1[1]	5.37[1]
Cyrtodaria kurriana	-	Body Weight = 0.0194(Total length)$^{3.2980}$	74.3(Dry Weight)	5.20[1]
Calanoid copepods	-	Dry Weight = 0.0016(length)$^{2.89}$	76.3(Dry Weight)	6.17[1]

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[1] Determined from bomb calorimetry results by Dr. D. Pattie, Northern Alberta Inst. Technology.

[2] Determined from data of Sars (1953).

[3] Determined for corresponding length intervals by Bradstreet (1977).

[4] Organisms in these groups were counted and wet weighed.

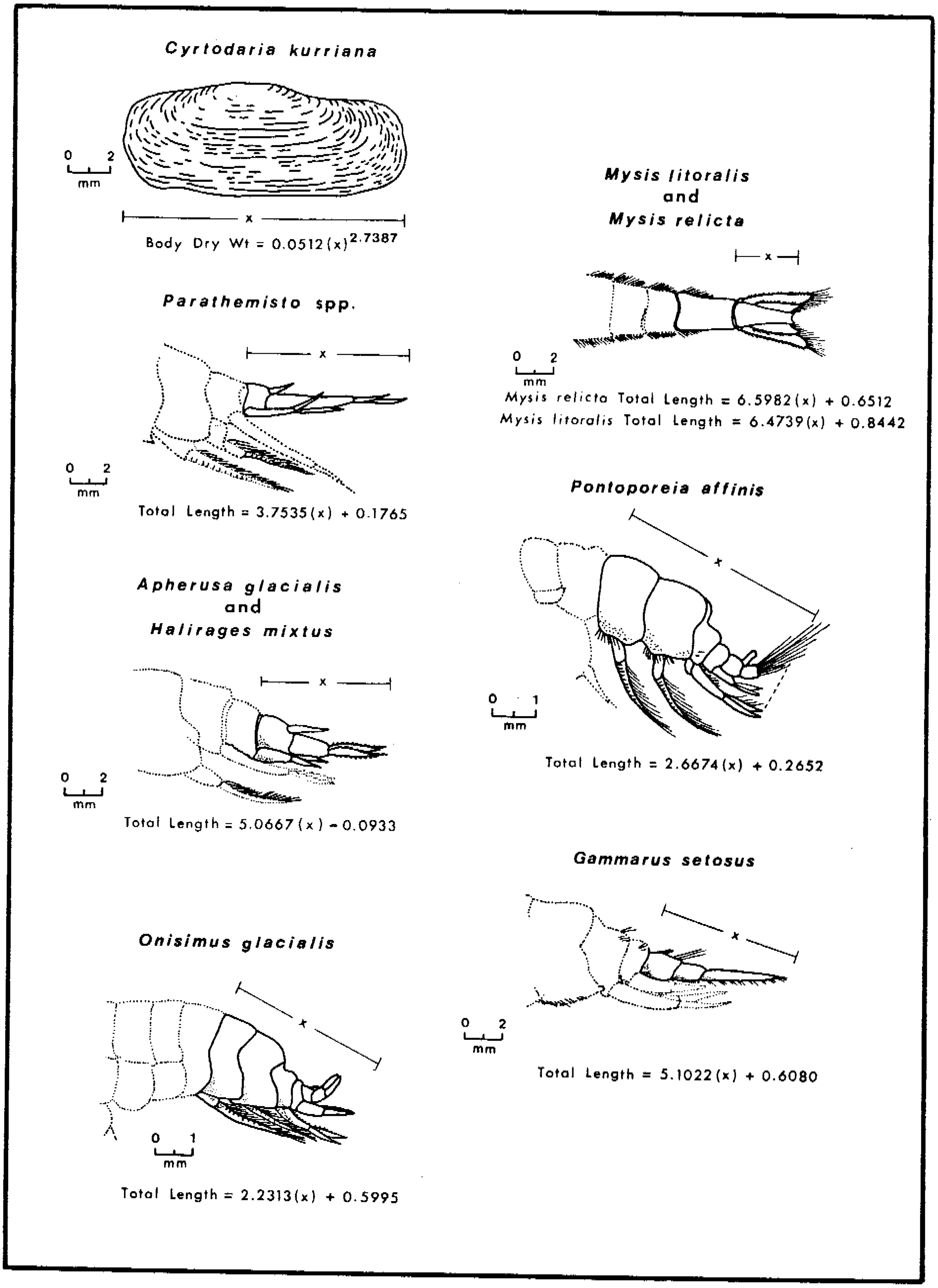

Figure 3. Anatomical Features of Invertebrates that were Measured for Later Conversion (by equations) to Total Lengths.

Drop Net

This net proved to be an excellent sampling device for epibenthic invertebrates, which were usually within 10 cm of the lagoon bottom. Diver observations of the operation of the drop net indicated that the move-and-freeze evasive behavior of mysids did not prevent their capture. The drop net was at maximum velocity just before it struck the bottom and sealed against the substrate. No animals were seen to avoid the descending net. Pursing of the net's bottom would be expected to cause mysids and amphipods to move upward and into the bag. The drop net did not effectively sample infaunal organisms because the pursing operation only scraped the substrate.

Visual Estimates by Divers

This method provided density estimates that were, for several reasons, biased downward.

1. As the number of organisms increased, the ability of divers to accurately count them within the quadrat decreased.
2. Early in the season organisms were small, almost transparent, and therefore difficult to see and count.
3. Many of the epibenthic organisms moved in and out of the detritus, and some thereby escaped observations.

Diver observations also provided only limited taxonomic differentiations of mysid and amphipod species since diagnostic characters are often only observable using a dissecting microscope.

Airlift Samples

Airlifts appear to be effective in sampling infaunal organisms to a depth of 2 cm; however, epibenthic animals are able to escape the airlift during the placement of the circular frame and prior to activation of the lift. This method is most effective when used for sampling soft bottom substrates.

Photographic Quadrats

This technique was used to acquire permanent records of benthic organisms and substrates at particular points in space and time. Its recording capabilities were limited because of the evasive behavior of the motile organisms (amphipods and mysids), the periodic turbidity of the water, and/or the presence of highly-effective cryptic coloration in some of the benthic organisms. The positioning of the strobe lights on the photographic frame was critical to the acquisition of good quality photographs, since animals were obscured by improperly reflected light. Because of this last reason in particular, most of the photographs made were not sufficiently distinct to use for estimating numbers of invertebrates.

Laboratory Techniques

Wet weights used in this study are from formalin-preserved samples. These wet weights must be considered approximate, since actual wet weights of crustaceans and some other invertebrates are significantly altered by preservation in 10% formalin (Conover and Lalli 1972; Bradstreet 1977; LGL Ltd. unpubl. data). The degree of weight alteration depends on the species; for example, various amphipods may show changes of ± 5-20% in weight.

Comparison of Sampling Techniques

The 1977 results indicated that traditional invertebrate sampling methodology causes underestimation of the actual densities of mobile epibenthic organisms of two to three orders of magnitude; diver estimates appear to provide more reliable values (Griffiths and Craig 1978). However, comprehensive coverage by divers is limited by expense, weather and ice conditions, and turbidity. In 1978 an effort was made to develop a sampling device that could be used to quantitatively sample epibenthic organisms from a small boat in most weather conditions. Clutter (1965) developed a large drop net to collect epibenthic invertebrates; this design was modified to produce two types of drop net (see METHODS), which were used in addition to diver observations and diver-operated sampling devices (airlift). In this report drop net results are used in most analyses since this method was applied more widely in time and space than were other methods, and its effectiveness compared favorably with that of other techniques, as discussed below.

Statistical comparisons of the density estimates obtained by the various sampling techniques used in 1978 are shown in Table 4. The comparisons are based on occasions when two or three methods were employed at the same place and time. Comparisions between the results of the two types of drop net showed no significant differences in the density estimates obtained for mysids or amphipods collected. There was also no significant difference in the density estimates of amphipods collected by airlift and drop net.

There was a significant difference among mysid density estimates by drop net and divers 1 and 2; the drop net tended to give lower estimates. Analysis showed that the probable cause of the difference was that diver 2 tended to estimate higher densities than were estimated from drop net samples (Table 4). No direct comparisons among all three divers were possible since only two divers were in the water at any one time. However, three independent paired t-tests of estimates by divers showed the following:

Diver 1 vs Diver 2	t=3.8753 d.f.=28	P<0.01
Diver 1 vs Diver 3	t=0.5333 d.f.=28 NS	P>0.50
Diver 2 vs Diver 3	t=1.3858 d.f.=28 NS	P>0.10

Divers 1 and 3 were the most experienced in estimating densities of epibenthic invertebrates and the agreement between them was the closest. Diver 2 tended to give higher estimates, possibly due to his inexperience, in the early part of the season.

Table 4. Statistical Comparisons of Density Estimates of Mysids and Amphipods Obtained with Various Sampling Techniques in Simpson Lagoon, 1978.

Sampling Techniques	Organisms Compared	Statistical Test	Results	Comments
Shallow vs Deep Water† Drop Net	Mysids Amphipods	Paired t-test Paired t-test	$t=0.068$, $P<0.01$, d.f. 4 $t=1.661$, $P<0.05$, d.f. 4	No significant difference between nets for either organism.
Shallow Water Drop Net vs Airlift	Amphipods Amphipods	t-test Mann-Whitney μ	$t=0.0496$, $P<0.10$, d.f. 12 $\mu=13$, $P<0.01$, $N_1=4$, $N_2=10$	No significant difference with either test.
Shallow Water Drop Net†† vs Estimate by Diver 1 vs Estimate by Diver 2	Mysids	Friedman Test	$\chi^2=9.4$ $P<0.01$ $K=3$, $N=10$	Significant differences among observations.
Shallow Water Drop Net vs Diver 1	Mysids	Friedman rank sums critical value table	Difference 1	No significant difference between shallow drop net vs diver 1 $P=0.05$
Shallow Water Drop Net vs Diver 2	Mysids	Friedman rank sums critical value table	Difference 11	Significant difference between shallow drop net vs diver 2 $P=0.037$
Diver 1 vs Diver 2	Mysids	Friedman rank sums critical value table	Difference 9	No significatn difference between diver 1 vs diver 2 $P=0.05$

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† Data collected in a pair wise fashion.

†† Only two divers were in the water at a time, so that diver 3 could not be used in the comparison.

RESULTS

Early Season Movements and Distribution of Epibenthic Invertebrates

Simpson Lagoon remains ice covered for approximately nine months of the year. Organisms inhabiting the lagoon during this period are subjected to low temperatures (-1.5 to -2.0°C) and high salinities (>40 ppt). Data on the winter utilization of Simpson Lagoon by invertebrates are sparse. This deficiency was partially addressed by limited sampling conducted on the bottom under the ice in Simpson Lagoon in April-May 1978 and by a more extensive sampling program carried out in Simpson Lagoon on 5-7 June 1978 prior to inundation of the lagoon ice by river discharge. Invertebrates were again collected under the ice in November 1978, and February 1979, and a further effort in May 1979 is planned. This sampling will complete the year-round sampling of epibenthic invertebrates in Simpson Lagoon. This section of the report is based on samples collected in April-June 1978; the results of the latter sampling efforts will be presented in the final report.

During the periods 12-15 April and 22-25 May 1978 baited amphipod traps were set beneath the ice at Milne and Oliktok Points (Fig. 4). All traps, with the exception of one set in May near Oliktok Point, were recovered after 24 hr and all contained amphipods. On both occasions at the Milne Point site in the central portion of the lagoon *Onisimus glacialis* was the dominant amphipod trapped. In the April sample near Oliktok Point *Boeckosimis affinis* was the principal amphipod.

Between 5-7 June 1978, prior to the time that river discharge reached the coast, baited amphipod traps were set under the ice at six sites in the lagoon and at one site offshore of the barrier islands (Fig. 4). Large *Onisimus glacialis* (8-10 mm) were the most abundant amphipods in collections from the lagoon, but on the ocean side of the barrier islands *Boeckosimis affinis* (8-10 mm) was the

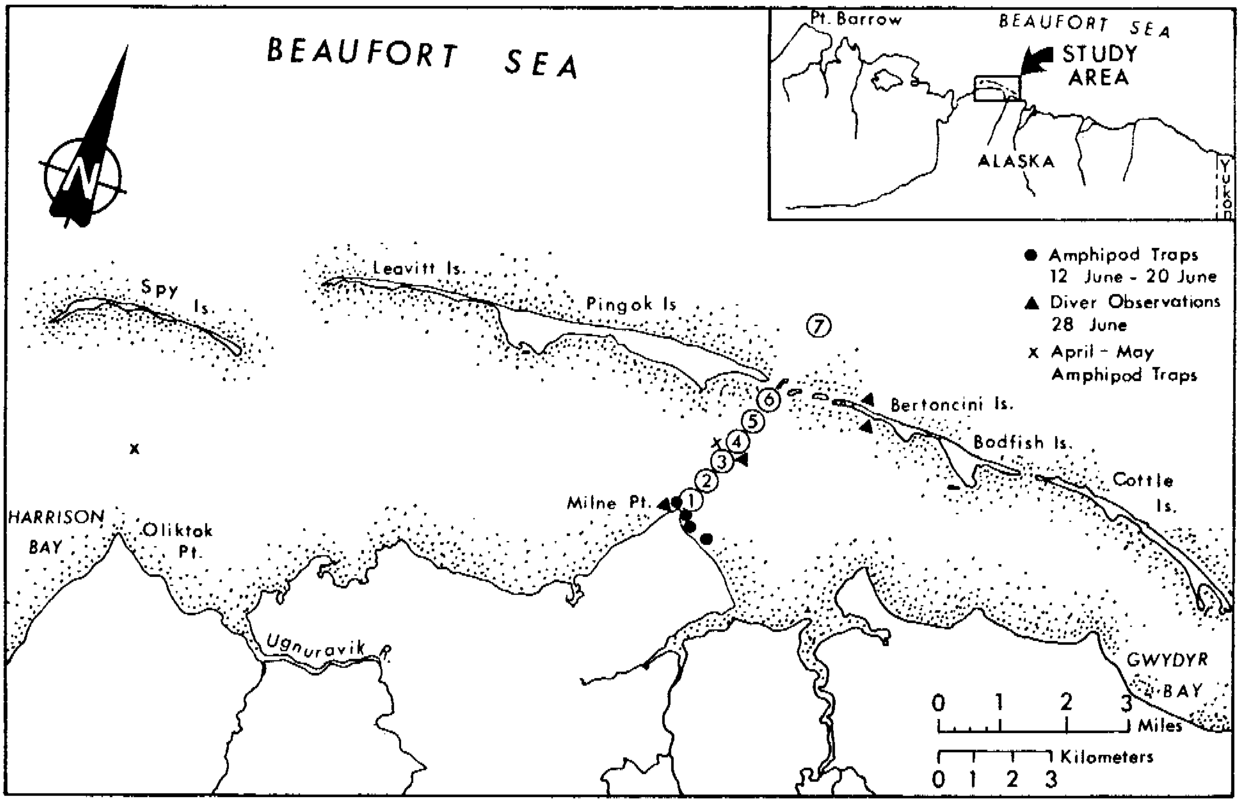

Figure 4. Map of Simpson Lagoon Early Season Invertebrate Sampling Sites, April-June 1978.

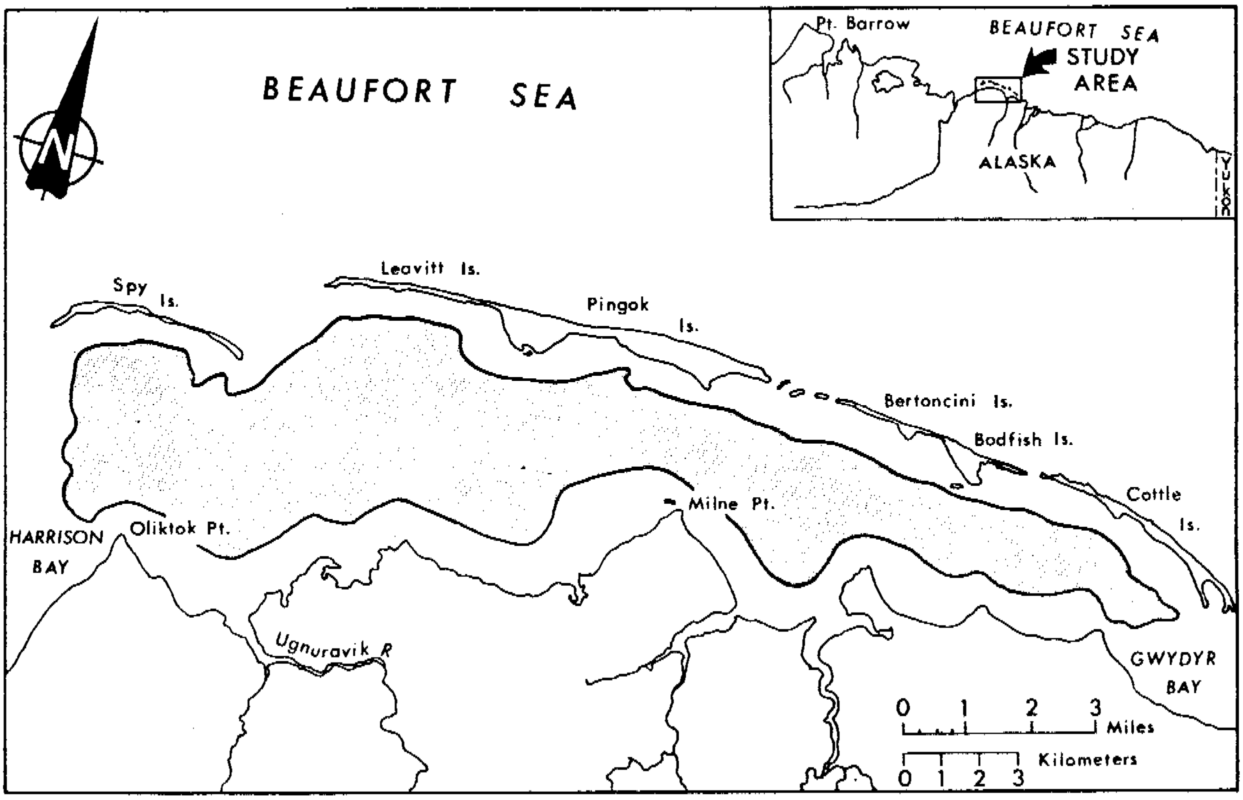

Figure 5. Map of Simpson Lagoon Showing Approximate Extent of Area Available to Epibenthic Invertebrates During Winter.

most abundant species (Table 5). The absence of small individuals (2-4 mm) of these species is not fully understood, but may indicate that young have different feeding habits (i.e., plankton feeders) and are not attracted to the meat baited traps or they may occupy a different habitat. Buchanan *et al.* (1977) reported large numbers of *Onisimus glacialis* and *O. littoralis* in the soft-ice layer in Bridport Inlet, Melville Island, N.W.T. Similar observations of *Onisimus glacialis* were reported in Brentford Bay, N.W.T. by Thompson *et al.* (1978).

On 12 June, after the peak of over-ice river runoff but before the nearshore fast ice lifted from the bottom, four baited amphipod traps were set in the shallow lead next to the mainland shore at Milne Pt. (Fig. 4). The intention was to determine the rate at which amphipods colonized previously frozen shoreline habitats. The traps were checked twice daily. No organisms were captured until 19 June, approximately 12 h after the land-fast ice had lifted from the bottom between the shore lead and the lagoon center. By 20 June all four traps contained numerous large *Onisimus glacialis* (8-10 mm) but no small individuals; in addition one *Mysis litoralis* (7.0 mm in length) was collected.

On 28 June divers observed that small mysids and amphipods (both 2-4 mm) were abundant in the leads next to the mainland and on the lagoon and ocean sides of the barrier islands (Table 6). A few large mysids and amphipods were also observed near Milne Point at this time. On 7 July four female mysids (1 *Mysis litoralis*, 3 *M. relicta*) that ranged from 11 to 16 mm in length and were still brooding young (4-16 individuals per female; 2-4 mm in length) were collected just north of Milne Point in shore leads. In the central portions of the lagoon at this time numerous small and large amphipods were seen, but only one large mysid (12-14 mm) and no small mysids were noted there by divers. In 1977 from 17 June to 3 July small (<5 mm) mysids and amphipods were noted in all the open leads around Pingok Island; however, no adults of either group were collected (Griffiths and Craig 1978:55).

Table 5. Early-Season Distribution of Epibenthic Invertebrates in Simpson Lagoon, 5-7 June 1978. Samples were collected under ice with baited amphipod traps placed on substrates. Sites 1-6 are located in the lagoon; site 7 was on the oceanside of the barrier islands. Abundance: x-present; xx-major component; xxx-only species found.

Site	Date in (June)	Depth (m)		Temp. (°C)	Salinity (°/oo)	Organisms Collected and Their Abundance
		ice	water			
1	5	1.5	0.0	-	-	- No organisms collected
	6	1.5	0.0	-	-	- No organisms collected
	7	1.5	0.0	-	-	- No organisms collected
2	5	1.6	0.2	-1.2	39.0	- *Onisimus glacialis* (xxx)
	6	1.6	0.2	-1.5	37.0	- *Onisimus glacialis* (xx); Isopods (x)
	7	1.6	0.2	-1.5	39.0	- Trap lost
3	5	1.6	0.5	-1.2	39.0	- *Onisimus glacialis* (xxx)
	6	1.6	0.5	-1.5	37.0	- Trap frozen in
	7	1.6	0.5	-1.5	39.0	- *Onisimus glacialis* (xxx)
4	5	1.8	0.5	-1.5	34.0	- *Onisimus glacialis* (xxx)
	6	1.8	0.5	-1.5	37.0	- *Onisimus glacialis* (xxx)
	7	1.8	0.5	0.0	33.0	- *Onisimus glacialis* (xx); Isopod (x)
5	5	1.8	0.5	-1.5	35.0	- *Onisimus glacialis* (xx); *Boeckosimis affinis* (x)
	6	1.8	0.5	-1.8	34.0	- Trap frozen in
	7	1.8	0.5	-1.8	34.0	- *Onisimus glacialis* (xx); *Boeckosimis affinis* (x)
6	5	1.5	0.0	-	-	- No organisms collected
	6	1.5	0.0	-	-	- No organisms collected
	7	1.5	0.0	-	-	- No organisms collected
7	5	2.0	2.0	-0.5	31.0	- *Boeckosimis affinis* (xx); *Onisimus glacialis* (x); Ispods (x)
	6	2.0	2.0	-1.0	37.0	- *Boeckosimis affinis* (xx); *Onisimus glacialis* (x); Isopods (x)
	7	2.0	2.0	-0.5	37.0	- Trap lost

Table 6. Diver Observations in Leads Inside and Outside Simpson Lagoon on 28 June 1978.

Location	Substrate	Water Depth (m)	Visibility (m)	Observations
Milne Point	Tundra clumps sand and gravel	0.5	0.5	1 large mysid (1 cm), many small mysids (2 mm), many small amphipods (2-4 mm), a few large amphipods of several genera (*Onisimus*, *Pontoporeia*, *Gammarus*)
0.5 km lagoonward[†] from Milne Point	Soft sediments and sand	2.5	1.0	A few amphipods and some polychaetes
Mid-lagoon[†]	Soft sediments and sand	3.0	1.0	Many polychaete worms, many Onisimus amphipods, only one mysid, 3 tunicates, 3 isopods
Lagoon side of Bertoncini Island	mostly sand	0.5	1.0	Numerous small mysids and amphipods. Most mysids were moving passively westward with the current (≈3 cm/sec); those not moving were close to the substrate
Ocean side of Bertoncini Island	fine sand, cobble bottom rippled with detritus in troughs	1.0	0.5	Amphipods of various sizes in water column; numerous small ones about 3 cm off bottom. Few large mysids but many small ones (2-4 mm) right on the substrate

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[†] Dives were conducted through large holes in the ice.

It appears that certain amphipods and isopods are able to utilize large areas of the ice-covered lagoon (>2.0 m deep) when salinities are high, prior to break up (Tables 5 and 6, Fig. 5). *Onisimus glacialis* was the primary species found in the lagoon at this time, whereas *Boeckosimus affinis* was most abundant on the ocean side of the barrier islands and in the samples taken close to Harrison Bay. (Similar distribution patterns for these species were found in samples collected under the ice in Simpson Lagoon and Harrison Bay in November 1978.) It is uncertain whether this differential distribution is the result of preferences or requirements. Amphipods appear to move quickly from the middle portion of the lagoon to the lagoon edges soon (within 12 h) after the ice lifts from the nearshore bottom in June. It should be remembered that this discussion concerns only those species attracted by baited traps; other epibenthic or ice-associated species may have been present but were not attracted to the traps.

In contrast to amphipods and isopods, mysids did not appear to extensively utilize the lagoon in late spring. They may recolonize the lagoon each year after break-up by moving from the adjacent ocean or bays along shallow shore leads adjacent to the mainland or island beaches. However, both species of mysids were still present under the ice in Simpson Lagoon during November 1978; their densities at that time were similar to those reported during the 1978 open-water season (*M. litoralis*, 30/m^2; *M. relicta*, 10/m^2). It is hoped that late winter sampling in early 1979 will resolve whether mysids leave the lagoon sometime after November.

Open-Water Season Movements, Distributions and Abundances of Epibenthic Invertebrates

Drop net and Faber net samples were collected in a systematic temporal and spatial pattern during the open-water season of 1978 to determine movements, distributions and abundances of the key invertebrate species. The drop net was used to sample invertebrates near or on the bottom, and the Faber net sampled invertebrates higher in the water column. Results of both sampling methods are presented in Appendicies 9 and 10. The results are expressed in terms of biomass (ash-free dry weight per m^2 for bottom samples or per 100 m^3 for samples in the water column), since this measure of the several available, most accurately describes the energy available to higher trophic levels (birds and fish) utilizing the system. By this measure, the two dominant groups of invertebrates, both in the water column and associated with the bottom, were mysids and amphipods. However, it should be noted that if a smaller (0.240 mm) mesh size had been used copepods would probably have been the dominant group collected. Discussion of the mysid and amphipod groups follow.

Mysids

Mysids were very abundant in the study area and were the major food item of vertebrate consumers in the system. Two species, *Mysis litoralis* and *M. relicta*, were identified in 1978 samples. Other preserved specimens identifiable only as *Mysis* sp., because of the absence of diagnostic characteristics, were most likely one or the other of the identified species. Divers observed (both in 1977 and 1978) that the density and biomass of mysids were much greater near the bottom than in the water column.

Mysids Near the Bottom. Mysid biomasses near the bottom at the seven standard stations during seven sampling periods are shown in Appendix 10 and Figures 6 and 7 and compared in Tables 7 and 8.

Within the lagoon, the biomass of *M. litoralis* was significantly lower at Station 1 than at Station 3 (P=0.028), and the biomass at Station 5 was significantly lower than that at Station 2 (0.049) and Station 3 (P=0.028), indicating that this species preferred the deeper (>1.2 m) central portions of the lagoon[†]. There were

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[†] Comparisons between specific pairs of stations are based on a non-parametric multiple comparison procedure applicable after the Friedman tests of Table 6 and 7 have been applied (see Hollander and Wolfe 1973).

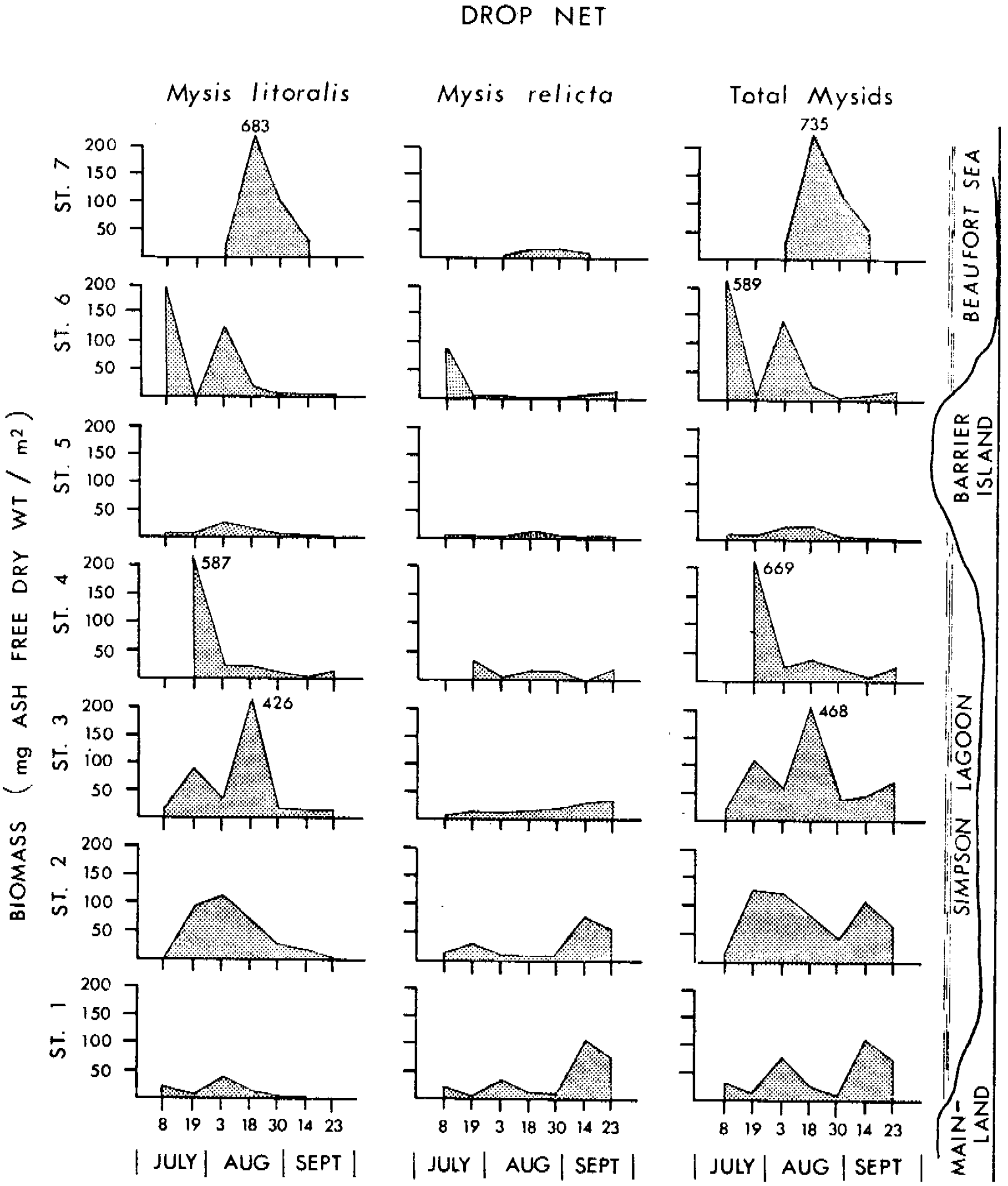

Figure 6. Biomass of Mysids Near the Bottom in Relation to Date and Sampling Station. (Each data point is a mean of five drop-net samples Collected in Simpson Lagoon 1978.)

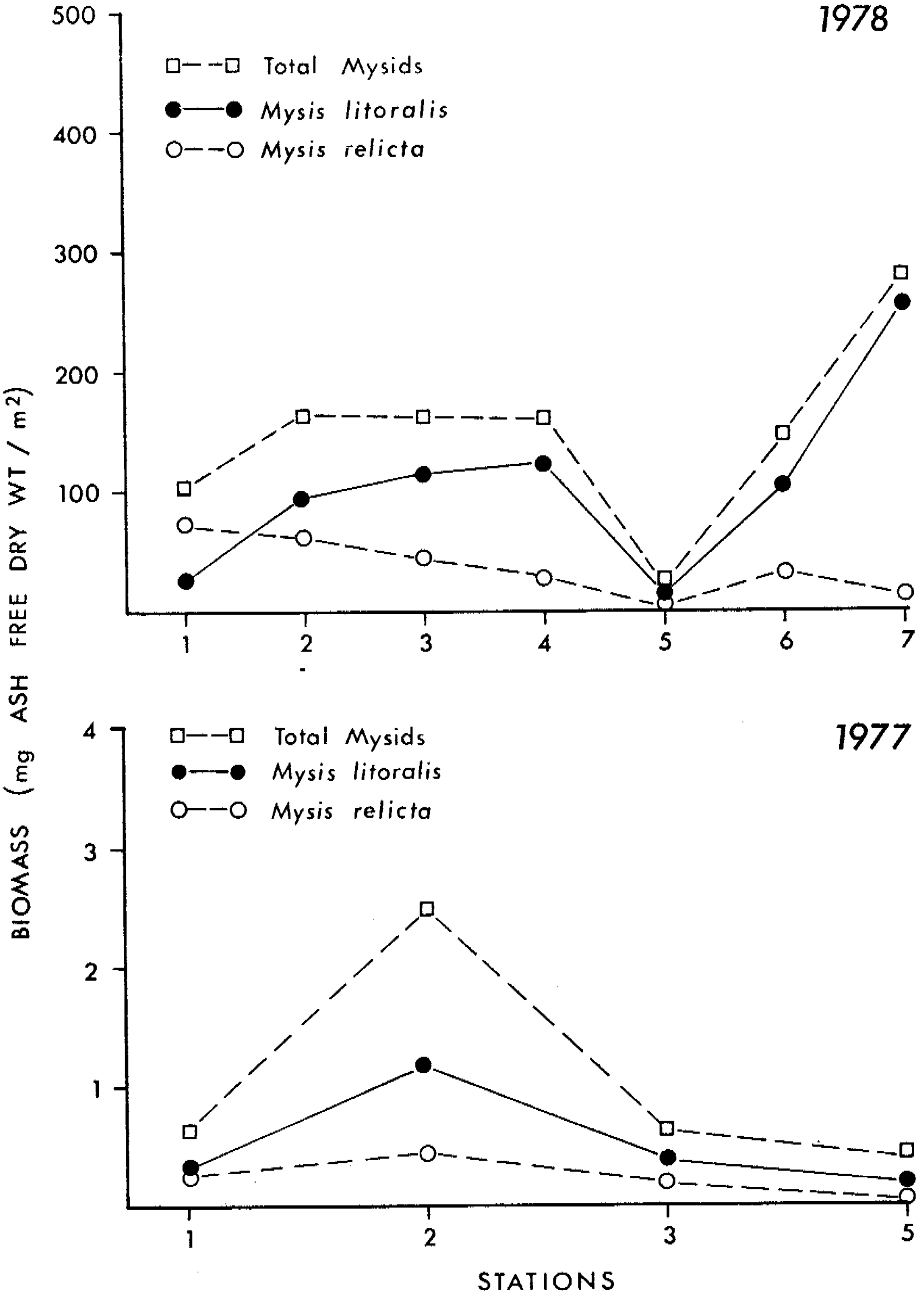

Figure 7. Biomass of Mysids Near the Bottom at the Various Sampling Stations in 1977 and 1978. (Each 1978 point is a mean of five drop-net samples for each sampling date within the period 8 July to 23 September 1978. The 1977 data are recalculated from Griffiths and Craig [1978]. Because different sampling techniques were used in the two years, only the general trends can be compared.)

Table 7. Comparisons of Mysid Biomass Near the Bottom (mg ash-free dry weight/m^2), Among Lagoon Stations (1-5)† and Among All (1-7)†† Using the Friedman Two-Way Analysis of Variance†††. Each station/date value was the mean from five drop-net samples at the station during the sampling period.

Species or Group	Comparisons Among Lagoon Stations (1-5) (df=5)†		Comparisons Among All Stations (1-7) (df=3)††	
Mysis litoralis	$\chi^2=14.33$,	$0.01<P<0.001$	$\chi^2=11.75$,	$0.10<P<0.05$
Mysis relicta	$\chi^2=6.99$,	$P>0.10$	$\chi^2=9.59$,	$P>0.10$
Total Mysids	$\chi^2=13.39$,	$0.02<P<0.01$	$\chi^2=9.49$,	$P>0.10$
Ratio of *M. litoralis* to *M. relicta*	$\chi^2=4.99$,	$P>0.20$	$\chi^2=10.29$,	$P>0.10$

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† Only sampling periods from 19 July to 23 September used in comparisons.

†† Only sampling periods from 3 August to 14 September used in comparisons.

†††See Siegel (1956).

Table 8. Comparisons of Mysid Biomass Near the Bottom (mg ash-free dry weight/m^2) Among Sampling Periods for Lagoon Stations (1-5)† and for Lagoon and Offshore Stations (1-7)†† Using the Friedman Two-Way Analysis of Variance†††. Each station/date value was the mean from five drop-net samples at the station during the sampling period.

Species or Group	Comparisons Among Sampling Periods† Considering Lagoon Stations (1-5) (df=5)		Comparisons Among Sampling Periods†† Considering Lagoon and Offshore Stations (1-7) (df=3)	
Mysis litoralis	$\chi^2=21.71$,	$P<0.001$	$\chi^2=14.47$,	$0.01<P<0.001$
Mysis relicta	$\chi^2= 1.98$,	$P>0.80$	$\chi^2= 1.23$,	$P>0.70$
Total Mysids**	$\chi^2= 9.83$,	$0.10<P<0.05$	$\chi^2= 7.61$,	$0.10<P<0.05$
Ratio of *M. litoralis* to *M. relicta*	$\chi^2=10.09$,	$0.10<P<0.05$	$\chi^2= 8.85$,	$0.02<P<0.01$

† Only sampling periods from 19 July to 23 September used in comparisons.

†† Only sampling periods from 3 August to 14 September used in comparisons.

†††See Siegel (1956).

no significant differences among lagoon stations in the biomass of *Mysis relicta* or in the ratio of the biomasses of *M. litoralis* and *M. relicta* in samples. However, total mysid biomass differed significantly among stations; the biomass at Station 5 (in shallow water on the lagoon side of barrier island) was significantly lower than that at two deeper stations nearer the mainland--Station 2 ($P<0.013$) and Station 3 ($P=0.028$).

The biomass of *M. litoralis* near the lagoon bottom declined markedly after 18 August 1978 (Fig. 8), and the seasonal variation in biomass of this species was statistically very significant ($P<0.001$, Table 8). The biomass of *M. relicta* averaged less than that of *M. litoralis*, and there was no significant difference in *M. relicta* biomass among sampling periods. However, the biomass of *M. relicta* was highest in September, after the biomass of *M. litoralis* had declined (Fig. 8). Consequently, the ratio of *M. relicta* to *M. litoralis* differed among sampling periods, and was significantly higher, all stations considered, on 14 September 1978 than on 3 August 1978 ($P=0.018$).

Although direct comparisons between 1978 and 1977 data results are not possible, since different collection techniques were used, general trends can be compared (Figs. 7 and 8). For lagoon stations, the biomasses of *M. litoralis* and of total mysids followed similar patterns. In both years both of the biomasses were highest in the deep central lagoon. *M. relicta* biomass tended to be highest near the mainland in 1978, but not in 1977. *M. relicta* biomass was low at offshore stations (1977 Station 5 and 1978 Station 7) in both years (Fig. 7). However, the 1978 trend for *M. litoralis* (and consequently total mysid) biomass to be higher at offshore stations was not seen in 1977 (Fig. 7).

A comparison of biomasses among dates shows marked differences between the two years for *M. litoralis, M. relicta* and total mysids at both lagoon and offshore stations (Figs. 8 and 9). In 1977 *M. litoralis* biomass and total mysid biomass within the lagoon increased continually as the season progressed. However, at the

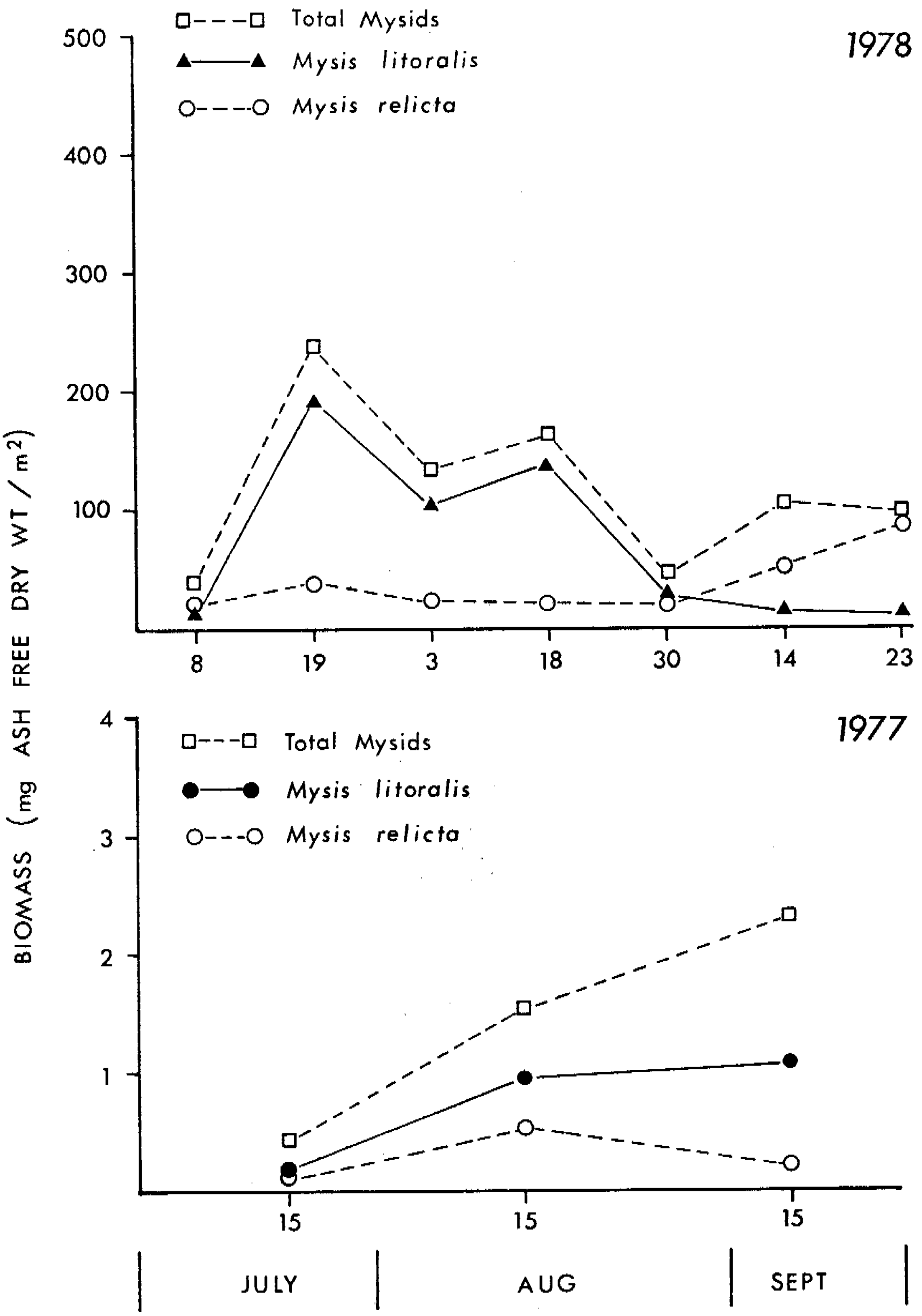

Figure 8. Biomass of Mysids Near the Bottom at Lagoon Stations in Simpson Lagoon in Relation to Date in 1977 and 1978. (Each 1978 point is a mean of five drop-net samples for each station on each date. The 1977 data are recalculated from Griffiths and Craig [1978]. Because different sampling techniques used in the two years, only the general trends can be compared.)

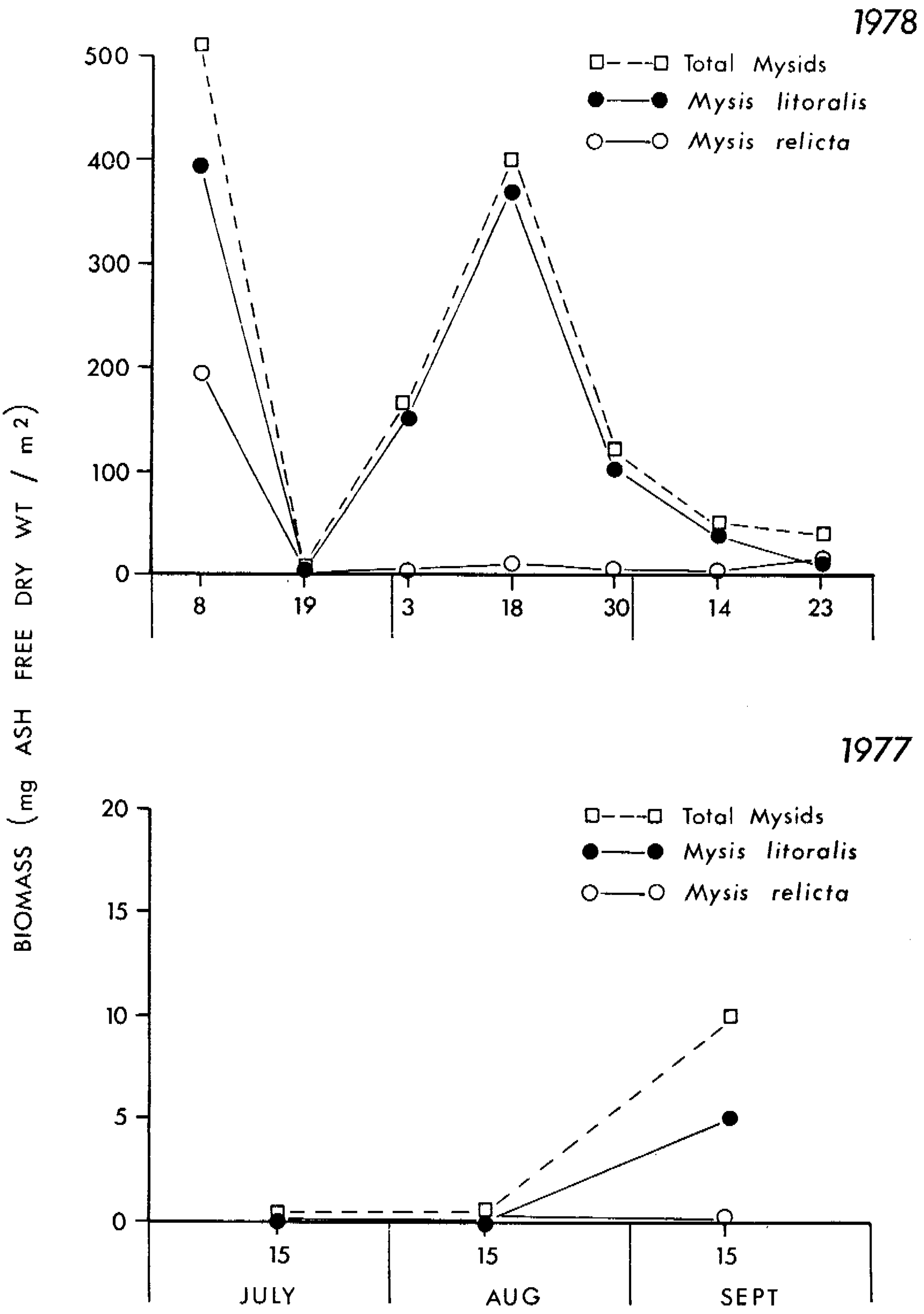

Figure 9. Biomass of Mysids Near the Bottom at Offshore Stations in Simpson Lagoon in Relation to Date in 1977 and 1978. (Each 1978 point is a mean of five drop-net samples for each station or each date. The 1977 data are recalculated from Griffiths and Craig [1978]. Because different sampling techniques used in the two years, only the general trends can be compared.)

offshore stations the increase was only noted at the end of the season. In 1978 these biomasses showed significant decreases at both lagoon and offshore stations late in the open-water season. *M. relicta* biomass, which was almost always low at offshore stations, decreased in the lagoon toward the end of the 1977 season, but increased in the lagoon late in the 1978 season. The reasons for these differing trends are not known at the present time.

In summary, in 1978 there appeared to be a marked reduction in *M. litoralis* biomass near the end of the open-water season, possibly due to emigration, predation or a combination of both. However, neither the biomass of *M. relicta* nor the total mysid biomass showed similar decreases. We postulate, therefore, that emigration was the main cause for the decrease in *M. litoralis* biomass, since it seems unlikely that predators would select between these two similar species. Mysid distribution within the lagoon was similar in both years but markedly higher *M. litoralis* biomass was found at offshore stations in 1978 than in 1977.

Mysids in the Water Column. Mysid biomasses in the water column at the four standard stations and seven sampling periods are shown in Appendix 9 and Figs. 10-13 and are compared in Tables 9 and 10.

The 1978 biomass estimates of *M. litoralis, M. relicta* and total mysids varied widely among stations throughout the open-water period. However, neither the differences among lagoon stations nor among the combined lagoon and offshore stations were statistically significant (Table 9, Figs. 10 and 11). Despite this there were marked differences in *M. relicta* biomass through the season among stations (Figs. 11-12). This species was most common at lagoon stations 2 and 3, and it was rare at Station 7 seaward of the islands. None were found in offshore samples taken after 17 August (the offshore marine station was not sampled on 23 September), while during this same late-season period *M. relicta* biomass increased markedly at the lagoon stations (Fig. 10).

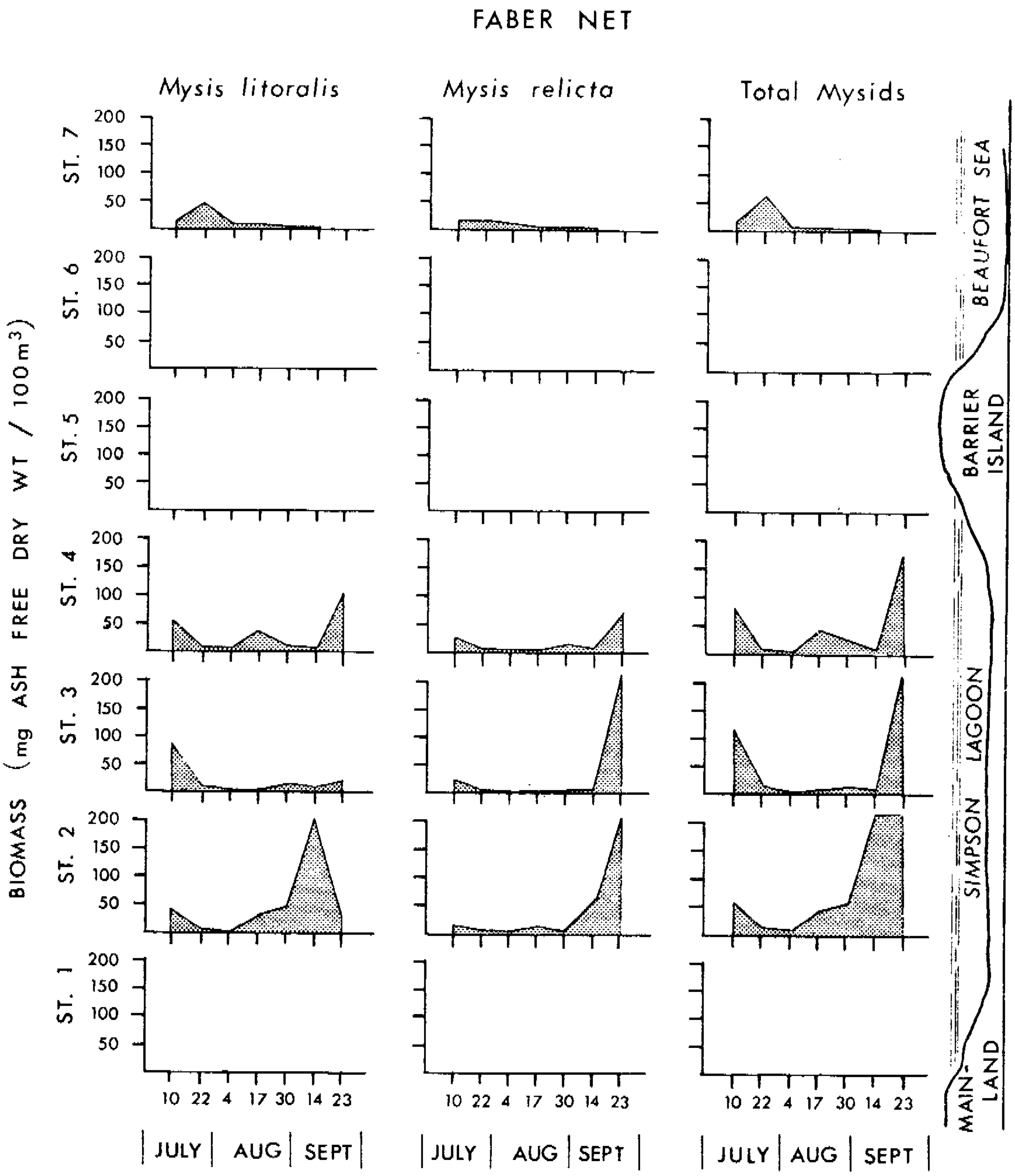

Figure 10. Biomass of Mysids in the Water Column in Relation to Date and Sampling Station. (Each data point is a mean of three Faber net samples collected in Simpson Lagoon in 1978.)

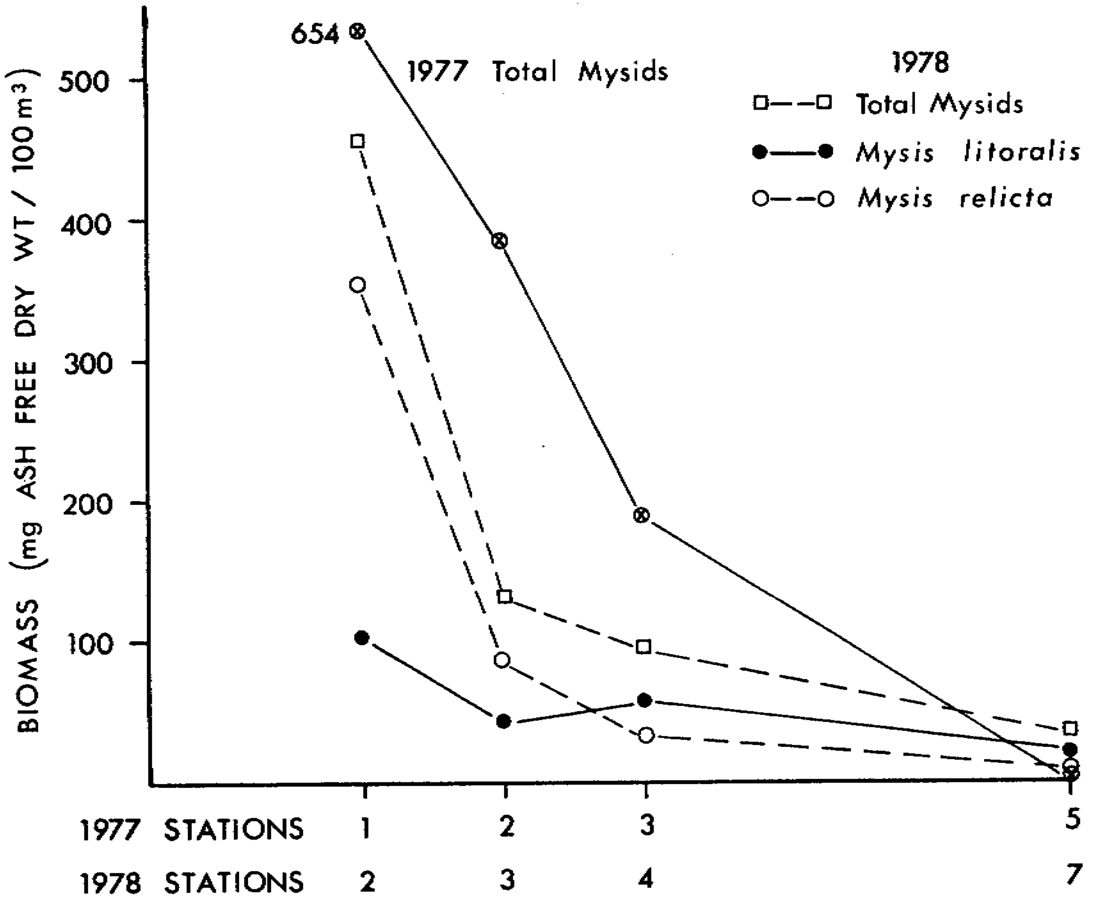

Figure 11. Biomass of Mysids in the Water Column at Various Sampling Stations in Simpson Lagoon in 1977 and 1978. (Each 1978 point is the mean of three Faber net samples from each collection period. The 1977 data are recalculated from Griffiths and Craig [1978]. In 1977 only total mysid biomass was available.)

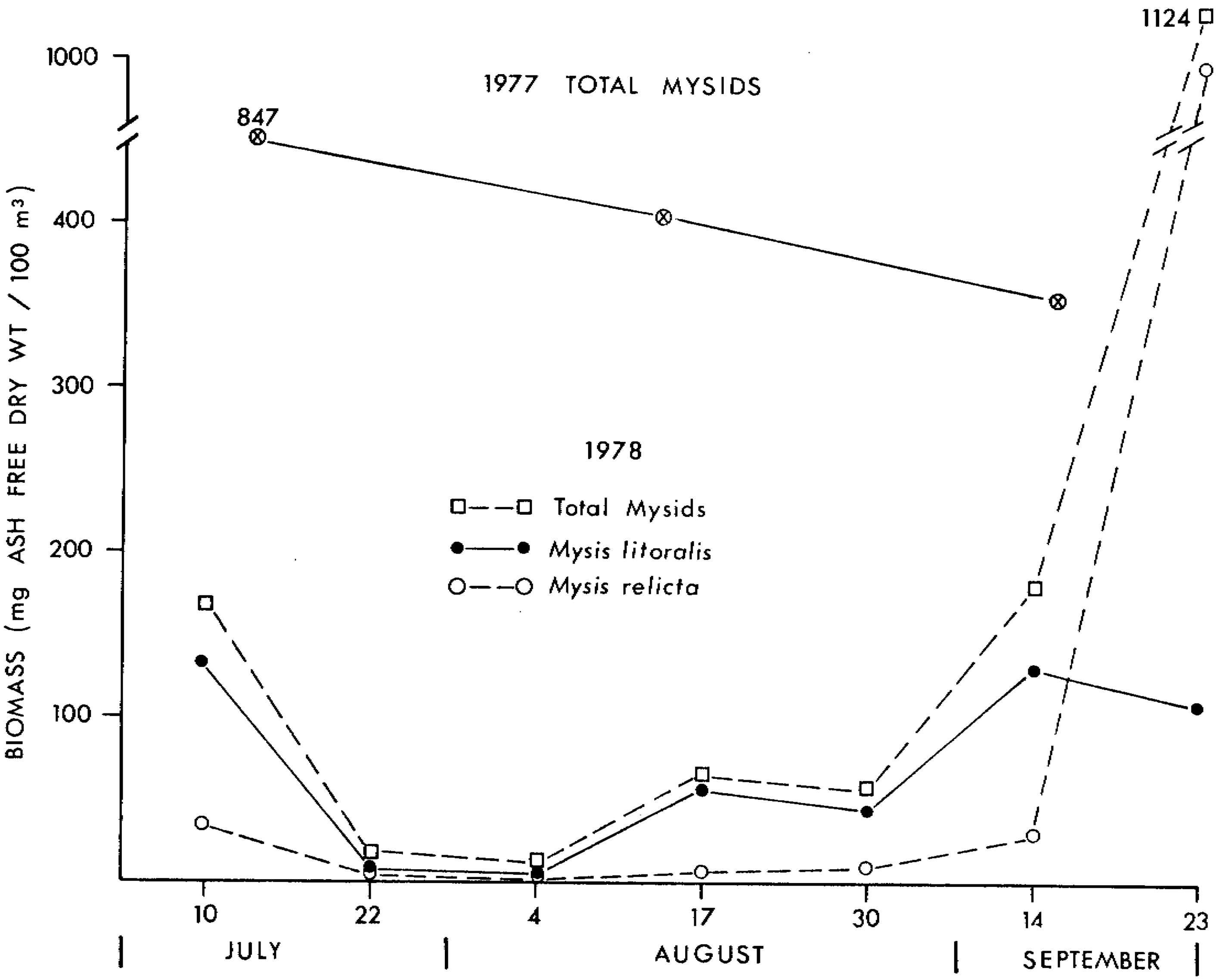

Figure 12. Biomass of Mysids in the Water Column at Lagoon Stations in Simpson Lagoon in Relation to Date in 1977 and 1978. (Each 1978 point is the mean of three Faber net samples from each station on each date. The 1977 data are recalculated from Griffiths and Craig [1978]. In 1977 only total mysid biomass was available.)

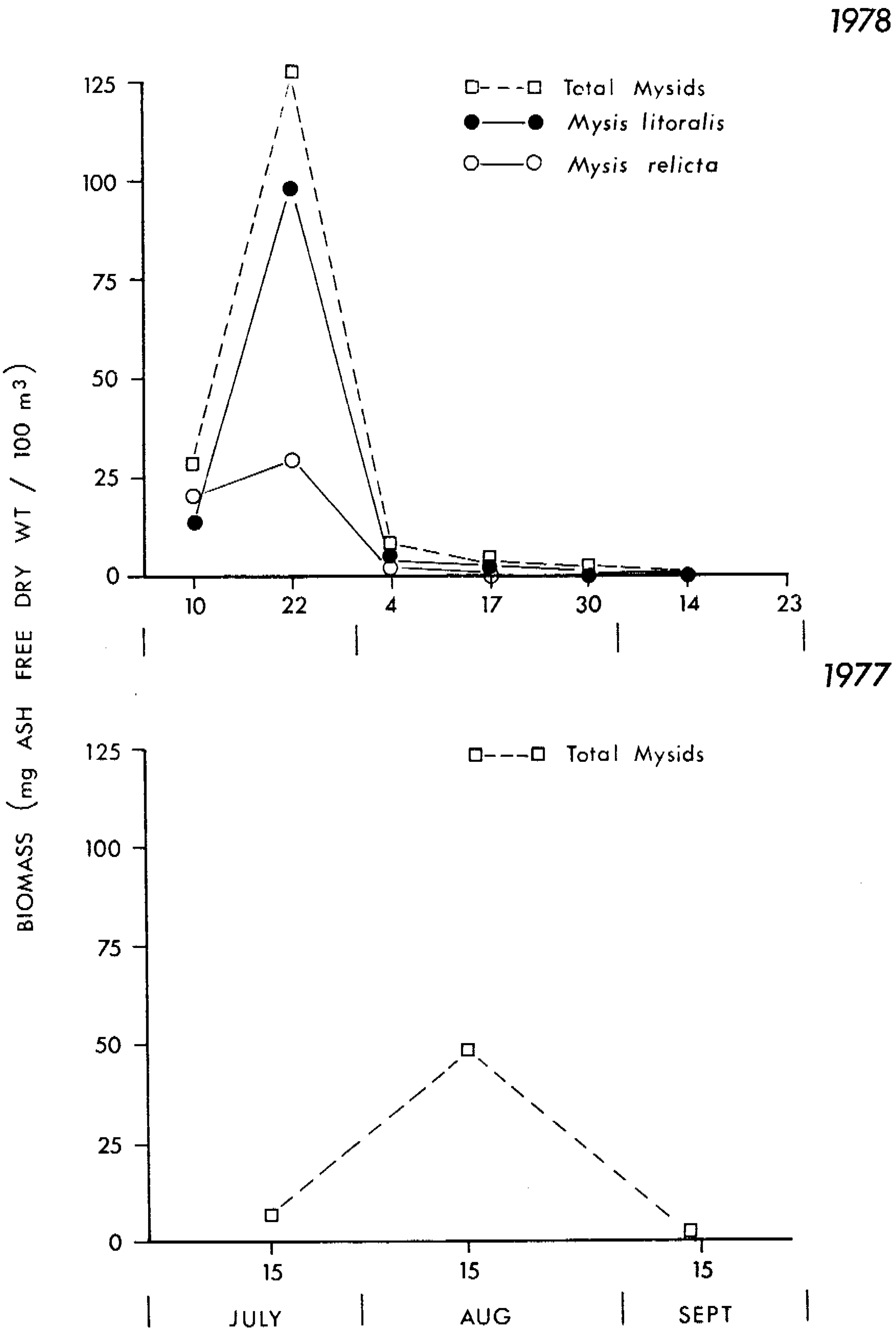

Figure 13. Biomass of Mysids in the Water Column at Offshore Stations in Simpson Lagoon in Relation to Date in 1977 and 1978. (Each 1978 point is the mean of three Faber net samples from each station on each date. The 1977 data are recalculated from Griffiths and Craig [1978]. In 1977 only total mysid biomass was available.)

Table 9. Comparisons of Mysid Biomass in the Water Column (mg ash-free dry weight/100 m^3) Among Lagoon Stations (2, 3, 4)† and Among Lagoon and Offshore Stations (2, 3, 4, 6/7††) Using the Friedman Two-Way Analysis of Variance†††. Each station/date value was the mean from three Faber net samples of the station during sampling period.

Species or Group	Comparisons Among Lagoon Stations (2, 3, 4) (df=2).		Comparisons Among Lagoon and Offshore Stations (2, 3, 4, 6/7) (df=3).	
Mysis litoralis	$\chi^2=2.09$,	$P>0.20$	$\chi^2=1.80$,	$P>0.50$
Mysis relicta	$\chi^2=3.60$,	$P>0.10$	$\chi^2=1.35$,	$P>0.70$
Total Mysids	$\chi^2=2.09$,	$P>0.20$	$\chi^2=0.70$,	$P>0.80$

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† Comparisons for lagoon stations are for 7 sampling periods, but for combined lagoon and offshore stations are for only 6 periods (see below).

†† 6/7 indicates that Station 6 was sampled during the first two sampling periods because of ice cover.

†††Siegel (1956).

Table 10. Comparisons of Mysid Biomass in the Water Column (mg ash-free dry weight/100 m^3) Among Sampling Periods for Lagoon and Offshore Stations. Comparisons were made using Friedman two-way analysis of variance. Each station/date value was the mean from three Faber net samples of the station during sampling period.

Species or Group	Comparisons Among Sampling Periods for Lagoon Stations (2,3,4) (df=6)		Comparisons Among Sampling Periods for Lagoon and Offshore Stations (2,3,4,6/7) (df=5)	
Mysis litoralis	$\chi^2=11.30$,	P=0.048	$\chi^2=7.54$,	P>0.10
Mysis relicta	$\chi^2=15.00$,	P<0.016	$\chi^2=8.36$,	P>0.10
Total Mysids	$\chi^2=14.39$,	P=0.048	$\chi^2=8.82$,	P>0.10

[†] Comparisons for lagoon stations are for 7 sampling periods, but for combined lagoon and offshore stations are for only 6 periods (see below).

[††] 6/7 indicates that Station 6 was sampled during the first two sampling periods because of ice cover.

[†††] Siegel (1956).

A comparison of mysid biomasses among sampling periods for all stations showed no significant differences (Table 10, Figs. 12-13). However, when only the lagoon stations (2, 3, 4) were considered there were significant differences among collection periods (Table 10, Fig. 12). *Mysis litoralis* biomass was greater in the lagoon on 10 July than on 4 August (P=0.048), and *M. relicta* and total mysid biomasses were markedly higher on 23 September than on 4 August (P=0.016). Although there were insufficient data to statistically compare sampling periods at the offshore station, from Figure 13 it appears that the biomass for all mysids was high early in the season and then declined dramatically to negligable levels after 4 August.

Comparisons of these 1978 data with 1977 results are limited to total mysid biomass, because mysids collected in the water column by Faber net in 1977 were not identified to species. The patterns of differences among lagoon and offshore stations were similar between years in that the offshore biomass was lower than nearshore biomass in both years (Fig. 11); the differences among stations were significant in 1977 (Friedman χ^2=6.49, P<0.05, K=3) but not in 1978. In 1977, total mysid biomass generally decreased during the course of the season at lagoon stations but showed a mid-season peak at the offshore station (Figs. 12-13). In 1978 it generally increased at lagoon stations and decreased markedly at offshore stations as the season progresses (Figs. 12-13). This increase was marked at lagoon stations during the last collection period because of the increase of *M. relicta* biomass (Fig. 12).

In summary, the wide variations in mysid biomass among stations and collection periods in both water-column and benthic habitats (in 1977 and 1978) indicates that there may be both uneven distribution and rapid rates of movement of these organisms within the nearshore system. The occurence of rapid movements is confirmed by an initial analysis of of Drift net samples (to appear in the final report) and by the apparent immigrations of mysids into the lagoon during early summer (see above).

Amphipods

The amphipod species collected in 1977 and 1978 were known from previous studies to occur along the Alaskan Beaufort Sea coast (MacGinitie 1955; Crane 1974; Feder and Schamel 1976; Feder *et al.* 1976). In 1977 all amphipods collected both near the bottom and in the water column were identified to species (Griffiths and Craig 1978). In 1978 only those amphipods that comprised a significant portion of the samples or contributed significantly to the stomach contents of birds and fish were analyzed to the species level.

Amphipods Near the Bottom. Amphipods near the bottom were collected at the seven standard stations during each sampling period of 1978. The results are shown in Appendix 10 and Figures 14-17 and are compared in Tables 11 and 12. It is apparent from these figures that *O. glacialis* was by far the most important amphipod in the lagoon on a biomass basis; it was also the most important species to birds and fish (Johnson 1978, 1979; Craig and Griffiths 1978).

Amphipod biomasses at the five lagoon stations are compared in Table 11. Only *Onisimus glacialis* of the four species considered individually, differed significantly in biomass among stations in 1978. Its biomass was significantly lower at Station 5 (nearshore barrier island) than at Station 3 (central lagoon) (P=0.049)[†]. When offshore stations (6 and 7) were included in the comparisons, the biomass of *O. glacialis* was found to be significantly lower at Station 7 (0.5 km offshore) than at either Station 2 (P=0.007), or Station 4 (P=0.007) (Figs. 14 and 15). These results indicate that the biomass of *O. glacialis* per unit area of bottom is greater in shallow lagoon waters than in deeper offshore areas (Figs. 14 and 15). A similar pattern of biomass distribution was noted in

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[†] Comparisons between specific pairs of stations are based on a non-parametric multiple comparison procedure applicable after the Friedman tests of Tables 6 and 7 have been applied (see Hollander and Wolfe 1973).

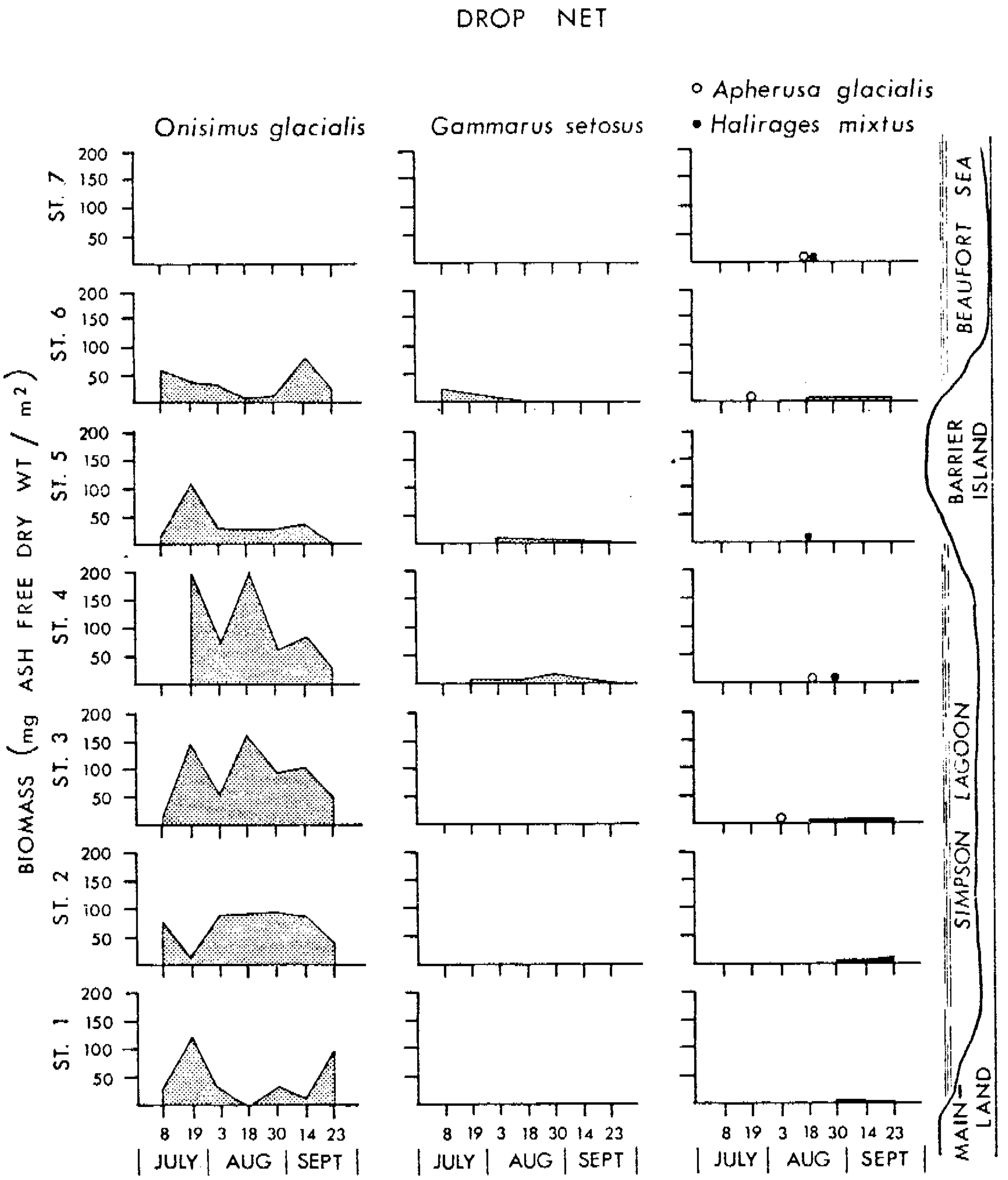

Figure 14. Biomass of Amphipods Near the Bottom in Relation to Date and Sampling Station. (Each data point is a mean of five drop-net samples collected in Simpson Lagoon 1978.)

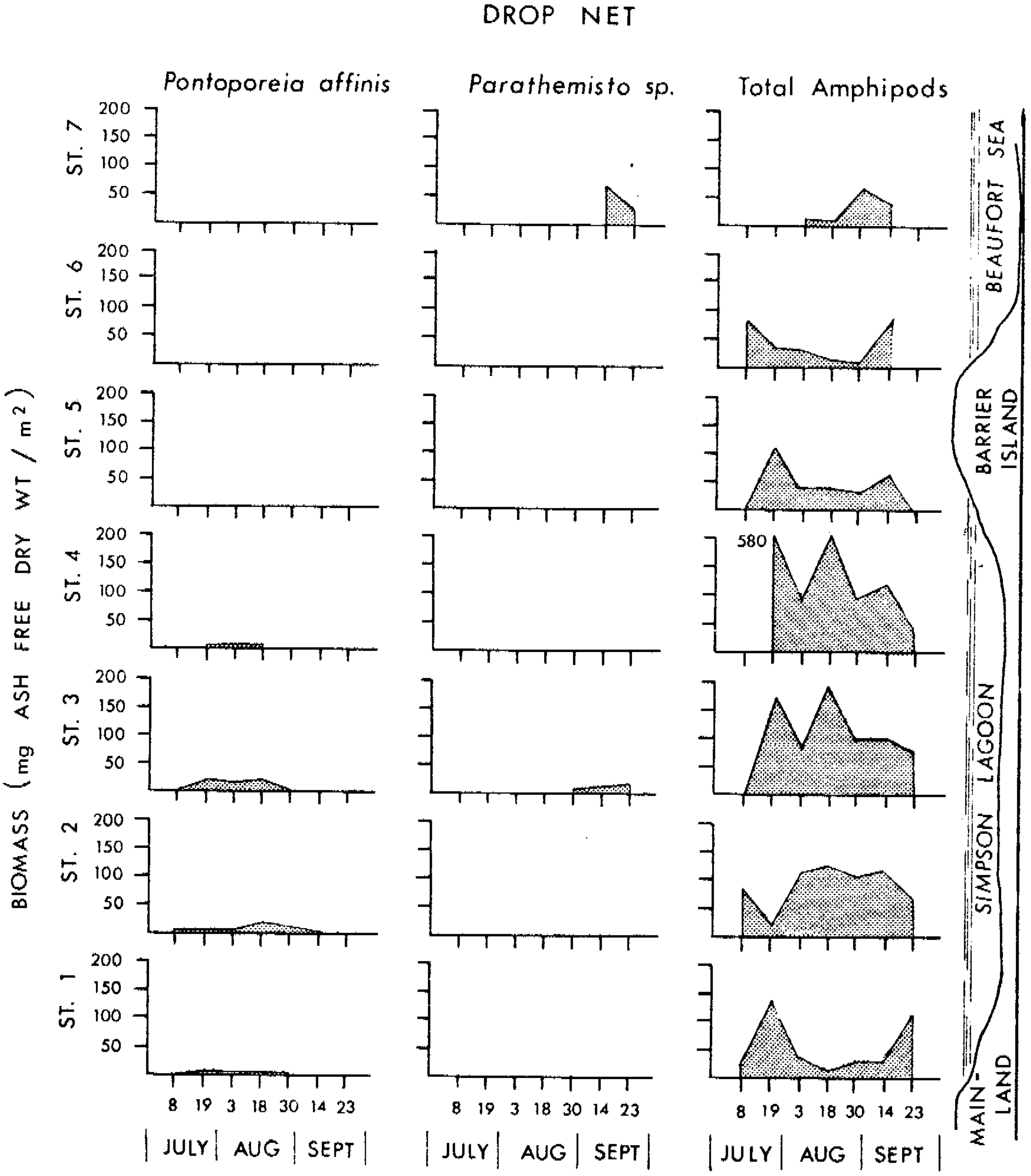

Figure 14. (continued).

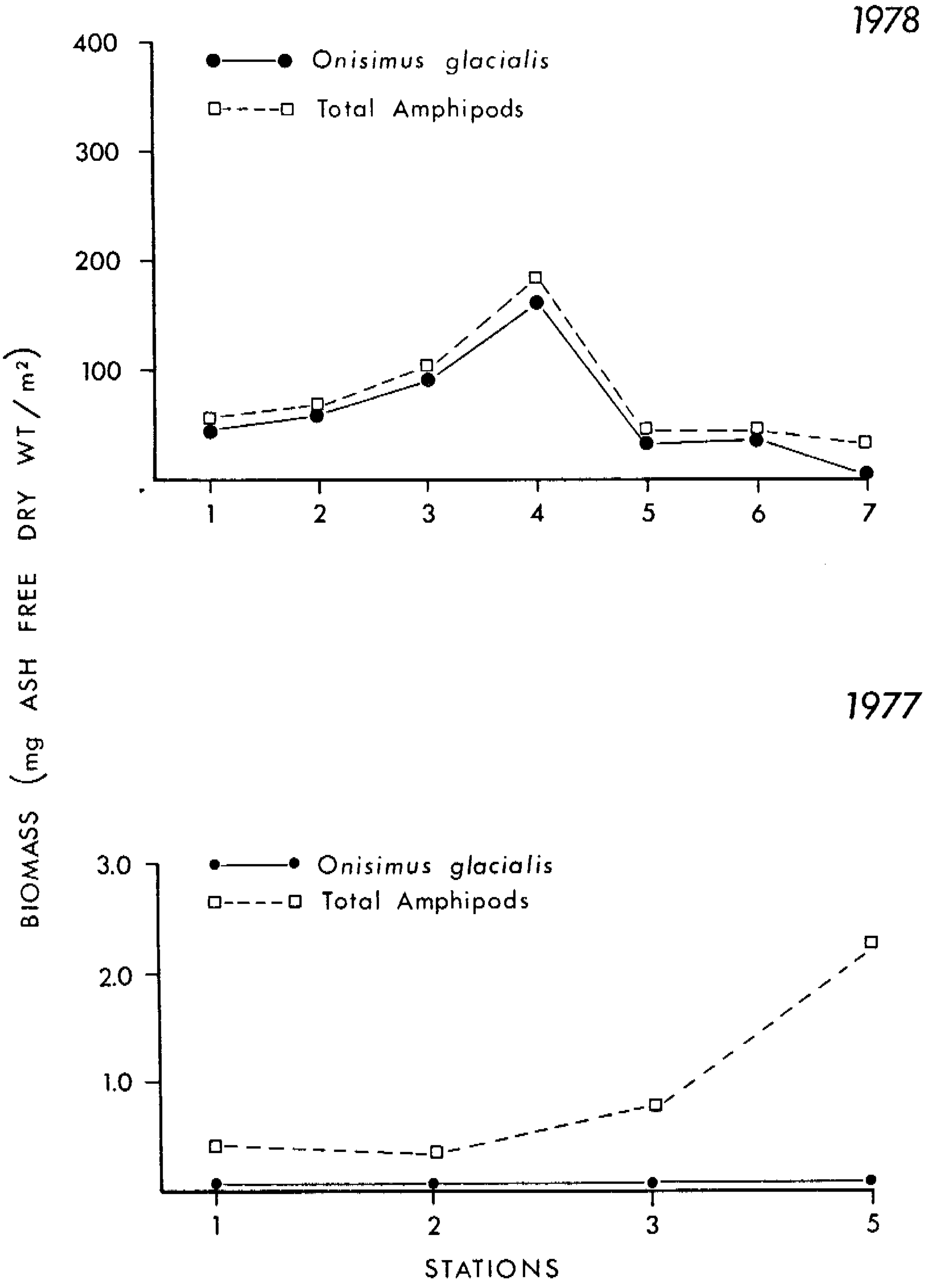

Figure 15. Biomass of Amphipods Near the Bottom at Various Sampling Stations in 1977 and 1978. (Each 1978 point is a mean of five drop-net samples for each sampling date within the period 8 July to 23 September. The 1977 data are recalculated from Griffiths and Craig [1978]. Because different sampling techniques were used in the two years, only the general trends can be compared.)

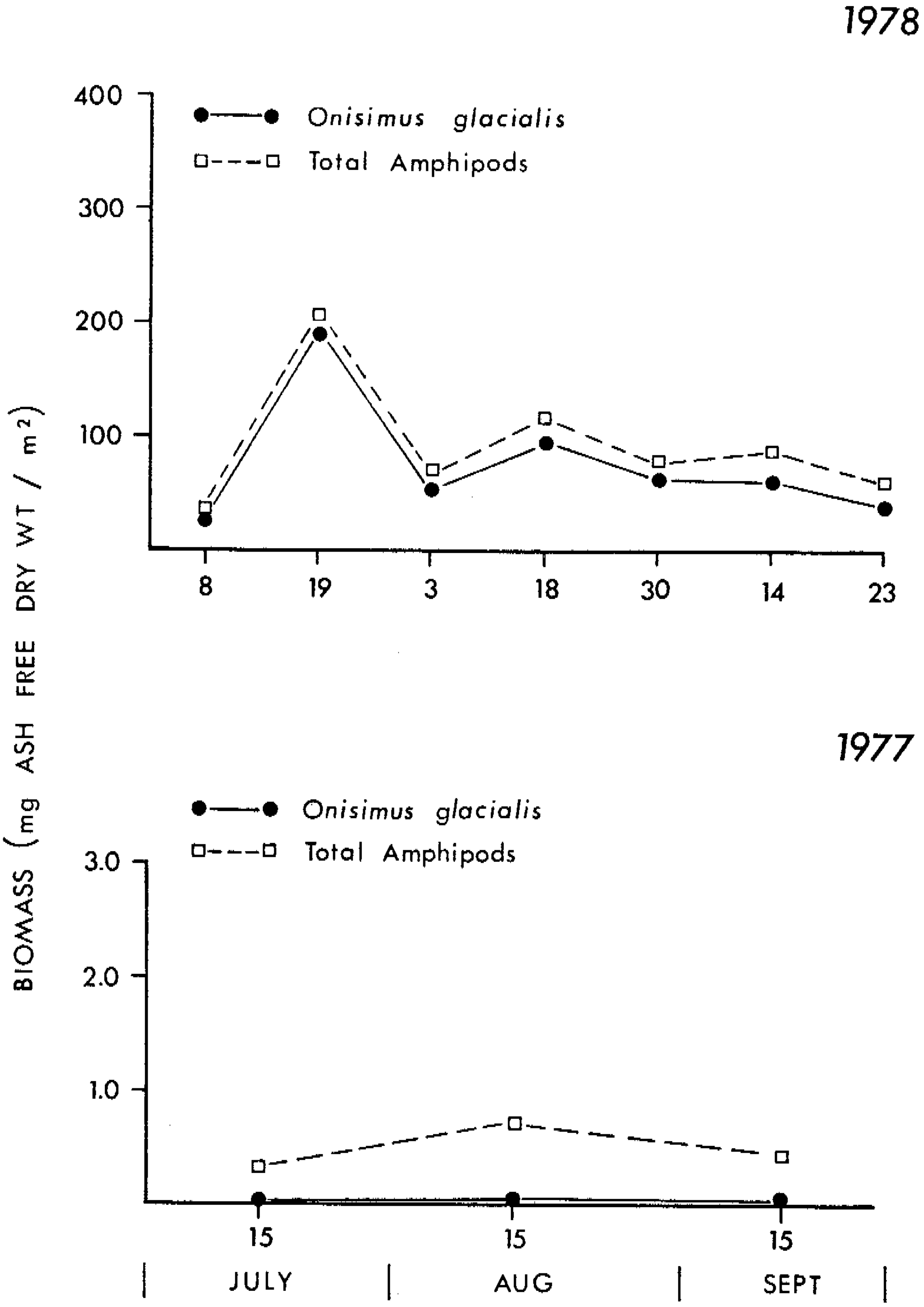

Figure 16. Biomass of Amphipods Near the Bottom at Lagoon Stations in Simpson Lagoon in Relation to Date in 1977 and 1978. (Each 1978 point is a mean of five drop-net samples from each station on each date. The 1977 data are recalculated from Griffiths and Craig [1978]. Because different sampling techniques were used in the two years, only general trends can be compared.)

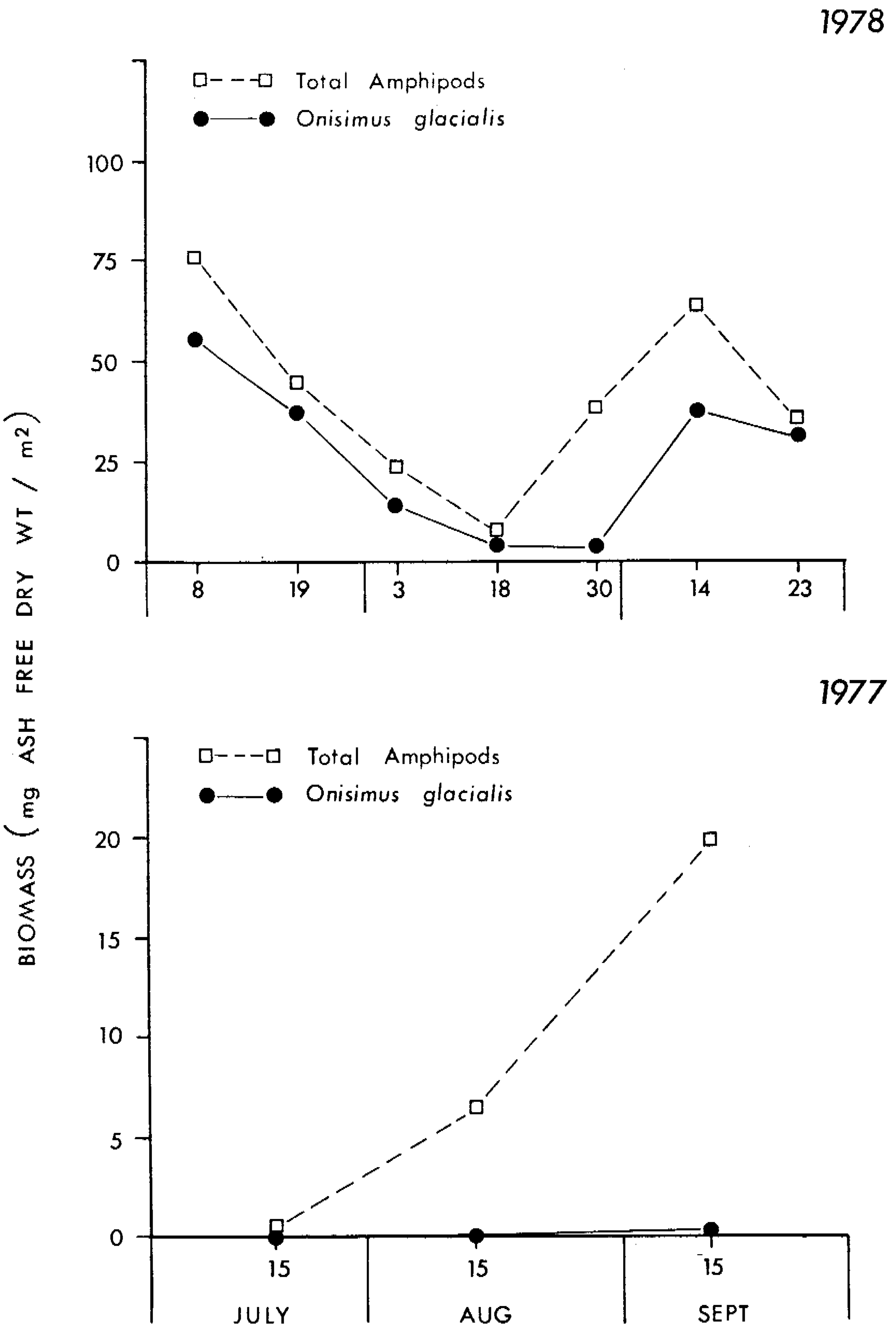

Figure 17. Biomass of Amphipods Near the Bottom at Offshore Stations in Simpson Lagoon in Relation to Date in 1977 and 1978. (Each 1978 point is a mean of five drop-net samples from each station on each date. The 1977 data is recalculated from Griffiths and Craig [1978]. Because different sampling techniques were used in the two years, only general trends can be compared.)

Table 11. Comparisons of Biomass (mg ash-free dry weight/m^2) for Amphipods Near the Bottom Among Lagoon Stations (1-5)[†] and Among Lagoon and Offshore Stations (1-7)[††] Using the Friedman Two-Way Analysis of Variance[†††]. Each station/date value was the mean from five drop-net samples at the station during sampling period.

Species or Group	Comparisons Among Lagoon Stations (1-5) on a Seasonal Basis (df=4)		Comparisons Among Lagoon and Offshore Stations (1-7) on a Seasonal Basis (df=6)	
Onisimus glacialis	$\chi^2=10.86$,	$0.05<P<0.02$	$\chi^2=20.63$,	$0.01<P<0.001$
Gammarus setosus	$\chi^2=3.29$,	$P>0.50$	$\chi^2=3.70$,	$P>0.70$
Halirages mixtus	$\chi^2=2.22$,	$P>0.50$	$\chi^2=3.40$,	$P>0.50$
Pontoporeia affinis	$\chi^2=7.16$,	$P>0.10$	$\chi^2=10.48$,	$P>0.10$
Total Amphipods	$\chi^2=9.93$,	$0.10<P<0.05$	$\chi^2=18.92$,	$0.01<P<0.001$

[†] Only sampling periods between 19 July and 23 September used in comparisons.

[††] Only sampling periods between 3 August and 14 September used in comparisons.

[†††] Siegel (1956).

Table 12. Comparisons of Biomass (mg ash-free dry weight/m^2) for Amphipods Near the Bottom Among Sampling Periods for Lagoon Stations (1-5)† and for Lagoon and Offshore Stations (1-7)†† Using the Friedman Two-Way Analysis of Variance†††. Comparisons were made using means from five samples from each station/sampling period. Each station/date value was the mean from five drop-net samples at station during sampling period.

Species or Group	Comparisons Among Sampling Periods for Lagoon Stations (1-5) (df=5)		Comparisons Among Sampling Periods for Lagoon and Offshore Stations (1-7) (df=3)	
Onisimus glacialis	$\chi^2 = 6.402$,	$P > 0.20$	$\chi^2 = 0.41$,	$P > 0.99$
Gammarus setosus	$\chi^2 = 0.89$,	$P > 0.95$	$\chi^2 = 0.41$,	$P > 0.90$
Halirages mixtus	$\chi^2 = 5.35$,	$P > 0.30$	$\chi^2 = 5.55$,	$0.10 < P < 0.05$
Pontoporeia affinis	$\chi^2 = 14.25$,	$0.02 < P < 0.01$	$\chi^2 = 14.62$,	$0.01 < P < 0.001$
Total Amphipods	$\chi^2 = 8.37$,	$P > 0.10$	$\chi^2 = 1.91$,	$P > 0.50$

† Only sampling periods between 19 July and 23 September used in comparisons.

†† Only sampling periods between 3 August and 14 September used in comparisons.

†††Siegel (1956).

the early season samples (see Early Season Movements).

Total amphipod biomass also differed significantly among the seven stations during 1978; however, the difference could not be attributed to any particular pairs of stations on the basis of multiple comparisons.

Total amphipod biomass near the bottom did not vary significantly among dates in 1978 (Table 12). Of the amphipods identified to species only *Pontoporeia affinis* showed significant seasonal differences in biomass near the bottom. Its biomass was higher from 19 July to 30 August 1978 than on earlier or later dates (Table 12 and Fig. 14). In the lagoon, the biomass of *P. affinis* was significantly lower on 23 September than on 19 July (P=0.047), at all seven stations considered together the biomass of *P. affinis* was lower on 23 September than on 3 August (P=0.05).

The large increase in total amphipod biomass at offshore Station 7 late in the 1978 season (Fig. 14) was the result of a large influx of *Parathemisto* spp., a genus of pelagic marine amphipod. A larger influx of *Parathemisto libellula* was noted in 1977 at offshore Station 5. That year large numbers of this amphipod were washed up in wind rows on the ocean side of the barrier islands. In 1978, *Onisimus glacialis* was the dominant bottom dwelling amphipod in Simpson Lagoon in terms of biomass, but in 1977 trawl samples showed this species to be only a minor component of the amphipod fauna (Figs. 15, 16 and 17). *Gammaracanthus loricatus* and *Gammarus setosus* were the most abundant amphipods in samples. However, their apparent importance that year was likely an artifact of the sampling technique--the large mesh size of the trawl used in 1977 selected against the relatively small *O. glacialis*. In 1978 the apparent importance of other smaller amphipod species (i.e., *Halirages mixtus* and *Pontoporeia affinis*) also increased relative to that of the larger amphipods *G. loricatus* and *G. setosus*; this may also have been caused by a sampling artifact. Consequently any between year comparisons of amphipod biomasses are confounded by this problem.

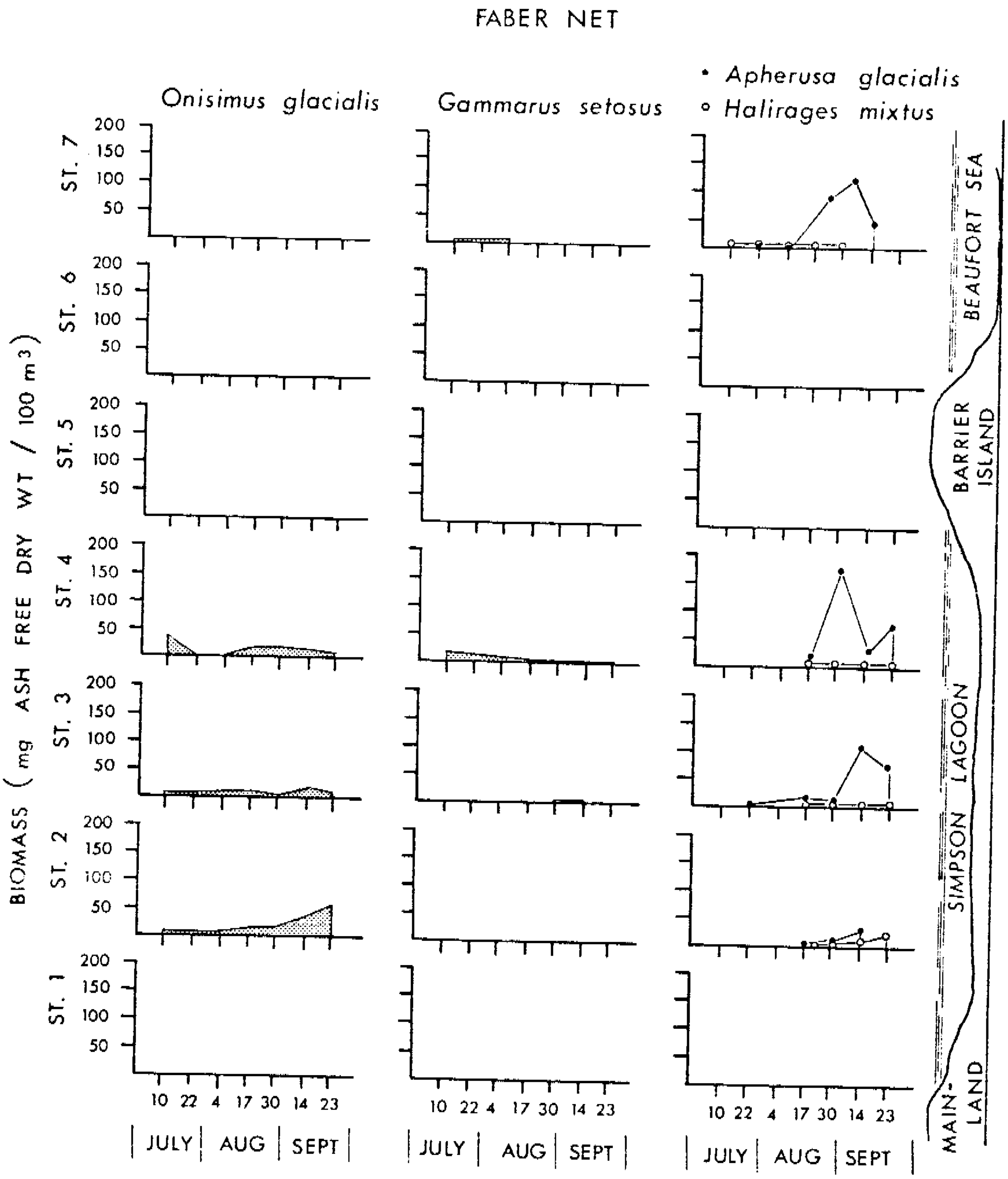

Figure 18. Biomass of Amphipods in the Water Column in Relation to Date and Sampling Station. (Each data point is a mean of three Faber net samples collected in Simpson Lagoon in 1978.)

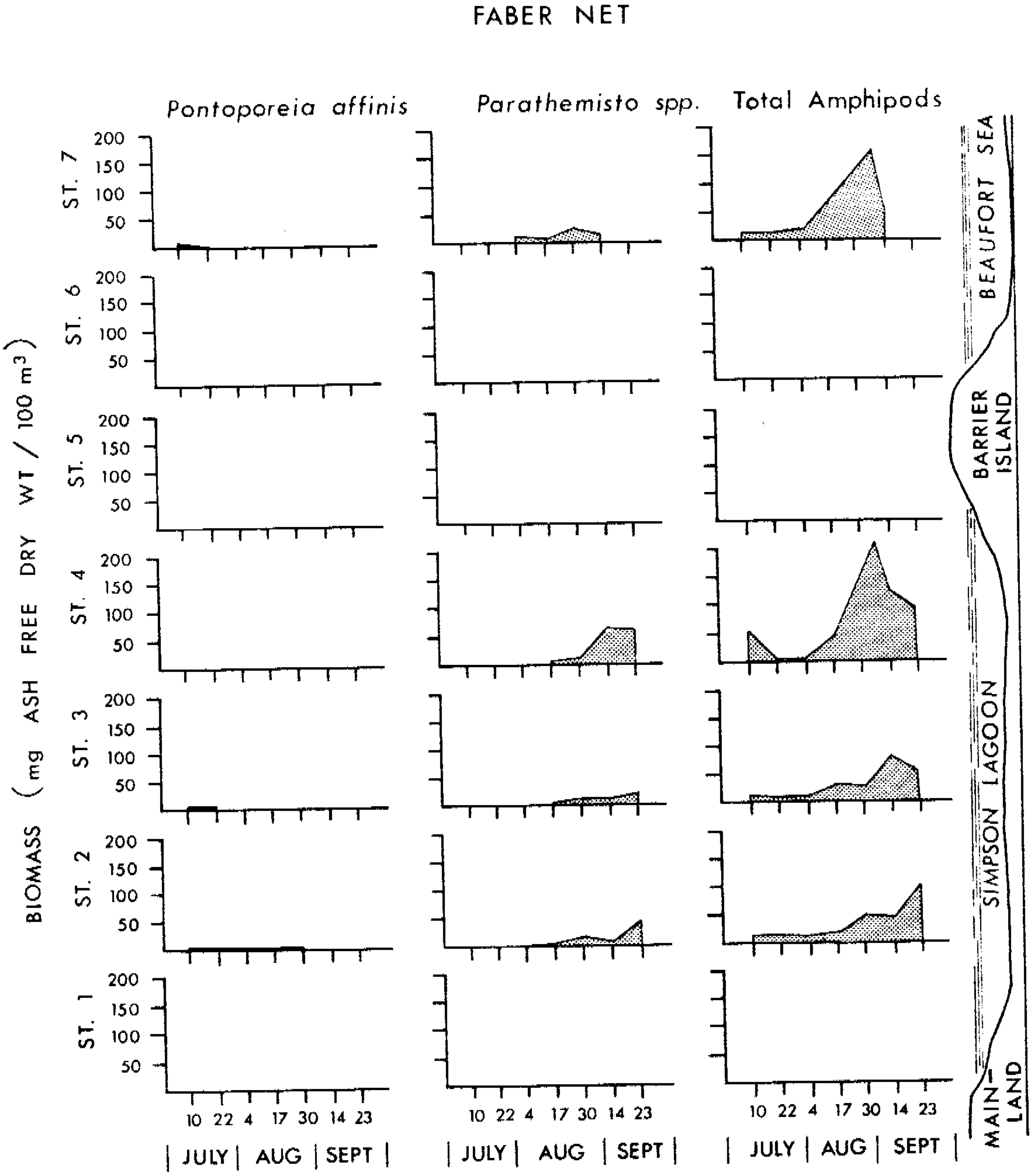

Figure 18. (continued).

Amphipods in the Water Column. Amphipods were collected in the water column regularly over the open-water season of 1978. The results for all collections are shown in Appendix 9, Figures 18-21 and are compared in Tables 13 and 14.

The total biomass of amphipods in the water columns of the lagoon during 1978 did not differ significantly among stations (Table 13). Only *Onisimus glacialis*, of key amphipod species, differed significantly in biomass among lagoon stations (2, 3, 4); the biomass of this species was significantly higher at Station 2 than at Station 3 (P=0.008) (Figs. 18 and 19). When biomass estimates of all stations (2, 3, 4, 7) were compared, the biomass of *Apherusa glacialis* was found to vary significantly among stations and to be higher at Station 7 (offshore) than at Station 2 (central lagoon) (P=0.037; Fig. 18). This difference may be attributable to the affinity of *A. glacialis* to first-year ice (Golikov and Averincev 1978); pan ice was much more prevalent during the open-water season at Station 7 than near the mainland shore of the lagoon.

The total biomass of amphipods in the water column of the lagoon increased markedly late in the 1978 season; the differences among dates were significant (Table 14). Biomass of *Onisimus glacialis*, *Apherusa glacialis*, *Halirages mixtus*, and *Parathemisto* spp. all increased late in the season. In the cases of *Halirages* and *Parathemisto* the seasonal effect was statistically significant, and in the case of *Apherusa* it was close to significant (Table 14). A comparison among sampling periods for lagoon stations (2, 3, 4) showed *Halirages mixtus* and *Parathemisto* spp. biomasses to be significantly higher on 23 September than on 10 July, 20 July and 4 August (P=0.048 in all cases) (Fig. 20). These marine pelagic amphipods apparently moved into Simpson Lagoon during August from deeper offshore areas. When all stations (2, 3, 4, 7) were compared, *Apherusa glacialis* biomass estimates differed significantly among dates, and were significantly higher on 14 September than on 10 July (P=0.047; Fig. 18).

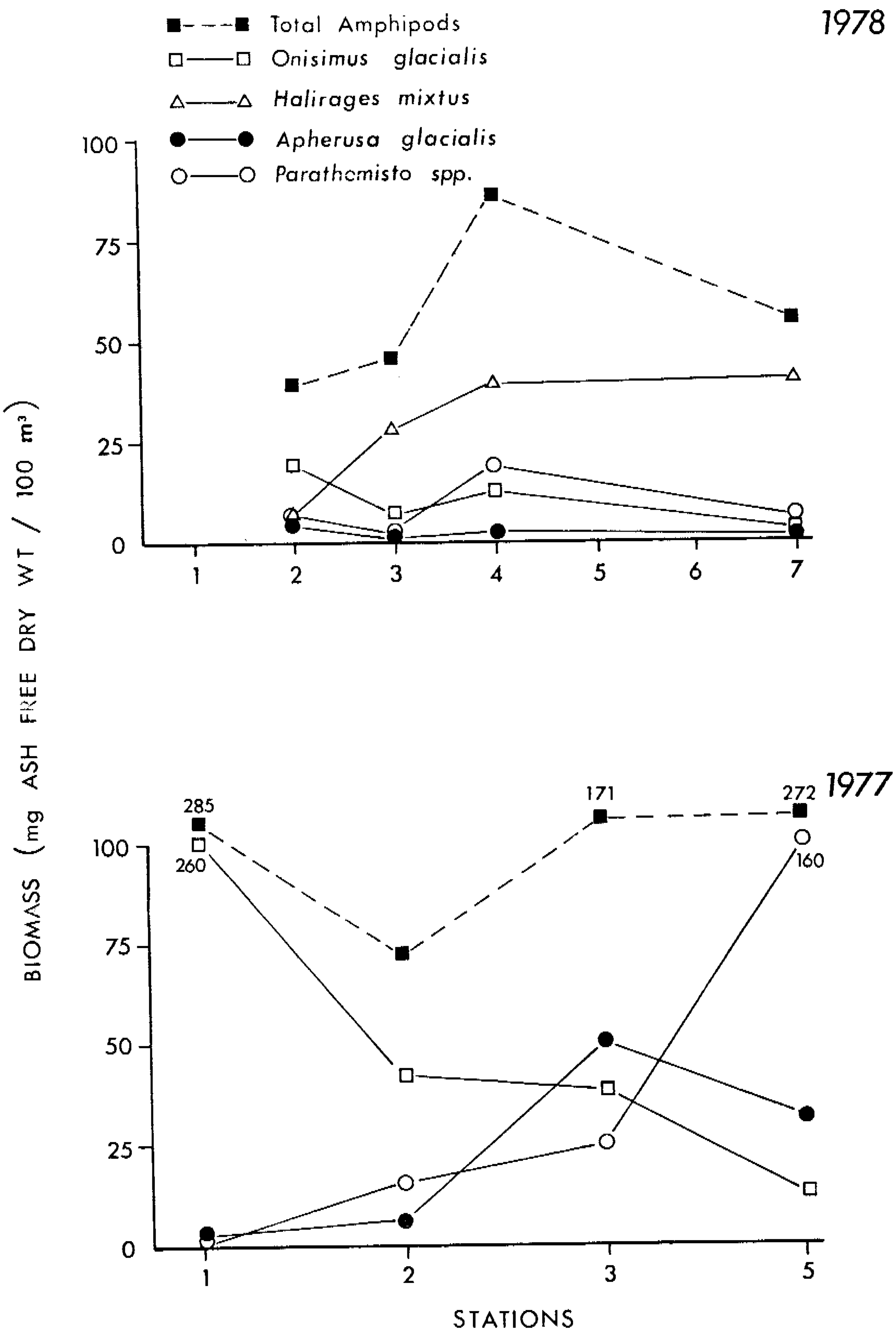

Figure 19. Biomass of Amphipods in the Water Column at Various Stations in Simpson Lagoon in 1977 and 1978. (Each 1978 point is a mean of three Faber net samples from each station on each sampling date. The 1977 data are recalculated from Griffiths and Craig [1978].)

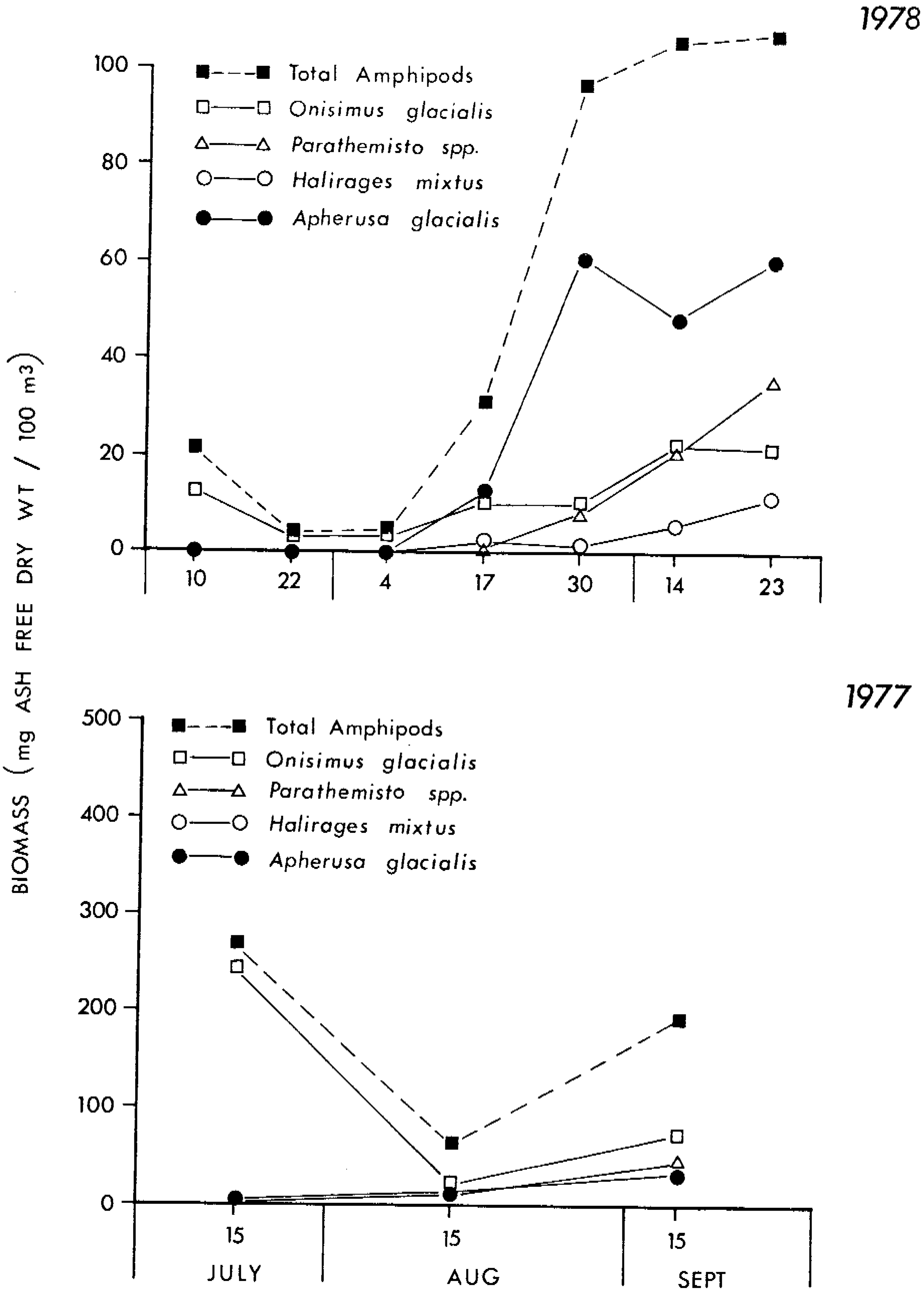

Figure 20. Biomass of Amphipods in the Water Column at Lagoon Stations in Simpson Lagoon in Relation to Date in 1977 and 1978. (Each 1978 point is the mean of three Faber net samples from each station on each date. The 1977 data are recalculated from Griffiths and Craig [1978].)

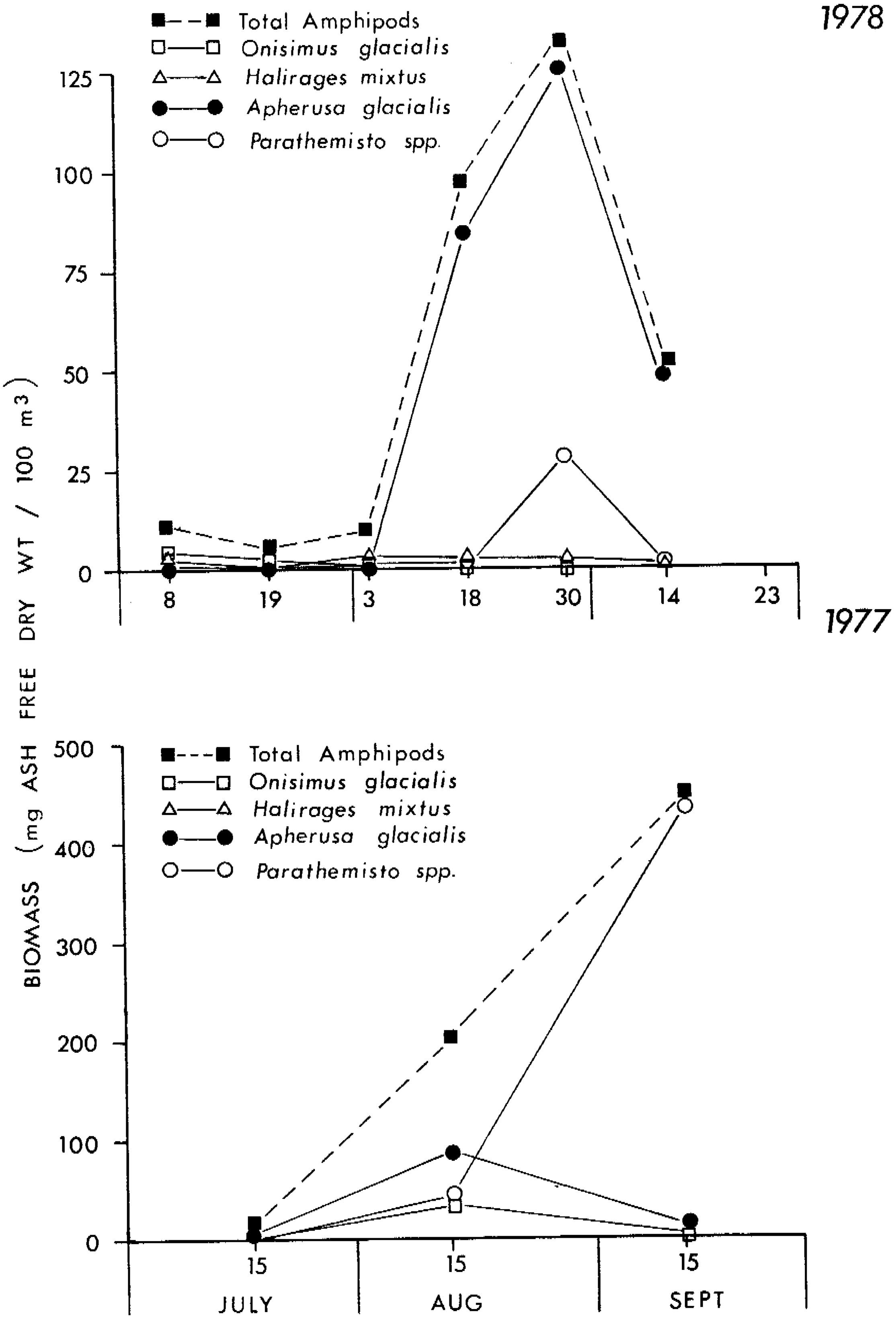

Figure 21. Biomass of Amphipods in the Water Column at Offshore Stations in Simpson Lagoon in Relation to Date in 1977 and 1978. (Each 1978 point is a mean of three Faber net samples from each station on each data. The 1977 data are recalculated from Griffiths and Craig [1978].)

Table 13. [†]Comparisons of Biomass (mg ash-free dry weight/100 m^3) for Amphipods in the Water Column Among Lagoon Stations and Among Lagoon and Offshore Stations Using the Friedman Two-Way Analysis of Variance.[†††] Each station/date value was the mean of three Faber net samples at the station during sampling period.

Species or Group	Comparisons Among Lagoon Stations (2, 3, 4)[†] on a Seasonal Bases (df=2)		Comparisons Among Lagoon and Offshore Stations (2, 3, 4, 6/7)[†] on a Seasonal Bases (df=3)	
Onisimus glacialis	$\chi^2 = 8.95$,	$P=0.048$	$\chi^2 = 6.20$,	$P>0.10$
Grammarus setosus	$\chi^2 = 1.44$,	$P>0.30$	$\chi^2 = 0.95$,	$P>0.80$
Apherusa glacialis	$\chi^2 = 4.45$,	$P>0.10$	$\chi^2 = 7.95$,	$P=0.048$
Halirages mixtus	$\chi^2 = 2.09$,	$P>0.20$	$\chi^2 = 3.80$,	$P>0.10$
Pontoporeia affinis	$\chi^2 = 3.80$,	$P>0.10$	$\chi^2 = 5.40$,	$P>0.10$
Parathemisto sp.	$\chi^2 = 2.09$,	$P>0.20$	$\chi^2 = 2.60$,	$P>0.30$
Total Amphipods	$\chi^2 = 3.80$,	$P>0.10$	$\chi^2 = 5.40$,	$P>0.10$

[†] Comparisons for lagoon stations are for all 7 sampling periods, while for lagoon and offshore stations are for only 6 periods (see below).

[††] 6/7 indicates that Station 6 was sampled during the first two sampling periods (7 was ice-covered) and Station 7 was sampled during the four subsequent sampling periods. No samples were collected from 6 or 7 during the last sampling period due to ice cover.

[†††] Siegel (1956).

Table 14. Comparisons of Biomass (mg ash-free dry weight/100 m^3) for Amphipods in the Water Column Among Sampling Periods for Lagoon Stations and for Lagoon Offshore Stations Using the Friedman Two-Way Analysis of Variance.††† Each station/date value was the mean of three Faber net samples at the station during sampling period.

Species or Group	Comparisons Among Sampling Periods for Lagoon Stations (2,3,4)† (df=6)		Comparisons Among Sampling Periods for Lagoon and Offshore Stations (2,3,4,6/7)† (df=5)	
Onisimus glacialis	$\chi^2=10.25$,	$P>0.10$	$\chi^2= 3.64$,	$P>0.50$
Gammarus setosus	$\chi^2= 4.65$,	$P>0.50$	$\chi^2= 1.75$,	$P>0.90$
Apherusa glacialis	$\chi^2=12.57$,	$0.10>P>0.05$	$\chi^2=14.14$,	$0.05>P>0.01$
Halirages mixtus	$\chi^2=16.39$,	$0.02>P>0.01$	$\chi^2= 8.96$,	$P>0.10$
Pontoporeia affinis	$\chi^2= 8.58$,	$P>0.20$	$\chi^2= 0.80$,	$P>0.98$
Parathemisto sp.	$\chi^2=15.82$,	$P=0.048$	$\chi^2=15.50$,	$0.01>P>0.001$
Total Amphipods	$\chi^2=14.39$,	$P=0.048$	$\chi^2= 8.82$,	$P>0.10$

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† Comparisons for lagoon stations are for all 7 sampling periods, while for lagoon and offshore stations are for only 6 periods (see below).

†† 6/7 indicates that Station 6 was sampled during the first two sampling periods (7 was ice-covered) and Station 7 was sampled during the four subsequent sampling periods. No samples were collected from 6 or 7 during the last sampling period due to ice cover.

††† Siegel (1956).

Early in the open-water season of 1978 (10 July-4 August) *O. glacialis* comprised most of the amphipod biomass in the water column at both lagoon and offshore stations (Fig. 20-21). As the season progressed (4 August-23 September) several species of amphipod (*Apherusa glacialis*, *Parathemisto* spp., *Onisimus glacialis* and *Halirages mixtus*) collectively dominated the amphipod biomass at lagoon stations (Fig. 20). At the same time at offshore stations, *A. glacialis* and *Parathemisto* spp. formed the largest portion of the amphipod biomass in the water column (Fig. 21).

The total amphipod biomass at both lagoon and offshore stations increased markedly late in the season in 1978. In 1977 the total amphipod biomass at lagoon stations was high early in the season, declined at mid-August and then increased into September, while at offshore stations it increased dramatically as the season progressed (Figs. 20 and 21). Species composition in the lagoon was similar in both years (except for *Halirages mixtus*). At the offshore stations in 1977 *Parathemisto libellula* dwarft all other species in the water column after mid-August. This result parallels the increase of this species in near bottom habitats (see previous section).

Summary

The variations in biomasses of amphipods and mysids, and species composition of amphipods, both in the water column and near the bottom, indicates uneven distribution and rapid movements of epibenthic and pelagic amphipods and mysids within the Simpson Lagoon and nearshore system. Diver observations (from 1977 and 1978) also indicated this trend for both amphipods and mysids; similar distribution patterns have been noted in arctic waters by numerous authors (MacGinitie 1955; Crane 1974; Feder *et al.* 1976; Griffiths *et al.* 1977). The occurence of rapid movement is confirmed by initial analysis of drift net data (to be present in the final report) and by the apparent immigration of mysids into the lagoon during early summer (see Early Season Movements). The patchness of mysid and amphipod distribution will be evaluated in the final report through analysis of data from replicate samples, which have been pooled in this report.

Periodically during the open-water season, plumes of water from offshore areas were observed moving into the lagoon through entrances between the barrier islands. Amphipods and mysids are carried into the lagoon entrained in this water. The high flushing rate of the lagoon (0.2 times/day on the average and as much as once per day during winds greater than 40 km/h, Mungall 1978) may result in the rapid movement of amphipods and mysids into and out of Simpson Lagoon at various times through the season. Onshore movements of marine epibenthic invertebrate species (i.e., amphpipods and mysids) are suggested by Feder and Schamel (1976), who postulated that offshore populations of these species may reoccupy nearshore areas during the open-water season.

During the open-water season amphipods and mysids may move into, out of and within Simpson Lagoon. These movements are probably augmented by wind-driven water exchange which provides a means of dispersal for adult and immature amphipods and mysids. Basically, two types of movements of amphipods and mysids into and out of the lagoon are postulated.

1. Movements parallel to the shore. Longshore movements might be a consequence of, or at least assisted by, wind-generated currents which typically move in an east-west direction during the open-water season.

2. Movements between shallow estuarine and deeper marine waters. During the open-water period these movements may depend on storm-driven wind and current action. The organisms may particularly respond to water motion near the bottom, where they exist in greatest abundance.

Trophic Relationships

The most important food sources for both fish and birds in Simpson Lagoon during summer are mysids (*Mysis litoralis, M. relicta*) and amphipods (especially *Onisimus glacialis*) (Craig and Griffiths 1978; Johnson 1978, 1979). This section compares the daily food requirements of fish and birds to the availability of food (mysids and amphipods) during the open-water season.

Daily food requirements of the key vertebrates (fish and birds) in the study area during both 1977 and 1978 were estimated using fish and bird densities estimated by Craig and Haldorson (1979) and Johnson (1978, 1979) (Tables 15 and 16). Bird densities were available for both years. Oldsquaw ducks were the prime avian consumers, and were the only birds considered in this analysis. The 1977 and 1978 energy requirements for birds have been computed using the following equation from Kendeigh *et al.* (1977:201): at 0°C, $M=4.142\ W^{0.5444}$, where M=daily existence energy requirements during the molting period (Kcal) and W=weight of bird (g). A digestive efficiency of approximately 70% (Owens 1970) has been used in converting daily existence energy requirements. Fish densities for 1977 were assumed to be the same as those reported for 1978 by Craig and Haldorson (1979), with the exception that the run of arctic cod encountered on 11-20 August 1978 was assumed to have been absent in 1977 (P. Craig, pers. comm. 1979). Fish species considered were Arctic char, Arctic cisco, least cisco, Arctic cod and fourhorn sculpin. Energy requirements of fish are assumed to correspond to an intake of 6% of body weight per day for small fish, and 5% per day for large fish. The 6% figure was derived by Craig and Haldorson (1979); the 5% figure is arbitrary but based on the general principle that energy requirements do not increase linearly with body weight.

The available amount of food (mysids and amphipods) in 1977 at lagoon stations 1, 2 and 3 was calculated using diver estimates of densities of mysids and amphipods in conjunction with results of

Table 15. Estimates of Daily Food Requirements (g ash-free dry wt*/m^2) of Small and Large Fish in Simpson Lagoon in 1977** and 1978.

Date	Lagoon Edge (6.9 km^2)				Lagoon Center (153.1 km^2)				Daily Ration (Weighted Mean) g/m^2x10^{-4}
	Small Fish (=15g)		Large Fish (=470g)		Small Fish (=15g)		Large Fish (=470g)		
	Density $No./m^2x10^{-4}$	Ration g/m^2x10^{-4}	Density $No./m^2x10^{-4}$	Ration g/m^2x10^{-4}	Density $No./m^2x10^{-4}$	Ration g/m^2x10^{-4}	Density $No./m^2x10^{-4}$	Ration g/m^2x10^{-4}	
July 1-10	5	0.5	5	14.1	0.5	0.1	0.5	1.4	2.3
11-20	20	2.2	20	56.4	2	0.2	1.5	4.2	6.7
21-31	50	5.4	40	112.8	5	0.5	4	11.3	16.4
Aug. 1-10	50	5.4	40	112.8	5	0.5	4	11.3	16.4
11-20	1450[††]	84.1	40	112.8	1400[††]	81.2[††]	4	11.3	97.0
21-31	70	7.6	40	112.8	7	0.8	4	11.3	16.8
Sept. 1-10	100	10.8	40	112.8	10	1.1	4	11.3	17.2
11-20	100	10.8	10	28.2	10	1.1	1	2.8	5.4
20-30	100	10.8	5	14.1	10	1.1	0.5	1.4	3.5

[*] Ash-free dry weight calculated by taking 12% (mean of mysids and amphipods) of wet weight.

[**] Density estimates for 1977 are assumed to be the same as 1978 less the arctic cod run 18-20 Aug.

[†] Density estimates from Craig and Haldorson (1979).

[††] Daily food rations are assumed to be 6% of body weight for small fish (Craig and Haldorson 1979) and 5% of body weight for large fish.

[†††] Food ration for this period is based on small fish approximately 8 g in weight (arctic cod).

Table 16. Estimated Daily Food Requirements (mg ash-free dry weight/m^2) of Oldsquaw Ducks in Simpson Lagoon in 1977 and 1978.

	5 June		20 June		5 July		28/29 July		15 August		30 August		22 September	
1977	No/m^2[†] x10^{-6}	mg/m^2[††] AFDW	No/m^2 x10^{-6}	mg/m^2 AFDW	No/m^2 x10^{-6}	mg/m^2 AFDW	No/m^2 x10^{-6}	mg/m^2 AFDW	No/m^2 x10^{-6}	mg/m^2 AFDW	No/m^2 x10^{-6}	mg/m^2 AFDW	No/m^2 x10^{-6}	mg/m^2 AFDW
	0.0	-	0.2	0.009	6.0	0.26	321.1	14.00	261.0	11.39	137.1	5.98	666.3	29.07

	23 June		5 July		15 July		25 July		5 August		15 August		25 August		5 September		15 September		23 September	
1978	No/m^2 x10^{-6}	mg/m^2 AFDW	No/m^2 x10^{-6}	mg/m^2 AFDW	No/m^2 x10^{-6}	mg/m^2 AFDW	No/m^2 x10^{-6}	mg/m^2 AFDW	No/m^2 x10^{-6}	mg/m^2 AFDW	No/m^2 x10^{-6}	mg/m^2 AFDW	No/m^2 x10^{-6}	mg/m^2 AFDW	No/m^2 x10^{-6}	mg/m^2 AFDW	No/m^2 x10^{-6}	mg/m^2 AFDW	No/m^2 x10^{-6}	mg/m^2 AFDW
	0.1	0.004	15.5	0.68	184.3	8.04	83.4	3.64	77.3	3.37	104.3	4.55	63.5	2.77	24.6	1.07	27.4	1.20	209.4	9.14

[†] Densities are based on results of aerial surveys and are weighted means for lagoon (Johnson 1979).

[††] Food Requirements were calculated assuming 240 k cal/bird-day as the gross energy needs of oldsquaw ducks. This was converted to mg ash free dry weight by assuming 5.5 k cal equals 1.0 g ash-free dry weight.

otter trawls (Griffiths and Craig 1978:19). A weighted mean for the whole lagoon was then determined for each sampling period (15 July, 15 Aug. and 15 Sept.) (Table 17). The estimate for Station 3 on 15 September 1977 was not used as it appeared unrealistically high (182.1 g ash-free dry weight/m^2), possibly due to a sampling artifact (i.e., only one otter trawl sample was collected at this station and date). In this case the weighted means for Stations 1 and 2 were assumed to apply to the entire lagoon.

For 1978 available biomass was determined using results from the drop net samples. For each sampling date the five lagoon stations were combined to produce a weighted mean for the entire lagoon (Table 17).

Comarisons of food (mysids and amphipods) available in the lagoon during 1977 and 1978 with the daily food requirements of the oldsquaw ducks and the major species of fish using the lagoon are shown in Figure 22. The energy available was considerably different in the two years. In 1977 it exceeded the daily requirements of consumers by two or three orders of magnitude; this suggests that food was not a limiting factor for the fish and birds in the lagoon during the summer of 1977. It should also be remembered that both otter trawls and diver estimated densities of epibenthic invertebrates are biased downwards (see Sampling Limitations and Biases). In 1978 the available supply of food apparently was an order of magnitude less than in 1977. The number, and thus the energy demand, of oldsquaw ducks in 1978 was approximately half of what it was in 1977, but fish densities and energy needs were greater in 1978 due to a large influx of arctic cod in mid-August of 1978 (Tables 15 and 16). Whether the year to year variations in numbers of consumers are related to differences in the energy available is not known. The interpretation problem is compounded by natural variations in the densities of all the organisms involved, and by their responses to various physical conditions (wind, temperature, salinity, ice conditions, etc.).

Table 17. Estimates of Food Available (Mysids and Amphipods) (g/m² ash-free dry wt) in Simpson Lagoon 1977 and 1978. Recalculated from Griffiths and Craig (1978).

Station	Approximate Lagoon Area Represented (km²)	1977 15 July *g/m²	15 August *g/m²	15 September *g/m²
1	36	0.40	1.27	0.87
2	102	0.45	2.50	3.78
3	22	0.92	3.20	-†
Total	160			
Weighted Means		0.50	2.33	3.02

†Estimates for Station 3 on this date not used as they appeared unrealistically high (182.1 g/m²).

Station	Approximate Lagoon Area Represented (km²)		1978 8 July *g/m²	19 July *g/m²	3 August *g/m²	18 August *g/m²	30 August *g/m²	14 September *g/m²	23 September *g/m²
1	36		0.11	0.16	0.22	0.068	0.06	0.27	0.25
2	34	51††	0.12	0.23	0.37	0.30	0.20	0.33	0.18
3	34	51††	0.40	0.39	0.19	0.66	0.18	0.20	0.23
4	34		-††	1.25	0.14	0.30	0.14	0.12	0.11
5	22		0.029	0.12	0.10	0.09	0.04	0.06	0.01
Total	160								
Weighted Means			0.079	0.45	0.22	0.30	0.12	0.21	0.17

*Biomass is the sum of all mysids and amphipods in g/m² ash-free dry weight.

††No sample collected on this date at Station 4. Stations 2, 3 represent 51 km² on this date.

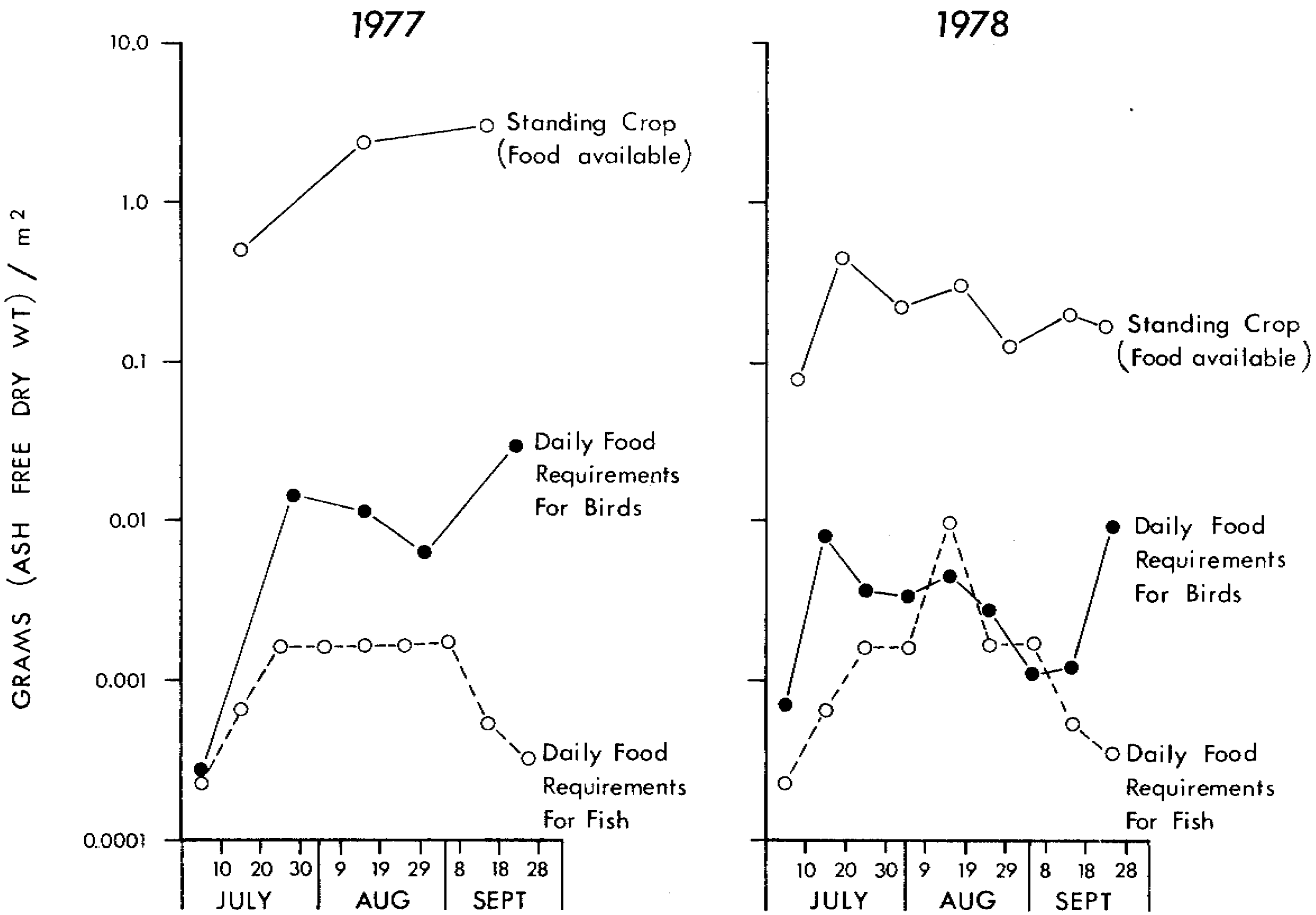

Figure 22. Comparison of the Food Available (Mysids and Amphipods) and the Daily Food Requirements of Birds and Fish in Relation to Time in Simpson Lagoon During 1977 and 1978.

The biomass of mysids and amphipods was similar in mid-July of the two years. In 1977 it increased thereafter until the end of the open-water period, but in 1978 it tended to decrease during the same period. The drop net results of 1978 showed that the biomasses of *M. relicta* and *O. glacialis* did not change significantly in the lagoon as the season progressed, but that the biomass of *M. litoralis* decreased significantly during the same period. Thus *M. litoralis* appears largely responsible for the reduction in biomass seen in 1978 relative to 1977. In both years the invertebrate biomass would have had to be replenished through growth of individuals and/or a net immigration of organisms into the lagoon from other locations (i.e., offshore and/or other nearshore areas).

Drift net data were collected in the gaps between the barrier islands during the 1978 season in an attempt to assess immigration. Only 6 of 42 samples were collected when water was moving into the lagoon, so no reliable estimate of the immigration rate of mysids and amphipods into the lagoon was possible. The drift net data are still undergoing analysis, and will be reported in the final report.

The growth rates (increase in weight) of *M. litoralis*, *M. relicta* and *Onisimus glacialis* were determined for the open-water period (8 July-23 September) and are summarized below.

Species	% of Body[1] Weight Gain/day	Doubling Rate in No. of Days
Mysis litoralis	5	14.2
Mysis relicta	3	23.4
Onisimus glacialis (age 1)	1	69.7

[1] Details concerning growth rates are given in species accounts below.

It is evident from these data and Figure 22 that growth along could have not accounted for the increase in biomass between 8 July and 19 July even assuming the unlikely event of no predation. It thus appears that the biomass of mysids and amphipods available to consumers depends largely on the net exchange of these organisms between the lagoon and surrounding waters. A disruption of the movements of water and the entrained organisms could have far-reaching effects on the secondary productivity of the system.

The feeding ecology of selected marine epibenthic invertebrates is at present being studied under a separate contract (D. Schneider, RU 356). Generally, he has found that most species of epibenthic invertebrates found in the study area are omnivorous (Table 18).

Table 18[†]. Major Species of Epibenthic Invertebrates and their Principal Foods.

Species	Principal Foods
Onisimus glacialis	Crustacean parts, Diatoms
Mysis relicta	Peat, Diatoms, Crustacean parts
Onisimus littoralis	Diatoms, Crustacean parts
Gammarus setosus	Peat, Diatoms, Crustacean parts
Apherusa glacialis	Diatoms, Dinoflagellates, Peat, Crustacean parts
Saduria entomon	Diatoms, Polychaetes, Peat

[†] Adapted from D.E. Schneider and H. Koch, RU 356.

Similar findings have been reported for the same and other arctic species: *Gammarus setosus*, Steele and Steele (1970) and Broad (1977); *Onisimus glacialis*, Broad (1977); *Parathemisto libellula*, Dunbar (1946), Wing (1976); *Parathemisto pacifica*, Wing (1976); *Pontoporeia affinis*, Segerstrale (1973).

The age of the carbon that selected invertebrates assimilate is also under investigation (D. Schell, RU 527). If the carbon is old*, this indicates that its source is terrestrial detritus formed by peat eroding into the lagoon. 'Old' carbon from peat could be assimilated either directly as detritus or indirectly in the form of microfauna living on the detritus; in either case detritus would be the main food source for the lagoon epibenthos. However, if the carbon is modern*, then recent primary production must be the main source of food for the epibenthic invertebrates. Recent production could be marine production (phytoplankton and ice algae) or recent terrestrial production carried to the lagoon by runoff.

Biology of Key Invertebrate Species

The three most important invertebrate species in diets of birds and fish in Simpson Lagoon are *Mysis litoralis, Mysis relicta* and *Onisimus glacialis* (Johnson 1978, 1979; Craig and Griffiths 1978; Craig and Haldorson 1979). This section discusses selected aspects of the life histories of these key species as well as brief outlines of other species of amphipods.

The biology of arctic marine epibenthic invertebrates is poorly known because most previous studies have been conducted over short periods of time during the open-water season or have been mainly concerned with the species composition of the invertebrate community. The kinds of information being acquired in this study permit a more detailed description of the biology of selected species than has previously been possible.

In 1978 systematic sampling commenced in early June and will continue to April-May 1979. This annual report is mainly concerned with information acquired between 5-7 June and 23 September 1978,

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*See Schell (RU 527) for a discussion of old and modern carbon, methods used of aging and use of the technique.

although some preliminary results of the November 1978 sampling period are also included. Males and females for each species have been combined in most analyses but will be treated separately, where data permit, in the final report; that report will include a more complete description of the life history of these three important species.

Mysis litoralis

In temperate areas mysids generally have a one-year life cycle (Wigley and Burns 1971; Morgan and Beeton 1978), but a two-year cycle has been postulated for mysid populations in the arctic (Lasenby and Langford 1972). Size-class frequencies of mysids based on data collected over the open-water season both in Simpson Lagoon and just offshore of the barrier islands, suggest that *M. litoralis* in this area may live as long as three years (Table 19, Figs. 23 and 24). First-year individuals (i.e., apparently released in the spring of 1978) reach 10-12 mm in length by the end of the open-water season, second-year animals are 16-18 mm at this time and third-year animals range from 22 mm to 35 mm. The Simpson Lagoon population consists predominantly of first-year animals and some two-year-old individuals (Fig. 24). Larger (30-35 mm) and presumably older *M. litoralis* of both sexes were found in otter trawl samples taken seaward (1-5 km) of Pingok Island in 1978, but were rarely collected by any sampling technique in Simpson Lagoon.

Seasonal Growth Rate. The seasonal (8 July-23 September) growth rate for year-class-one *M. litoralis* is shown in Table 18 and Figure 23. Insufficient data are available to accurately determine growth rates for second- and third-year animals. For first-year individuals there was a significant linear relationship between time and both total length and wet weight:

Table 19. Growth (Total Length and Wet Weight) of *Mysis litoralis* Collected in Simpson Lagoon 8 July-23 September 1978. It should be noted that these equations only represent growth during the open-water season.

	First Year Class					Second Year Class					Third Year Class				
Date	Day Number	$\bar{x}$ Length (mm)	S.D.	Wet* Weight (mg)	n	Day Number	$\bar{x}$ Length (mm)	S.D.	Wet* Weight (mg)	n	Day Number	$\bar{x}$ Length (mm)	S.D.	Wet* Weight (mg)	n
8 July	1[†]	5.2	0.7	1.7	208	366[††]	14.7	2.2	20.9	7	731[††]	-	-	-	-
19 July	11	6.6	1.2	3.0	938	377	16.4	2.1	27.3	161	742	23.1	2.4	63.0	5
3 August	26	8.8	0.9	6.0	628	392	-	-	-	-	757	-	-	-	-
18 August	41	9.7	1.0	7.6	666	407	18.3	2.4	35.7	9	772	25.8	2.3	82.6	2
30 August	53	10.6	2.1	9.4	112	419	16.2	0.8	26.5	9	784	-	-	-	-
14 September	68	10.9	0.9	10.1	54	434	-	-	-	-	799	-	-	-	-
23 September	77	12.2	1.2	13.3	50	443	17.0	-	29.8	1	808	-	-	-	-

Best-fit Equations

Total length = 0.084 (day) + 5.78
r = 0.97 $P<0.001$

Wet weight = 0.14 (day) + 1.72
r = 0.99 $P<0.001$

Insufficient data at present to accurately determine rates for these size classes.

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* Wet Weight determined using total length-wet weight equations for *M. litoralis* Appendix 1.

[†] Day 1 was arbitrarily assigned to the first date when a sample was collected (Day 1 does not correspond to the date of release from brood pouch).

[††] Similarly day 366 and day 731 assumes these mysids are one and two years older, respectively than Day 1 mysids.

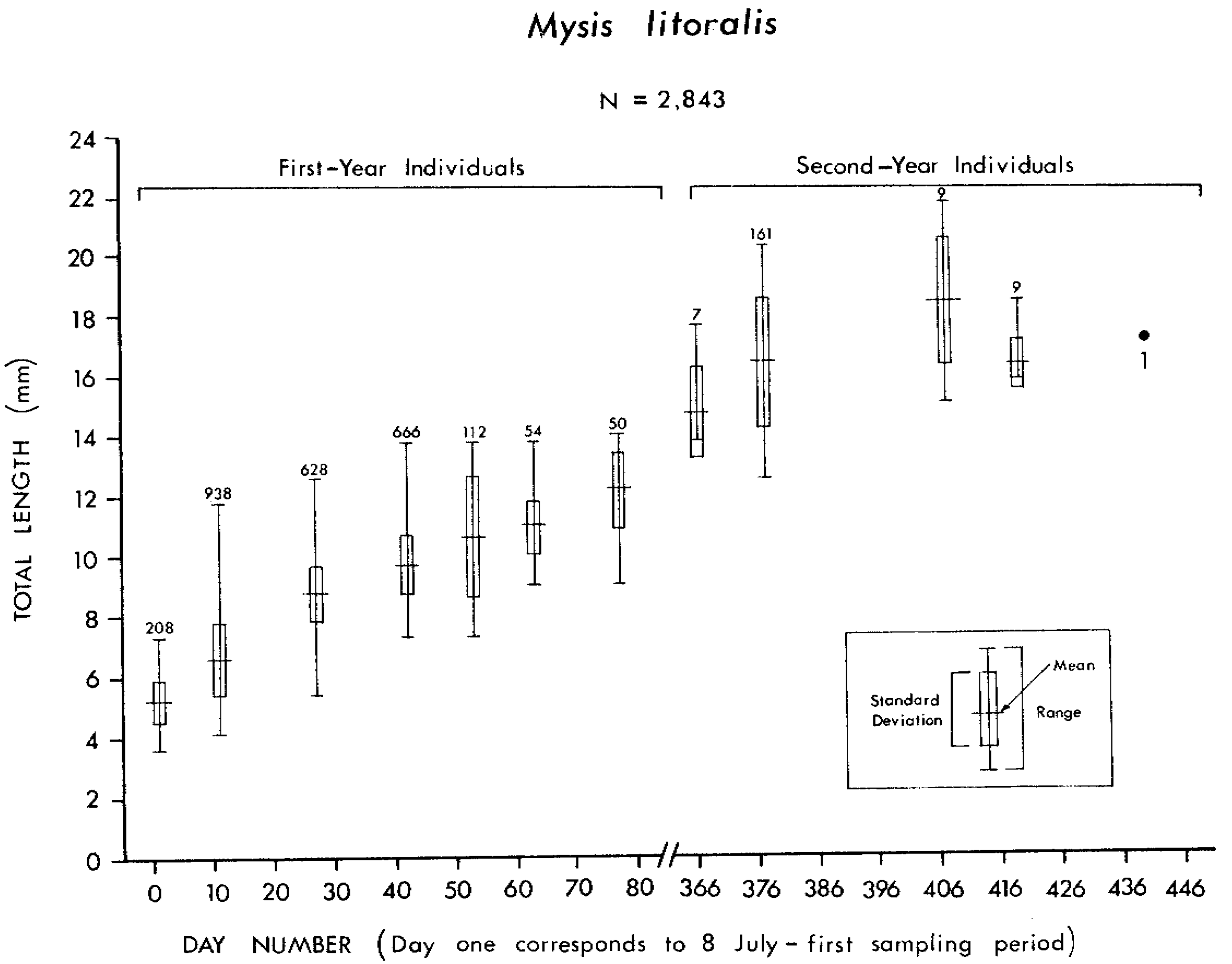

Figure 23. Increase in Total Length of First- and Second-Year *Mysis litoralis* During the Open Water Season (8 July-23 September 1978) in Simpson Lagoon. (Samples were collected by drop-net.)

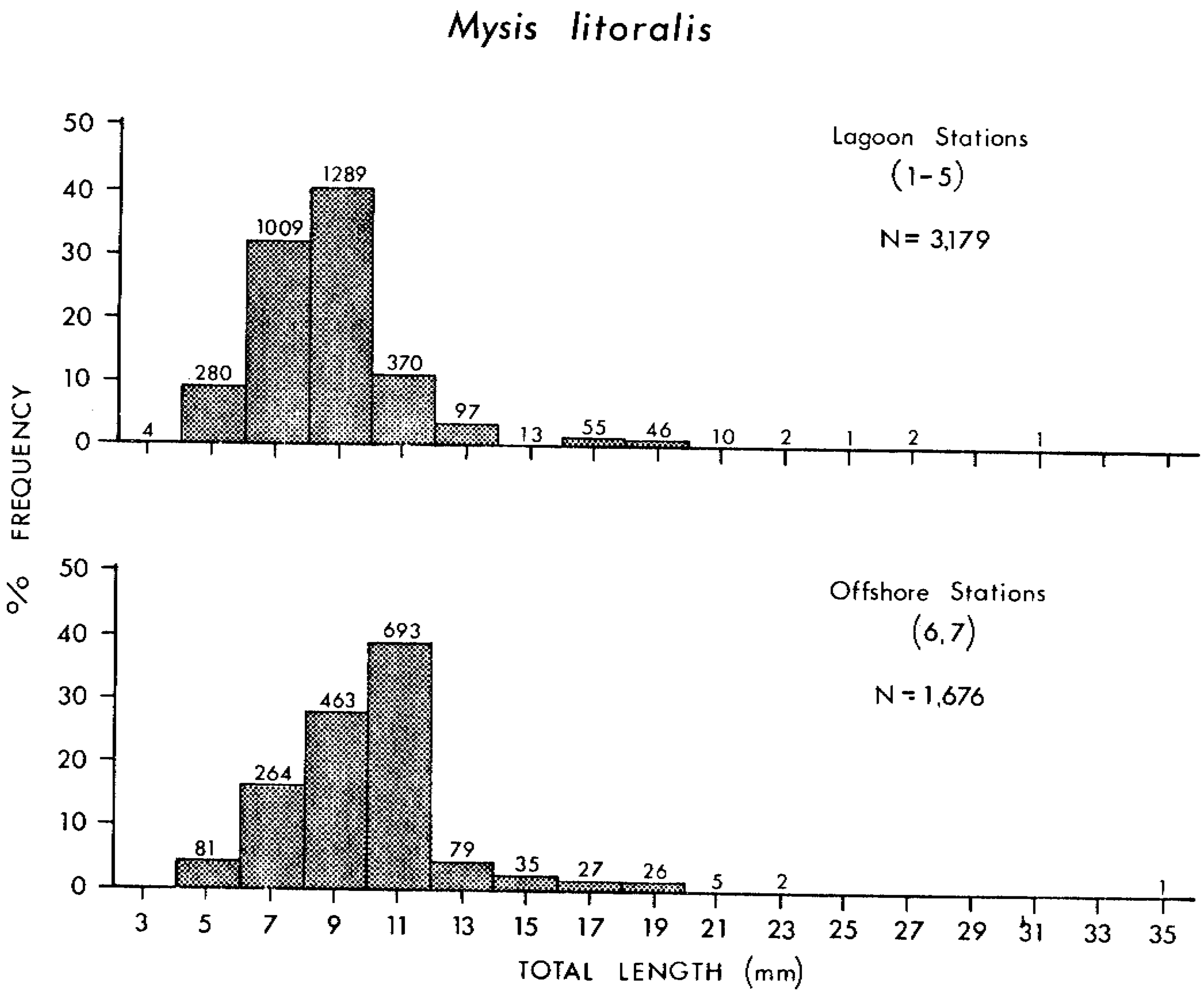

Figure 24. Length-Frequency of *Mysis litoralis* Collected by Drop-Nets in Lagoon and Offshore Stations During the Open Water Season 1978.

Total Length=0.084 (day) + 5.78 r=0.97
Wet Weight=0.14 (day) + 1.72 r=0.99

First-year individuals increase in length at an average rate of 2.5 mm/30 days and in wet weight at an average rate of 4.2 mg/ 30 days (approximately a 5% increase in body weight/day). Growing at this rate, year-class-one individuals would double their weight every 14 days over the open-water season. The growth rate undoubtedly declines during winter since *M. litoralis* would have reached approximately 36 mm in length and 52 mg in weight by the next spring if this rate had continued through the winter (*cf* Table 19).

Reproduction. When mysids reach 6 mm in length the sexes can be distinguished on the basis of sexual characteristics described by Tattersall (1951) and Tattersall and Tattersall (1951). Sexually mature first-year males (10-12 mm in length) with elongated fourth pleopods (a breeding characteristic) were noted by the end of September. During the same period no first-year females showing secondary breeding characteristics were found in our collections. Female *M. litoralis* (10-12 mm on 23 September) apparently do not breed, because none of this size were found with eggs or brood pouches in any November samples (from Thetis Island to Stefansson Sound). Breeding is apparently confined to second- and third-year males and females with a possible contribution from first-year males. Differences in secondary sexual development have been reported for other mysid species (Mauchline 1967, 1968, 1969, 1970, 1971; Wigley and Burns 1971).

Breeding probably occurs in late September or early October as gravid *M. litoralis* were collected in November 1978 in Simpson Lagoon. The young appear to be brooded during the winter and are released the following spring, by which time they are 2-4 mm in length. February 1979 samples contained *M. litoralis* that were brooding developing embryos and a female *M. litoralis* (16 mm in length) brooding six young (2.5-3.0 mm in length) was collected on 7 July in Simpson Lagoon. The exact time of release of young probably depends on conditions immediately surrounding the female; because the coastal environment is spatially variable, release for the population as a whole probably occurs over a long period.

Fecundity. Gravid *M. litoralis* were collected in Simpson Lagoon in November 1978. A preliminary analysis showed that 23 females (20-29 mm in length) carried 34-81 eggs of mean diameter 0.8 mm in their brood pouches (Table 20). A more detailed analysis relating fecundity to total length of individuals is now underway and will be presented in the final report.

Mysis relicta

Mysis relicta collected in Simpson Lagoon and nearshore areas were divided into two-year classes on the basis of length-frequency distribution data (Table 21, Figs. 25 and 26). First-year individuals (released in the spring of 1978) reached a mean length of 8-10 mm (range 4-11 mm) by 23 September, and second-year individuals had reached a mean length of 14-16 mm (range 13-20 mm). A few larger *M. relicta* (23-28 mm) of both sexes were collected in otter trawls both inside and outside the lagoon; this suggests that some portion of the population lives at least three years. Insufficient numbers of these larger *M. relicta* have been collected to permit their inclusion in the following analysis.

In temperate lakes *M. relicta* has essentially a one-year life-cycle, although in some cases a few females live an additional three months and produce a second brood (Tattersall 1951; Lasenby and Langford 1972; Morgan and Beeton 1978). McWilliams (1970) found that in Lake Michigan the life span of this species varied with depth and that individuals in shallow water lived only seven months but they lived in deep water as long as 20 months. Larkin (1948) found *M. relicta* to live slightly longer than two years in Great Slave Lake; and a similar life span was reported for this species in Char Lake in the high Arctic (Lasenby and Langford 1972).

Table 20. Fecundity of Selected Species of Arctic Marine Epibenthic Invertebrates. Only animals with intact brood pouches were used in the analysis.

Species	n	Date Collected	Total length of Animal (mm)	Number of Eggs	Mean Egg Diameter (mm)	Source
Onisimus glacialis	82	Nov. 1978	10-13	10-16	0.8	LGL
Onisimus littoralis	1	Nov. 1978	20-13	25	0.8	LGL
Gammarus setosus	8	Feb. 1979	20-28	70-136	0.6	LGL
Gammarus setosus		-	13-26	20-100	0.7	Steele & Steele 1970
Gammarus wilkitzkii	68	April 1954-55	25-33	197	-	Barnard 1959
Boeckosimus affinis	8	Feb. 1979	11-13	8-15	0.8	LGL
Gammaracanthus loricatus	1	April 1954-55	40	320	-	Barnard 1959
Gammaracanthus loricatus	1	Feb. 1979	-	350	0.8	LGL
Atylus carinatus	1	Nov. 1978	-	84	1.0	LGL
Ampelisca birulai	1	Oct. 1949	-	14-15	0.8	MacGinitie 1955
Melita formosa	1	Aug. 1949	-	44-81	0.7	MacGinitie 1955
Pontoporeia affinis	36	March 1943	6-9	8-25	-	Mathieson 1953
Paroediceros lynceus	1	Feb. 1979	28	220	0.6	LGL
Apherusa megalops	2	Feb. 1979	6.0-6.5	3-7	1.4-2.6	LGL
Anonyx sarsi	1	Feb. 1979	50.5	56	1.3	LGL
Saduria entomon	1	Nov. 1978	57.5	390	1.0	LGL
Diastylis sulcata	1	Aug. 1978	10	22	0.4	LGL
Diastylis sulcata	2	Nov. 1978	9.7-12.5	15-38	0.4	LGL
Mysis litoralis	23	Nov. 1978	20-19	34-81	0.8	LGL
Mysis relicta	5	Nov. 1978	18-20	30-35	0.8	LGL
Eualus gaimardii	2	Aug. 1978	54-55	405-616	0.9	LGL

It appears that the life span of *M. relicta* increases with latitude and water depth.

Seasonal Growth Rate. Growth rates of *M. relicta* in Simpson Lagoon and nearshore areas during the open-water season (8 July-23 September) for each year class are shown in Table 21 and Figure 25. The relationship between time and both length and weight for each size class and for the whole population are summarized below. The year classes were separated to give a clear picture of growth during the first year; first-year individuals comprise the dominant group in the lagoon.

First-year class	Total Length=0.072 (day) + 5.59	r=0.97
	Wet Weight=0.11 (day) + 2.10	r=0.99
Second-year class	[†]Total Length=0.03 (day) + 3.41	r=0.96
	[†]Wet Weight=0.11 (day) - 19.27	r=0.96
First-year class and Second-year class	Total Length=4.32 $(\text{day})^{0.21}$	r=0.99
	Wet Weight=1.28 $(\text{day})^{0.40}$	r=0.99

[†] These equations are only valid for day numbers 366-443 (Table 21).

First-year individuals increased in total length at an average rate of 2.2 mm/30 days and in wet weight at a mean rate of 3.3 mg/30 days (approximately a 3% increase in body weight/day, thus doubling in weight every 23.4 days). Second-year animals increased in total length at an average rate of 0.9 mm/30 days and in wet weight by 3.3 mg/30 days. The growth rate exhibited by first-year *M. relicta* over the open-water season declines during the winter, if it remained at the rate observed during the open-water season they would be 26 mm in length and 40 mg in weight after 365 days, which is clearly not the case (Table 21). The relative roles of reduced mean temperature, reduced food levels and other factors in

Table 21. Growth Rate (Total Length and Wet Weight) for *Mysis relicta* Collected in Simpson Lagoon 8 July-23 September 1978.

	First Year Class					Second Year Class				
Date	Day Number	$\bar{x}$ Length (mm)	S.D.	Wet* Weight (mg)	n	Day Number	$\bar{x}$ Length (mm)	S.D.	Wet Weight (mg)	n
8 July	1*	4.9	0.9	1.7	76	366[††]	14.0	1.8	19.6	17
19	11	6.3	0.7	3.1	177	377	14.8	1.8	22.2	74
3 August	26	8.3	1.0	5.8	175	392	15.4	1.6	24.4	34
18	41	9.1	1.0	7.2	79	407	15.7	1.9	25.5	26
30	53	9.6	1.1	8.2	46	419	15.8	1.0	25.9	30
14 September	68	10.3	0.7	9.6	304	434	16.0	1.7	26.6	31
23	77	10.7	0.6	10.5	239	443	16.8	2.2	29.8	20

Best-fit Equations

First Year Class:

Total length = 0.072 (day) + 5.59
$r = 0.97$ $P<0.001$

Wet weight = 0.11 (day) + 2.10
$r = 0.99$ $P<0.001$

Second Year Class:

Total length = 0.03 (day) + 3.41[†††]
$r = 0.96$ $P<0.01$

Wet weight = 0.11 (day) + 19.27[†††]
$r = 0.96$ $P<0.01$

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* Wet weights calculated using total length-wet weight relationship from Appendix 2.

[†] Day one corresponds to the first collection period. It should be remembered that young *M. relicta* had reached 4.9 mm in length by this date (i.e., day one does <u>not</u> correspond to the date of release from the brood pouch).

[††] Day 366 assumes these *M. relicta* are one year older than day one mysids.

[†††] These equations are only valid for day 366 to 443.

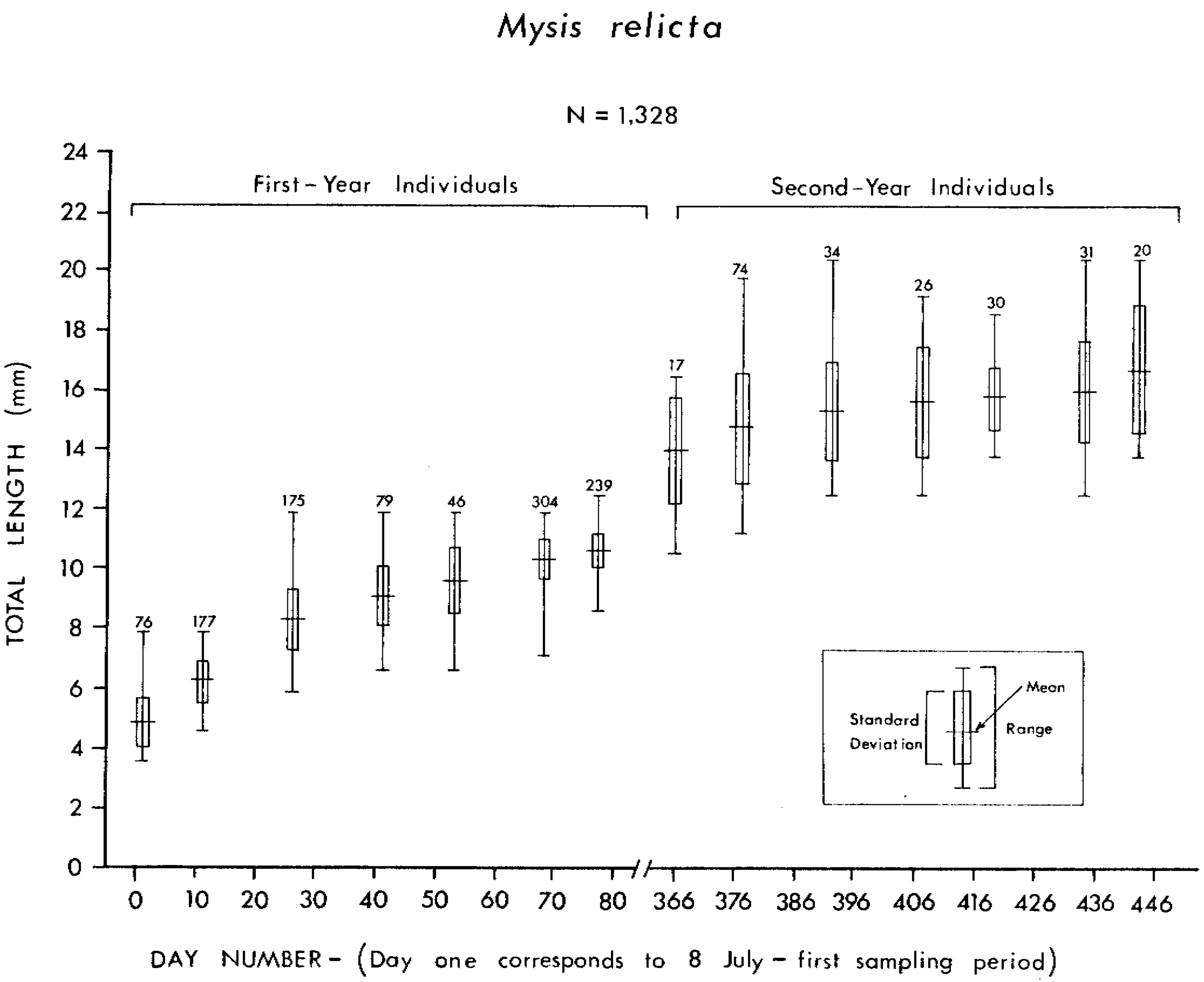

Figure 25. Increase in Total Length of First- and Second-Year *Mysis relicta* During the Open Water Season (8 July-23 September 1978) in Simpson Lagoon. (Samples were collected by drop-nets.)

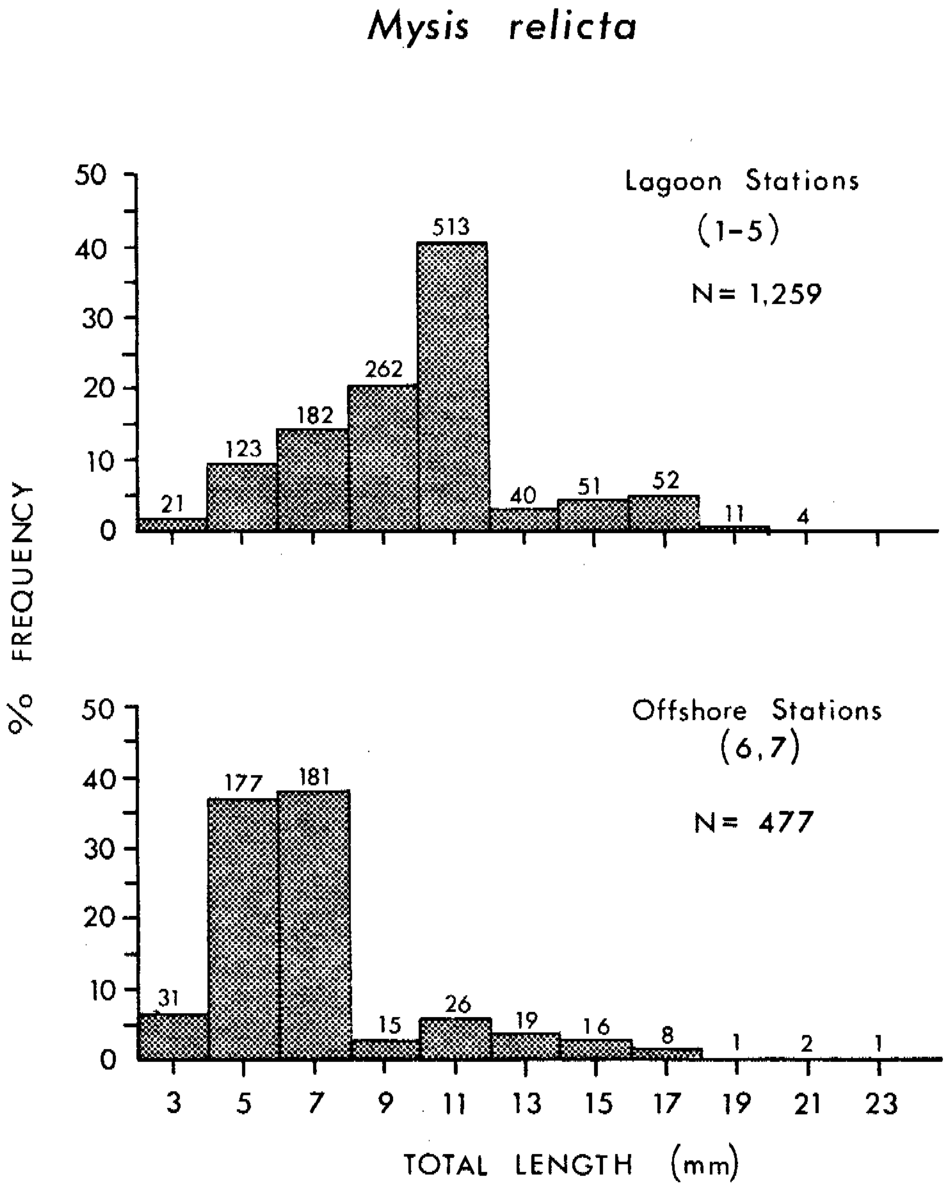

Figure 26. Length-Frequency of *Mysis relicta* Collected by Drop-nets at Lagoon and Offshore Stations During the Open Water Season 1978.

causing this decrease in growth rate are not known at present. Morgan and Beeton (1978) found young-of-the-year *M. relicta* in Lake Michigan to grow at a rate of 0.7 mm/30 days between March and September. Similar findings were reported for *M. relicta* by Lasenby and Langford (1972). This rate was slower than that of first-year individuals but approximately the same as that of second-year animals in Simpson Lagoon. However, it should be noted that after 365 days young-of-the-year *M. relicta* had reached 14.0 mm in both Lake Michigan and in Simpson Lagoon. Thus the overal growth rate in the first year for *M. relicta* was similar in both areas. Growth appears to be faster in the summer in the Arctic but slower in the winter.

Reproduction. The sexes can be distinguished when they reach 6 mm, although the animals are not sexually mature until they are 11-12 mm in length (Tattersall 1951). Large numbers of 8-10 mm (first-year) *M. relicta* were collected on 23 September; this collection contained males with breeding characteristics (elongated 4th pleopod). However, no females in this size class showed similar development (i.e., no brood pouch). A preliminary analysis of samples collected in November 1978 showed that gravid *M. relicta* (16-20 mm in length) were present thus breeding took place in late September or early October. In temperate zones *M. relicta* breeds from October to May (Juday and Birge 1928; Tattersall 1951). No first-year females (8-10 mm) were found in gravid condition in November samples. This indicates that first-year female *Mysis relicta*, like first-year female *Mysis litoralis*, do not breed. McWilliams (1970) also reported size differences between breeding male and breeding female *M. relicta* in Lake Michigan (mean lengths 14.5 and 17.8 mm, respectively).

In the Simpson Lagoon study area the young were brooded until sometime in early spring when they were released. Their length at release appears to be about 2-4 mm. This size range was represented by numerous individuals in the lagoon in late June and early July 1978. In addition, three female *M. relicta* with ruptured brood pouches containing several juveniles (2-4 mm) were found at this time.

In addition to the major breeding season in October, some evidence is available that suggests another, possibly minor, breeding phase took place during the open-water season. Drift net samples collected from late July to late September between the barrier islands contained male and female *M. relicta* (10-12 mm) with secondary breeding characteristics. No newly released *M. relicta* or gravid females were captured during the summer; however, 4-mm juveniles (which had been released sometime after ice cover formed) were collected in Simpson Lagoon in November 1978.

Fecundity. Preliminary results of November collections showed female *M. relicta* to have between 30 and 35 eggs (Table 20). A more detailed account of the fecundity of *M. relicta* will be given in the final report.

Onisimus glacialis

Onisimus glacialis collected during the open-water season in Simpson Lagoon were separated into two year classes on the basis of size-frequency distribution (Figures 27 and 28). First-year animals (released in spring 1978) averaged 5.1 mm in length (range 2.8-6.9 mm) by 23 September, and second-year individuals (released in spring 1977) averaged 9.7 mm in length (range 7.1-12.9 mm). As was the case with *M. relicta* these results indicate that a two-year life-cycle predominates. Steele (1961) has also postulated a two-year life-cycle for *Onisimus glacialis* in the western Arctic. However, several individuals of both sexes were 15-16 mm in total length when collected, suggesting that some portion of the population lives beyond two years. Insufficient numbers of these large *Onisimus glacialis* have been collected to permit their inclusion in these analyses.

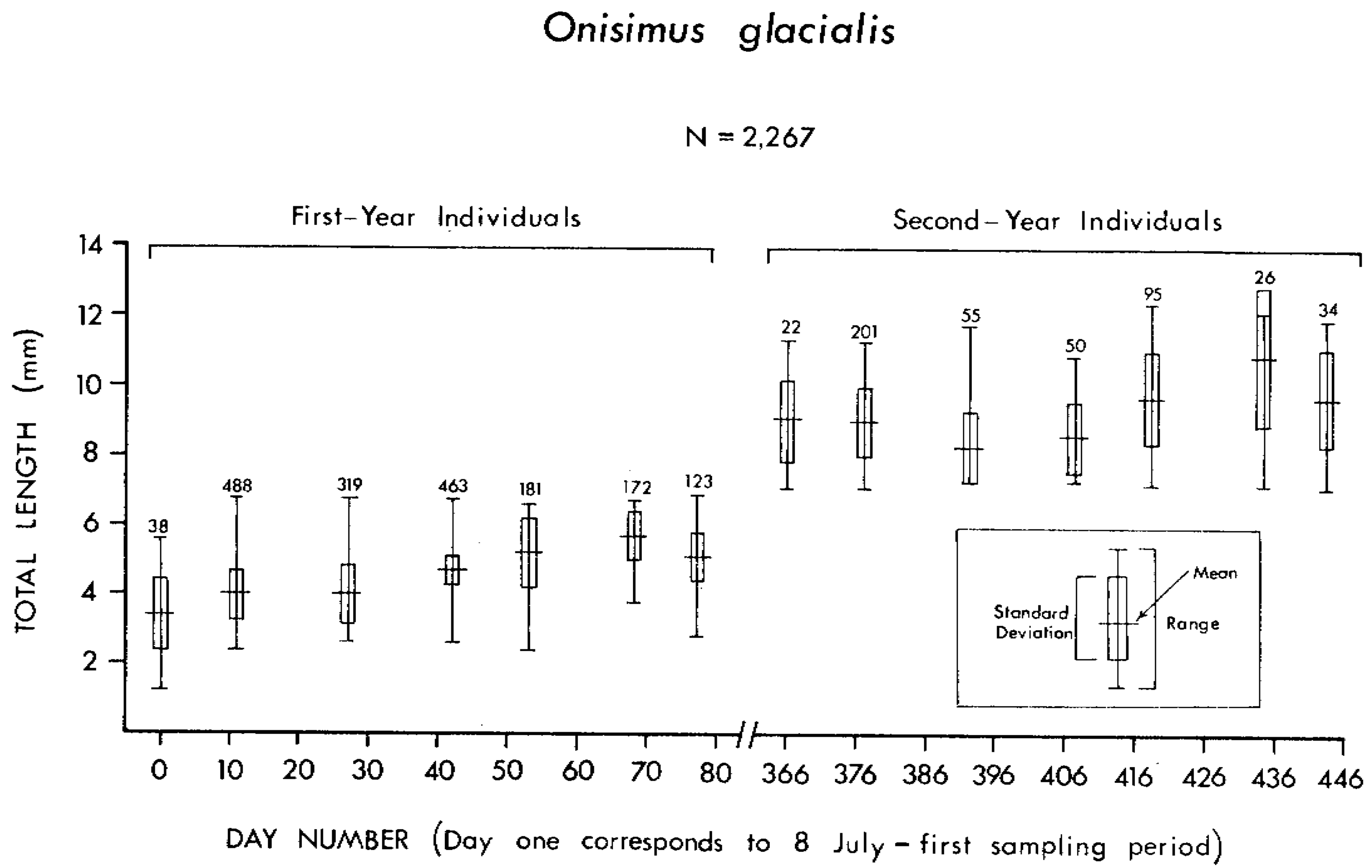

Figure 27. Increase in Total Length of First- and Second-Year *Onisimus glacialis* During the Open Water Season (8 July-23 September 1978) in Simpson Lagoon. (Samples were collected by drop-nets.)

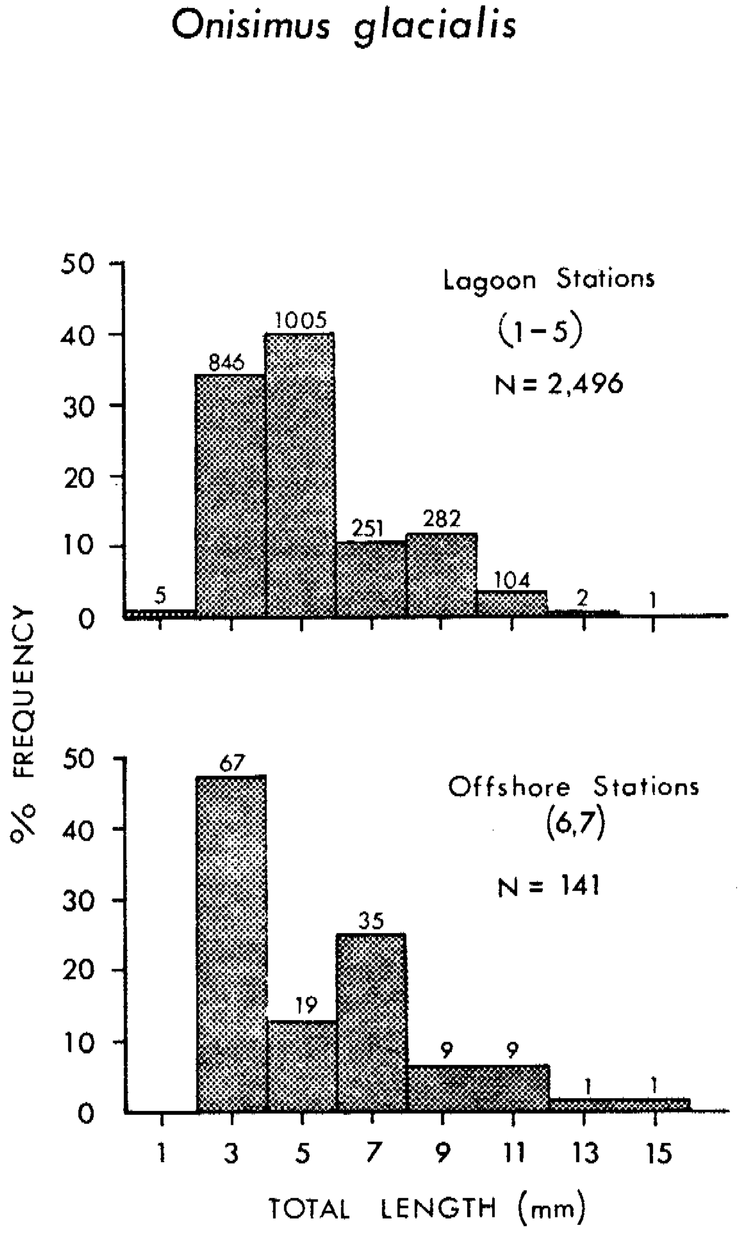

Figure 28. Length-Frequency of *Onisimus glacialis* Collected by Drop-Nets at Lagoon and Offshore Stations During the Open Water Season 1978.

Seasonal Growth Rates. The growth rate data of *O. glacialis* during the open-water season in Simpson Lagoon for both year classes and the population as a whole are shown in Table 22 and Figure 27. The relationships between time and both length and weight are summarized below.

First-year class	Total Length=0.027 (day) + 3.49 Wet Weight=0.04 (day) + 1.21	r=0.93 r=0.90
Second-year class	No significant relationships	
First and Second-year class	Total Length=2.53 $(\text{day})^{0.21}$ Wet Weight=0.57 $(\text{day})^{0.53}$	r=0.93 r=0.93

First-year individuals increased in total length by an average of 0.8 mm/30 days and in wet weight by a mean of 1.2 mg/30 days (approximate 1% of their body weight/day, doubling weight every 70 days). This rate of growth is markedly lower than the rates determined for *M. litoralis* (5%/day) and *M. relicta* (3%/day). If the first-year growth rate were continued through the winter, *O. glacialis* would be 10.0 mm in length and 14.5 mg in weight, after 365 days. This corresponds almost exactly to the sizes and weights for 366 day *O. glacialis* collected in Simpson Lagoon. Thus it appears that the growth rate is continuous over the entire year (during its first year) in contrast to *M. litoralis* and *M. relicta* both of which show reduced growth rates during the winter.

Reproduction. Length-frequency data showed the majority of *O. glacialis* in the lagoon in summer to be juveniles (<7.0 mm). They did not attain sufficient size (8-0 mm) to permit us to distinguish gender by 23 September when sampling was terminated.

Breeding times of *Onisimus* amphipods are not well defined. Some breeding occurs in September or October, as several researchers reported finding male *O. glacialis* in varying stages of breeding condition at this time (Dunbar 1942, Dunbar 1954, Steele 1961).

In Simpson Lagoon, males collected in September showed some lengthening of antennae, a breeding characteristic of *Onisimus* amphipods. However, females collected at this time showed no brood pouch development or egg production. Samples collected from Simpson Lagoon two months later in November 1978 contained numerous gravid *O. glacialis* females (10-12 mm in length) indicating that *O. glacialis* breed in late September or early October. The eggs produced in late fall are brooded during the winter. It is interesting to note that our collections from late winter (March-April 1978) and early spring (June 1978) contained no females brooding young. It is possible that the release of young occurred either prior to the middle of April, or in areas other than Simpson Lagoon.

Although a major breeding in the Simpson Lagoon population appears to occur in the fall, some breeding must also occur in the summer. Small individuals (2-3 mm) were collected in November 1978. The young must have been recently released. In August Feder and Schamel (1976) found *O. glacialis* with empty brood pouches in Prudhoe Bay. Although most *O. glacialis* appear to breed in the fall, this species appears to be an undeterminate breeder continually breeding and releasing young. This phenomenon has been reported for other arctic amphipods (*Stegocephalus inflatus*, *Pontoporeia femorata* and *Anonyx nugax*) by Steele (1961).

Fecundity. Gravid *O. glacialis* (10-15 mm in length) carrying 10 to 16 eggs (Table 20) in their brood pouches were collected in Simpson Lagoon during November. A detailed presentation of the relationship between size and fecundity awaits the complete analysis of the winter samples and will appear in the final report.

Table 22. Growth Rate (Total Length and Wet Weight) for *Onisimus glacialis* Collected in Simpson Lagoon 8 July-23 September 1978.

	First Year Class					Second Year Class				
Date	Day Number	$\bar{x}$ Length (mm)	S.D.	Wet[*] Weight (mg)	n	Day Number	$\bar{x}$ Length (mm)	S.D.	Wet[*] Weight (mg)	n
8 July	1[*]	3.4	0.9	1.2	38	366[†††]	9.1	1.2	15.5	22
19 July	11	4.0	0.7	1.9	488	377	9.0	0.9	15.1	201
3 August	26	4.0	0.8	1.9	319	392	8.3	1.0	12.3	55
18 August	41	4.4	0.7	2.4	463	407	8.6	1.0	13.4	80
30 August	53	5.2	1.0	3.7	181	419	9.7	1.4	18.3	75
14 September	68	5.7	0.7	4.7	172	439	10.9	2.8	24.6	26
23 September	77	5.1	0.8	3.5	123	443	9.7	1.4	18.3	34

Best-fit Equation

First Year Class:

Total length = 0.027 (day) + 3.49
$r = 0.93$ $P<0.05$

Wet weight = 0.04 (day) + 1.21
$r = 0.90$ $P<0.05$

Second Year Class:

No significant best-fit equation could be determined for this data.

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[*] Wet weight was calculated using a total length-wet weight relationship shown in Appendix 3.

[†] Day 1 corresponds to the first collection date (8 July).

[††] Day 366 assumes these *O. glacialis* are one year older than Day 1 individuals.

Other Amphipod Species

Apherusa glacialis (Hansen). This pelagic amphipod is circumpolar, arctic-subarctic, and usually occurs in the upper portions of the water column (Dunbar 1957). It is considered to be a member of the ice associated amphipod community in the Soviet Arctic and the Canadian High Arctic (Sekerak *et al.* 1976; Golikov and Averincev 1978). It occurs in large numbers in the summer on floe ice, but it also occurs in the water column nearshore and offshore (to depths of at least 300 m) (Shoemaker 1955).

Pontoporeia affinis (Lindstrøm). *Pontoporeia affinis* is a widespread northern species, although it is not circumpolar in distribution. It is found in shallow brackish marine habitats and freshwater lakes in Europe and North America. In northern marine waters, individuals do not breed until the winter of their second year, and young are released in the following spring. In other areas, such as the Baltic Sea, a one-year life-cycle has been recorded; the shorter cycle presumed to have been a consequence of the higher environmental temperature (Segerstrale 1967). *P. affinis* is considered, by Segerstrale (1973), to be a deposit feeder; this author recorded it feeding heavily on bivalve sprat in the Baltic Sea.

Haliragas mixtus (Stephenson). This species was first described by Stephenson (1931) in eastern Greenland. Dunbar (1954) found *H. mixtus* in Ungava Bay and it was also captured in plankton samples taken in Frobisher Bay (Steele 1961). The species appears to be Arctic in distribution although there are relatively few distribution records.

Gammarus setosus (Dementieva). This circumpolar species is predominantly carnivorous (Steele and Steele 1970) and generally inhabits intertidal zones and shallow water (Ellis and Wilce 1961).

It is euryhaline and can survive in low-salinity waters (Steele and Steele 1970). Only one brood is produced each year and young are released in early spring when plant production begins (Steele and Steele 1970). Broad (1977) speculates that this species feeds mainly on diatoms and organic detritus.

Parathemisto libellula (Lichenstein). This species is circumpolar and is found in the Pacific as well, but only in the Bering and Okhotsk Seas. It is predominantly carnivorous but also ingests some vegetable matter (Dunbar 1946). *P. libellula* is the largest member of the genus (up to 60 mm long) and is found in waters as deep as 2500 m (Shoemaker 1955). It has a two-year life-cycle in arctic waters and spawns from September to May or June (Dunbar 1957). The young are brooded in the female's marsupium and are released when they reach a length of 2-3 mm.

CONCLUSIONS

1. Invertebrate Use of Simpson Lagoon

Late winter (March-June) sampling showed that amphipods (particularly *Onisimus glacialis*) and isopods were common in Simpson Lagoon while it was covered with ice 2 m thick. Mysids, in contrast, were not found in the lagoon at this time but appeared to repopulate the lagoon during spring breakup, presumably from offshore marine waters.

Drop net and Faber net samples showed *Mysis litoralis*, *M. relicta* and *Onisimus glacialis* to be the most abundant species of epibenthic organisms in Simpson Lagoon during the open-water period. Densities of these organisms varied considerably in time and space in both 1977 and 1978.

2. Trophic Relationships

Food available (g/m^2) for key vertebrate consumers, in the form of mysids and amphipods, was an order of magnitude less in 1978 than in 1977. In 1978 the total biomass of these key invertebrates slowly declined during late summer after it reached a peak in July. In 1977 the biomass generally increased throughout the open-water period. Growth and predation could not account for the flucuations in biomass recorded during the open-water season. It appears that immigration plays an important role in keeping the biomass in the lagoon at high levels.

3. Life History Information

Mysids grew rapidly during the open-water period: *M. litoralis* (2.5 mm/30 days) and *M. relicta* (2.2 mm/30 days), while *Onisimus glacialis* (0.7 mm/30 days) grew more slowly. However, the growth rates from *M. litoralis* and *M. relicta* decreased during winter, but the rate for *O. glacialis* was the same throughout the year.

M. litoralis, M. relicta and *O. glacialis* appeared to live as long as three years. Breeding appears to occur in late fall and early winter; young are brooded until the following spring.

First-year individuals formed the dominant groups for all three species in the lagoon during the open-water season; thus Simpson Lagoon may act as a nursery area for these key invertebrates.

RECOMMENDED FURTHER RESEARCH

1. The importance of immigration into and emigration out of the lagoon of epibenthic invertebrates has been shown to be of great importance in maintaining the levels of food available to higher consumers (fish and birds). More refined estimates

of the rates of these movements in relation to currents would enhance the ability to determine the effects of particular types of development (i.e., causeway and artificial island construction).

2. Laboratory investigations on the salinity-temperature preferences vs necessities for *Mysis litoralis*, *M. relicta* and *Onisimus glacialis* and the effects of temperature on the rapid growth reported during the open-water season for the two mysid species would help to determine if the warmer brackish waters of barrier island-lagoon systems are critical habitats for these organisms.

SUMMARY OF 4TH QUARTER OPERATIONS

Fourth quarter operations consisted of data analysis and the preparation of this annual report.

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APPENDICES

Appendix 1. Estimates of Total Length and Wet Weight[1] for *Mysis litoralis* for Different Length Intervals.

Length Interval		Number of Individuals	Partial Length mm		Estimated Total Length[2] mm	Wet Weight[1] mg		Estimated Wet Weight[2] mg
mm	mid-point		Mean	SD		Mean	SD	
0-2	1	-	-	-	-	-	-	-
2-4	3	50	0.3	0.0	2.8	0.8	0.1	0.4
4-6	5	50	0.5	0.0	4.1	1.0	0.2	1.5
6-8	7	66	1.0	0.1	7.3	3.4	0.8	3.4
8-10	9	50	1.2	0.2	8.6	5.1	0.9	6.3
10-12	11	50	1.5	0.2	10.6	7.2	1.2	10.3
12-14	13	10	2.1	0.3	14.4	13.6	3.0	15.5
14-16	15	32	2.3	0.4	15.7	23.6	5.4	22.0
16-18	17	30	2.5	0.4	17.0	29.9	5.0	29.8
18-20	19	48	2.9	0.3	19.6	33.2	4.5	39.1
20-22	21	51	3.2	0.3	21.6	49.4	3.2	49.9
22-24	23	50	3.3	0.4	22.2	69.9	3.2	62.4
24-26	25	46	4.0	0.2	26.7	80.9	2.6	76.5
26-28	27	48	4.0	0.3	26.7	106.0	2.5	92.3
28-30	29	21	4.2	0.4	28.0	128.5	0.5	109.9
30-32	31	8	4.4	0.5	29.3	143.0	0.0	129.3
32-34	33	2	5.0	0.0	33.2	154.0	0.0	150.6

Best-fit Equations	Estimated Total Length=6.4739 (Partial Length)+0.8442	Estimated Wet Weight=0.0294 $(\text{Total Length})^{2.4426}$
	$r=0.9955 \quad P<0.001$	$r=0.9905 \quad P<0.001$

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[1] Wet weights used in calculations are formalin preserved wet weights.

[2] Estimated values determined using best-fit equations and mid-point of length interval.

Appendix 2. Estimates of Total Length and Wet Weight[1] for *Mysis relicta* for Different Length Intervals.

Length Interval		Number of Individuals	Partial Length mm		Estimated Total Length[2] mm	Wet Weight[1] mg		Estimated Wet Weight[1, 2] mg
mm	mid-point		Mean	SD		Mean	SD	
0-2	1	-	-	-	-	-	-	-
2-4	3	33	0.3	0.0	2.6	0.8	0.3	0.6
4-6	5	42	0.9	0.1	6.6	1.5	0.6	1.8
6-8	7	50	1.0	0.0	7.2	3.6	0.2	3.9
8-10	9	51	1.3	1.0	9.2	5.3	0.8	7.1
10-12	11	47	1.5	0.1	10.5	8.5	1.7	11.2
12-14	13	43	1.8	0.3	12.5	16.2	2.6	16.5
14-16	15	50	2.0	0.1	13.8	21.1	0.6	22.9
16-18	17	49	2.3	0.2	15.8	33.1	6.7	30.6
18-20	19	50	3.0	0.2	20.4	49.4	3.5	39.6
20-22	21	50	3.1	0.4	21.1	62.2	5.9	49.9
Best-fit Equations			Estimated Total Length=6.5982 (Partial Length)+0.6512 $r=0.9878$ $P<0.001$			Estimated Wet Weight=0.0442 $(\text{Total Length})^{2.3087}$ $r=0.9890$ $P<0.001$		

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[1] Wet weights used in calculations are formalin preserved wet weights.

[2] Estimated values determined using best-fit equations and mid-point of length interval.

Appendix 3. Estimates of Total Length and Wet Weight[1] for *Onisimus glacialis* for Different Length Intervals.

Length Interval mm	mid-point	Number of Individuals	Partial Length mm Mean	SD	Estimated Total Length[2] mm	Wet Weight[1] mg Mean	SD	Estimated Wet Weight[2] mg
0-2	1	-	-	-	-	-	-	-
2-4	3	50	1.4	0.2	3.7	1.2	0.1	0.9
4-6	5	50	1.8	0.5	4.6	1.7	0.4	3.4
6-8	7	50	2.6	0.5	6.4	11.5	1.0	7.9
8-10	9	50	3.8	0.4	9.1	15.2	2.0	15.1
10-12	11	50	4.7	0.4	11.1	25.7	2.5	25.2
12-14	13	56	5.6	0.5	13.1	38.6	2.9	38.7

Best-fit Equations

Estimated Total Length=2.2313 (Partial Length)+0.5995

$r=0.9925$ $P<0.001$

Estimated Wet Weight=0.0544 (Total Length)$^{2.5597}$

$r=0.9667$ $P<0.01$

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[1] Wet weights used in calculations are formalin preserved wet weights.

[2] Estimated values determined using best-fit equations and mid-point of length interval.

Appendix 4. Estimates of Total Length and Wet Weight[1] for *Pontoporeia affinis* for Different Length Intervals.

Length Interval		Number of Individuals	Partial Length mm		Estimated Total Length[2] mm	Wet Weight[1] mg		Estimated Wet Weight[2] mg
mm	mid-point		Mean	SD		Mean	SD	
0-2	1	1	0.5	0.0	1.6	1.0	0.0	0.6
2-4	3	31	0.7	0.3	2.1	1.2	0.5	2.6
4-6	5	44	1.9	0.5	5.3	4.5	2.0	4.9
6-8	7	27	2.5	0.6	6.9	6.7	3.5	7.5
8-10	9	29	3.4	0.6	9.3	13.1	4.5	10.4
10-12	11	5	3.9	0.7	10.7	18.0	4.4	13.4
Best-fit Equations			Estimated Total Length=2.6674 (Partial Length)+0.2652 $r=0.9896$ $P<0.001$			Estimated Wet Weight=0.6395 (Total Length)$^{1.2687}$ $r=0.9322$ $P<0.01$		

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[1] Wet weights used in calculations are formalin preserved wet weights.

[2] Estimated values determined using best-fit equations and mid-point of length interval.

Appendix 5. Estimates of Total Length and Wet Weights[1] for *Apherusa glacialis* and *Halirages mixtus* for Different Length Intervals.

Length Interval mm	Mid-point	Number of Individuals	Partial Length mm Mean	Partial Length mm SD	Estimated Total Length mm[2]	Wet Weight mg[1] Mean	Wet Weight mg[1] SD	Estimated Wet Weight mg[2]
0-2	1	-	-	-	-	-	-	0.1
2-4	3	9	0.7	0.2	3.5	1.0	0.0	0.8
4-6	5	12	1.0	0.2	5.0	1.8	0.8	2.5
6-8	7	50	1.4	0.3	7.0	5.4	1.8	5.0
8-10	9	46	1.6	0.3	8.0	8.2	1.4	8.5
10-12	11	4	2.3	0.3	11.6	14.5	4.4	13.0
Best fit Equations		Estimated Total Length=5.0667(Partial length)$^{-0.0933}$ $r = 0.9812$		$p < 0.01$		Estimated Wet Weight=0.0832(Total length)$^{2.1070}$ $r = 0.9845$		$p < 0.01$

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[1] Wet Weights used in calculations are formalin preserved wet weights.

[2] Estimated values determined using best-fit equations and mid-point of length interval.

[3] The same relationships are used for *Apherusa glacialis* and *Halirages mixtus* as the two species have identical length-weight relationships and data insufficient to treat each separately.

Appendix 6. Estimates of Total Length and Wet Weights[1] for *Gammarus setosus* for Different Length Intervals.

Length Interval mm	mid-point	Number of Individuals	Partial Length mm $\bar{x}$	SD	Estimated Total Length[2] mm	Wet Weight[1] mg $\bar{x}$	SD	Estimated Wet Weight[1,2] mg
0-2	1	-	-	-	-	-	-	0.05
2-4	3	21	0.5	0.1	3.2	1.2	0.5	0.8
4-6	5	53	0.9	0.2	5.2	1.5	0.6	2.8
6-8	7	16	1.4	0.3	7.8	7.0	5.1	6.5
8-10	9	26	1.7	0.3	9.3	12.8	4.6	12.2
10-12	11	15	1.8	0.3	9.8	17.9	6.8	20.1
12-14	13	7	2.5	0.2	13.4	29.4	4.8	30.6
14-16	15	10	2.6	0.5	13.8	41.3	8.6	43.8
16-18	17	1	3.4	0.0	18.0	73.0	0.0	59.9
18-20	19	24	3.5	0.4	18.4	84.7	31.9	79.2
20-22	21	-	-	-	-	-	-	101.7
22-24	23	3	4.7	0.8	24.6	118.7	9.6	127.7
24-26	25	2	4.5	0.0	23.6	172.0	17.0	157.4

Best-Fit Equations	Estimated Total length	Estimated Weight
	Estimated Total length = 5.1022 (Partial length) + 0.6080	Weight = $0.0497 (\text{Total length})^{2.5045}$
	$r = 0.9910 \quad p < 0.001$	$r = 0.9882 \quad p < 0.001$

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[1] Wet weights used in calculations are formalin preserved wet weights.

[2] Estimated values determined using best-fit equations and mid-point of length interval.

Appendix 7. Estimated Total Length and Wet Weight[1] for *Parathemisto*[2] sp. for Different Length Intervals.

Length mm	Interval mid-point	Number of Individuals	Partial Length mm $\bar{x}$	Partial Length mm SD	Estimated Total Length[3] mm	Wet Weight[1] mg	Wet Weight[1] mg SD	Estimated Wet Weight[3] mg
0-2	1	-	-	-	-	-	-	0.1
2-4	3	5	0.9	0.2	3.6	1.0	0.0	0.8
4-6	5	48	1.3	0.2	5.1	3.7	4.3	2.9
6-8	7	65	1.7	0.2	6.6	5.1	2.0	6.5
8-10	9	30	2.3	0.3	8.8	8.7	2.9	12.1
10-12	11	29	2.8	0.2	10.7	14.6	5.3	19.8
12-14	13	6	3.4	0.5	12.9	26.5	3.8	29.7
14-16	15	3	4.0	0.3	15.2	47.0	8.9	42.2
16-18	17	4	4.5	0.5	17.1	60.3	16.7	57.3
18-20	19	2	5.1	0.6	19.3	97.0	14.1	75.1
20-22	21	5	5.5	0.3	20.8	110.4	20.0	96.0

Best-fit Equations

Estimated Total Length = 3.7535 (Partial length) + 0.1765 $r = 0.9988$ $p < 0.001$

Estimated wet weight = 0.0564 $(\text{Total length})^{2.4436}$ $r = 0.9890$ $p < 0.001$

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[1] Wet weights used in calculations are formalin preserved wet weights.

[2] Mostly *Parathemisto libellula* plus a few *P. abyssorum*.

[3] Estimated values determined using best-fit equations and mid-point of length interval.

Appendix 8. Relationship of Total Length to Body Wet Weight[1] and Body Dry Weight[1] for *Cyrtodaria kurriana* of Different Length Intervals.

Total Length Interval mm	Mid-point	Number of Individuals	Total length mm		Body Wet Weight mg		Body Dry Weight mg	
			$\bar{x}$	SD	$\bar{x}$	SD	$\bar{x}$	SD
0-2	1	-	-	-	-	-	-	-
2-4	3	5	4.0	0.0	2.2	1.1	1.2	0.4
4-6	5	12	5.2	0.7	3.8	2.1	1.3	0.7
6-8	7	24	7.1	0.7	10.8	5.2	2.3	1.5
8-10	9	11	9.1	0.7	30.7	12.2	4.3	2.0
10-12	11	17	11.4	0.5	61.9	17.9	9.3	3.8
12-14	13	22	13.5	0.4	97.6	22.1	13.8	6.8
14-16	15	12	15.8	0.4	159.9	41.7	34.2	16.3
16-18	17	6	17.3	0.5	266.2	37.6	61.8	17.3
18-20	19	3	19.7	0.6	345.0	75.1	62.0	14.0

Best-fit Equations

$\text{Body Wet Weight} = 0.0194\ (\text{Total length})^{3.2930}$ $r = 0.9980$ $p < 0.001$

$\text{Body Dry Weight} = 0.0152\ (\text{Total Length})^{2.7387}$ $r = 0.9721$ $p < 0.001$

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[1] Wet weight and Dry weight determined from fresh (frozen) and formalin preserved material.

Appendix 9. Abundance (No./100m^3) and Biomass (mg ash free dry weight/100m^3) of Important Species of Epibenthic Invertebrates Collected in the Water Column in Faber Net Samples in Simpson Lagoon and Nearshore Areas, 10 July-23 September 1978. (N=3 for each station-day).

		10 July		22 July		4 August		17 August		30 August		14 September		23 September	
		Abun.	Biomass	Abun.	Biomass	Abun.	Biomass	Abun.	Biomass	Abun.	Biomass	Abun.	Biomass	Abun.	Biomass
Station 2 Water Column															
Mysis litoralis	$\bar{x}$	305.3	93.9	25.2	9.4	1.4	0.8	95.8	71.0	96.0	99.5	317.9	403.8	48.8	56.0
	sd	156.9	62.9	25.6	9.7	1.4	1.0	44.8	30.0	31.3	34.7	120.1	170.9	27.7	54.6
Mysis relicta	$\bar{x}$	56.4	13.0	32.2	9.6	0.8	0.5	21.5	13.0	8.0	7.2	89.7	110.4	2242.8	2324.1
	sd	41.3	10.7	7.1	1.5	0.7	0.5	7.6	6.1	5.8	5.8	25.4	42.6	705.1	714.8
Mysid spp.	$\bar{x}$	25.8	1.1	26.8	3.9	-	-	2.0	0.4	0.5	0.4	7.5	5.2	34.6	37.8
	sd	13.2	0.5	3.8	1.1	-	-	2.0	0.3	0.9	0.7	6.5	5.5	40.5	34.7
Onisimus glacialis	$\bar{x}$	18.5	3.0	13.4	3.7	11.9	5.3	28.2	15.0	36.2	16.3	140.0	34.0	141.6	33.1
	sd	1.6	0.6	2.2	1.5	5.5	3.2	3.4	4.9	32.0	14.6	47.8	6.6	54.5	15.0
Gammarus setosus	$\bar{x}$	-	-	-	-	-	-	-	-	-	-	2.2	3.1	-	-
	sd	-	-	-	-	-	-	-	-	-	-	3.8	5.4	-	-
Apherusa glacialis	$\bar{x}$	-	-	-	-	-	-	6.0	2.3	9.5	9.6	-	-	38.1	34.5
	sd	-	-	-	-	-	-	3.6	1.7	5.1	4.8	-	-	12.0	25.7
Halirages mixtus	$\bar{x}$	-	-	-	-	-	-	1.9	1.2	4.9	1.5	11.5	8.6	69.0	23.2
	sd	-	-	-	-	-	-	0.2	1.0	0.5	1.0	12.8	10.1	38.2	5.5
Pontoporeia affinis	$\bar{x}$	9.3	4.5	6.0	2.9	0.5	0.2	-	-	0.6	0.5	-	-	-	-
	sd	4.9	2.2	2.0	0.7	0.8	0.4	-	-	1.0	0.9	-	-	-	-
Parathemisto spp.	$\bar{x}$	-	-	-	-	-	-	0.6	0.3	6.1	13.3	1.0	0.1	4.6	40.3
	sd	-	-	-	-	-	-	1.1	0.5	4.9	9.1	1.7	0.2	5.5	40.8
Amphipod spp.	$\bar{x}$	3.7	1.1	-	-	0.5	0.1	2.5	0.6	25.5	5.8	3.5	0.5	64.2	11.1
	sd	2.1	0.4	-	-	0.8	0.2	2.2	0.5	12.7	4.3	6.1	0.9	15.7	7.8

Appendix 9 (continued).

		10 July		22 July		4 August		17 August		30 August		14 September		23 September	
		Abun.	Biomass	Abun.	Biomass	Abun.	Biomass	Abun.	Biomass	Abun.	Biomass	Abun.	Biomass	Abun.	Biomass
Station 3 Water Column															
Mysis litoralis	$\overline{x}$	339.8	184.6	20.9	10.4	-	-	9.6	7.2	17.1	20.4	3.3	4.1	41.1	53.3
	sd	224.9	13.9	23.3	12.2	-	-	9.1	7.9	18.2	19.8	5.8	7.1	17.0	27.8
Mysis relicta	$\overline{x}$	212.5	46.7	8.2	2.3	-	-	5.4	3.7	1.1	0.4	3.0	3.1	398.3	539.2
	sd	52.7	11.2	5.3	0.9	-	-	4.8	2.8	1.1	0.5	4.0	4.2	19.8	31.1
Mysid spp.	$\overline{x}$	20.5	1.9	16.5	2.5	-	-	0.6	0.2	-	-	1.3	0.8	13.4	4.4
	sd	18.4	2.6	12.5	2.4	-	-	1.0	0.4	-	-	3.1	1.4	18.6	7.4
Onisimus glacialis	$\overline{x}$	27.5	1.7	4.0	0.9	8.0	2.9	13.2	9.6	6.8	3.4	54.8	19.8	25.7	6.2
	sd	1.3	0.9	2.9	0.6	3.4	0.1	7.5	4.3	3.2	2.2	33.9	12.5	29.4	7.6
Gammarus setosus	$\overline{x}$	-	-	-	-	-	-	-	-	1.8	0.6	0.4	0.03	-	-
	sd	-	-	-	-	-	-	-	-	1.7	0.9	0.8	0.06	-	-
Apherusa glacialis	$\overline{x}$	-	-	0.3	0.1	-	-	24.2	13.9	22.6	9.9	159.8	110.4	73.9	73.1
	sd	-	-	0.5	0.2	-	-	13.2	10.0	5.9	6.7	67.8	69.9	6.2	8.0
Halirages mixtus	$\overline{x}$	-	-	-	-	-	-	4.2	1.7	1.6	0.9	3.4	2.4	7.5	6.8
	sd	-	-	-	-	-	-	2.1	1.0	2.8	1.6	3.3	2.5	1.0	2.1
Pontoporeia affinis	$\overline{x}$	1.4	0.8	1.7	0.8	-	-	-	-	-	-	-	-	-	-
	sd	0.6	0.5	2.2	1.0	-	-	-	-	-	-	-	-	-	-
Parathemisto spp.	$\overline{x}$	-	-	-	-	-	-	0.6	0.6	1.1	1.4	3.1	2.6	3.9	15.9
	sd	-	-	-	-	-	-	1.0	1.0	1.1	1.3	2.8	2.7	3.3	14.2
Amphipod spp.	$\overline{x}$	14.7	2.9	0.3	0.04	-	-	9.6	7.1	7.2	7.6	1.3	0.2	-	-
	sd	5.0	2.4	0.5	0.07	-	-	4.5	5.8	5.1	5.6	2.2	0.3	-	-

Appendix 9 (continued)

		10 July		22 July		4 August		17 August		30 August		14 September		23 September	
		Abun.	Biomass	Abun.	Biomass	Abun.	Biomass	Abun.	Biomass	Abun.	Biomass	Abun.	Biomass	Abun.	Biomass
Station 4 Water Column															
Mysis litoralis	$\bar{x}$	367.9	117.5	15.2	7.0	2.2	2.6	103.9	92.3	18.8	22.3	5.8	7.6	157.2	222.4
	sd	304.8	87.5	15.1	7.7	0.8	2.4	150.5	135.6	11.9	9.7	7.5	10.0	73.4	116.6
Mysis relicta	$\bar{x}$	183.7	50.4	2.0	0.8	-	-	3.3	3.0	20.5	19.4	0.8	0.9	92.3	134.7
	sd	158.4	35.7	1.8	0.7	-	-	2.9	4.2	34.2	32.4	1.4	1.5	65.1	93.3
Mysid spp.	$\bar{x}$	80.2	5.6	4.9	1.5	-	-	1.6	0.5	0.5	0.3	-	-	3.5	1.4
	sd	37.3	0.5	2.5	1.9	-	-	2.7	0.9	2.0	0.5	-	-	3.1	2.2
Onisimus glacialis	$\bar{x}$	293.5	36.2	10.8	2.1	4.9	1.8	22.9	11.1	31.5	14.9	51.6	15.7	26.6	7.3
	sd	70.1	26.1	8.0	1.7	4.3	2.3	15.1	8.7	8.5	1.3	12.2	3.9	3.3	1.8
Gammarus setosus	$\bar{x}$	1.6	11.0	-	-	-	-	1.8	1.3	-	-	2.2	1.2	1.0	0.09
	sd	2.8	19.0	-	-	-	-	3.1	2.3	-	-	0.4	0.7	1.7	0.1
Apherusa glacialis	$\bar{x}$	-	-	-	-	-	-	20.9	19.0	218.3	173.1	43.9	36.2	86.2	78.0
	sd	-	-	-	-	-	-	14.7	13.7	124.0	62.5	28.3	6.2	20.1	15.6
Halirages mixtus	$\bar{x}$	-	-	-	-	-	-	8.8	3.0	2.8	1.6	13.8	7.7	11.1	8.1
	sd	-	-	-	-	-	-	7.0	2.4	2.6	1.9	10.1	6.7	1.1	0.4
Pontoporeia affinis	$\bar{x}$	-	-	0.6	0.3	-	-	-	-	-	-	-	-	-	-
	sd	-	-	1.1	0.5	-	-	-	-	-	-	-	-	-	-
Parathemisto spp.	$\bar{x}$	-	-	-	-	-	-	0.9	1.6	4.8	9.1	22.7	58.4	6.3	52.9
	sd	-	-	-	-	-	-	1.6	2.8	3.0	8.0	5.3	34.9	5.2	43.1
Amphipod spp.	$\bar{x}$	9.1	1.6	0.3	0.05	0.5	0.6	31.6	10.4	15.5	8.6	28.2	17.9	33.3	11.7
	sd	4.8	1.1	0.5	0.08	0.8	1.1	43.3	10.7	4.9	3.3	29.7	9.9	17.3	2.4

Appendix 9 (continued)

		10 July		22 July		4 August		17 August		30 August		14 September		23 September*	
		Abun.	Biomass	Abun.	Biomass	Abun.	Biomass	Abun.	Biomass	Abun.	Biomass	Abun.	Biomass	Abun.	Biomass
<u>Station 7 Water Column</u>															
Mysis litoralis	$\bar{x}$	16.0	13.6	136.7	94.6	12.3	5.2	2.7	4.1	0.4	0.2	-	-		
	sd	11.3	18.7	103.2	42.7	3.9	3.5	4.7	7.2	0.7	0.3	-	-		
Mysis relicta	$\bar{x}$	19.6	18.2	57.1	29.3	0.6	2.3	-	-	-	-	-	-		
	sd	19.0	27.7	60.8	37.2	1.1	4.0	-	-	-	-	-	-		
Mysid spp.	$\bar{x}$	1.3	0.08	34.7	4.8	1.8	0.6	-	-	-	-	-	-		
	sd	2.3	0.1	57.3	5.3	2.0	0.9	-	-	-	-	-	-		
Onisimus glacialis	$\bar{x}$	46.3	4.5	23.7	4.6	1.5	0.9	0.7	0.1	0.8	0.7	1.6	0.7		
	sd	36.2	3.6	21.4	3.5	1.7	1.4	1.2	0.2	1.4	1.3	2.5	1.0		
Gammarus setosus	$\bar{x}$	0.3	0.03	0.3	0.02	0.5	1.9	-	-	-	-	-	-		
	sd	0.6	0.05	0.5	0.04	0.9	3.2	-	-	-	-	-	-		
Apherusa glacialis	$\bar{x}$	-	-	2.6	0.4	1.4	0.3	93.6	89.1	89.9	127.6	59.6	49.1		
	sd	-	-	2.6	0.5	1.3	0.3	21.2	22.5	81.1	117.8	63.5	34.3		
Halirages mixtus	$\bar{x}$	1.7	2.0	0.5	0.2	6.8	2.1	6.0	2.3	3.6	1.7	-	-		
	sd	1.3	3.1	0.5	0.2	9.1	3.2	9.0	2.9	3.2	1.5	-	-		
Pontoporeia affinis	$\bar{x}$	0.4	0.3	-	-	-	-	-	-	-	-	-	-		
	sd	0.6	0.6	-	-	-	-	-	-	-	-	-	-		
Parathemisto spp.	$\bar{x}$	-	-	-	-	2.2	1.9	1.2	0.5	24.5	26.9	3.6	2.9		
	sd	-	-	-	-	1.0	1.3	2.1	0.9	32.8	26.4	3.6	2.8		
Amphipod spp.	$\bar{x}$	3.8	2.4	1.7	0.8	1.4	1.4	3.1	4.9	0.5	0.6	-	-		
	sd	3.1	1.5	3.0	1.4	1.3	1.2	2.6	4.5	0.9	1.0	-	-		

*No sample was taken on 23 September 1978 at Station 7 due to ice conditions.

Appendix 10. Abundance (No./m^2) and Biomass (mg ash-free dry weight/m^2) of Important Species of Epibenthic Invertebrates Collected Near the Bottom in Drop Net Samples in Simpson Lagoon and Nearshore Areas, 8 July-23 September 1978. (N=5 for each station-day.)

		8 July		19 July		3 August		18 August		30 August		14 September		23 September	
		Abun.	Biomass	Abun.	Biomass	Abun.	Biomass	Abun.	Biomass	Abun.	Biomass	Abun.	Biomass	Abun.	Biomass
Station 1 Bottom															
Mysis litoralis	$\bar{x}$	193.3	38.2	38.0	16.14	148.0	88.7	18.0	28.4	4.0	4.0	3.0	3.6	-	-
	sd	126.6	23.1	34.7	10.0	87.6	53.5	19.6	36.0	4.2	3.7	4.5	5.4	-	-
Mysis relicta	$\bar{x}$	101.7	38.8	5.0	1.3	143.0	87.6	21.0	21.1	10.0	12.6	166.0	244.7	10.2	145.9
	sd	93.0	30.6	8.7	2.3	49.6	32.6	24.8	25.2	6.1	10.7	98.1	136.1	68.3	82.4
Mysid spp.	$\bar{x}$	38.3	5.9	4.0	1.2	9.0	1.5	9.0	4.7	3.0	1.96	2.0	11.4	-	-
	sd	27.5	7.4	6.5	2.3	4.2	0.78	4.2	2.3	4.5	3.0	2.7	15.7	-	-
Onisimus glacialis	$\bar{x}$	28.3	25.4	72.0	122.8	44.0	36.2	4.0	2.2	27.0	32.9	7.0	12.1	70.0	98.0
	sd	22.5	20.5	48.2	80.2	34.2	24.9	6.5	4.3	23.6	33.2	5.7	17.7	43.0	49.3
Pontoporeia affinis	$\bar{x}$	1.7	4.3	3.0	5.0	2.0	2.2	3.0	4.1	1.0	3.4	-	-	-	-
	sd	2.9	7.4	6.7	11.3	2.7	3.1	2.7	4.1	2.2	5.3	-	-	-	-
Halirages mixtus	$\bar{x}$	-	-	-	-	-	-	-	-	-	-	1.0	0.3	2.0	0.2
	sd	-	-	-	-	-	-	-	-	-	-	2.2	.76	2.8	0.3
Apherusa glacialis	$\bar{x}$	-	-	-	-	-	-	-	-	-	-	-	-	-	-
	sd	-	-	-	-	-	-	-	-	-	-	-	-	-	-
Gammarus setosus	$\bar{x}$	-	-	4.0	18.1	-	-	-	-	-	-	-	-	-	-
	sd	-	-	8.9	40.6	-	-	-	-	-	-	-	-	-	-
Parathemisto spp.	$\bar{x}$	-	-	-	-	-	-	-	-	-	-	-	-	-	-
	sd	-	-	-	-	-	-	-	-	-	-	-	-	-	-
Amphipod spp.	$\bar{x}$	3.3	0.5	6.0	7.0	5.0	3.6	6.0	7.7	5.0	4.2	53.0	27.2	28.0	8.0
	sd	5.7	0.87	6.5	10.5	6.1	5.8	5.5	9.7	3.5	4.2	26.6	29.5	20.8	6.6

Appendix 10 (continued).

		8 July		19 July		3 August		18 August		30 August		14 September		23 September	
		Abun.	Biomass	Abun.	Biomass	Abun.	Biomass	Abun.	Biomass	Abun.	Biomass	Abun.	Biomass	Abun.	Biomass
Station 2 Bottom															
Mysis litoralis	$\bar{x}$	18.3	5.1	572.0	196.6	353.0	229.2	175.0	153.7	49.0	66.2	34.0	41.2	2.0	2.4
	sd	7.6	0.9	390.2	116.6	87.9	51.9	60.9	49.5	15.6	30.9	7.4	8.7	2.7	3.3
Mysis relicta	$\bar{x}$	40.0	29.6	75.0	62.0	13.0	16.3	4.0	11.5	13.0	24.4	123.0	164.3	92.0	117.7
	sd	32.8	36.4	35.7	41.0	9.1	12.3	4.2	11.6	9.1	12.9	66.6	76.1	19.2	23.1
Mysid spp.	$\bar{x}$	10.0	1.1	25.0	6.1	29.0	12.8	7.0	3.6	-	-	2.0	11.3	1.0	1.7
	sd	10.0	1.2	31.0	5.0	17.8	9.6	5.7	3.0	-	-	2.7	19.9	2.2	3.8
Onisimus glacialis	$\bar{x}$	45.0	65.5	14.0	16.5	79.0	81.9	81.0	87.6	45.0	96.9	59.0	80.2	37.0	43.0
	sd	34.6	58.2	6.5	10.6	23.8	22.2	29.0	34.0	7.9	44.7	37.3	56.3	18.6	29.9
Pontoporeia affinis	$\bar{x}$	3.3	2.2	1.0	1.8	2.0	2.2	17.0	18.7	-	-	1.0	0.8	-	-
	sd	5.8	3.9	2.2	4.1	2.7	3.1	15.7	18.5	-	-	2.2	1.9	-	-
Halirages mixtus	$\bar{x}$	-	-	-	-	-	-	4.0	1.3	-	-	8.0	7.7	-	-
	sd	-	-	-	-	-	-	8.9	2.8	-	-	7.6	1.1	-	-
Apherusa glacialis	$\bar{x}$	-	-	-	-	-	-	-	-	-	-	-	-	-	-
	sd	-	-	-	-	-	-	-	-	-	-	-	-	-	-
Gammarus setosus	$\bar{x}$	-	-	-	-	-	-	-	-	-	-	2.0	1.7	1.0	1.4
	sd	-	-	-	-	-	-	-	-	-	-	2.7	2.9	2.2	3.0
Parathemisto spp.	$\bar{x}$	-	-	-	-	-	-	-	-	-	-	-	-	-	-
	sd	-	-	-	-	-	-	-	-	-	-	-	-	-	-
Amphipod spp.	$\bar{x}$	13.3	14.9	1.0	0.9	23.0	26.7	37.0	24.5	22.0	8.9	33.0	21.7	51.0	16.3
	sd	14.4	23.7	2.2	2.0	9.7	24.4	22.2	24.7	14.4	9.9	25.6	30.3	48.3	18.4

Appendix 10 (continued).

		8 July		19 July		3 August		18 August		30 August		14 September		23 September	
		Abun.	Biomass	Abun.	Biomass	Abun.	Biomass	Abun.	Biomass	Abun.	Biomass	Abun.	Biomass	Abun.	Biomass
Station 3 Bottom															
Mysis litoralis	$\bar{x}$	12.0	13.3	98.7	181.3	121.0	89.1	471.0	426.1	38.0	34.5	17.0	20.9	23.0	29.1
	sd	7.6	15.3	54.5	102.3	66.4	47.7	217.8	184.9	7.6	14.6	13.0	15.8	13.5	13.8
Mysis relicta	$\bar{x}$	10.0	15,6	25.0	30.4	8.0	12.2	26.0	32.0	22.0	42.0	46.0	72.9	90.0	116.2
	sd	10.0	12.3	17.3	29.0	7.6	14.2	27.7	49.6	9.1	21.2	37.3	65.7	24.2	22.7
Mysid spp.	$\bar{x}$	-	-	10.0	7.5	-	-	21.0	9.9	-	-	-	-	3.0	3.6
	sd	-	-	7.1	12.7	-	-	24.6	11.8	-	-	-	-	2.7	3.5
Onisimus glacialis	$\bar{x}$	8.0	7.0	98.8	106.0	102.0	50.8	159.0	161.2	115.0	93.3	77.0	100.5	48.0	57.0
	sd	11.5	15.5	53.0	75.0	17.2	17.7	28.2	76.9	76.4	66.9	102.7	197.1	37.8	24.6
Pontoporeia affinis	$\bar{x}$	3.0	2.3	8.8	18.3	10.0	10.7	12.0	16.2	1.0	1.3	-	-	-	-
	sd	2.7	2.7	7.5	11.3	9.4	10.2	5.7	7.3	2.2	3.0	-	-	-	-
Halirages mixtus	$\bar{x}$	-	-	-	-	-	-	4.0	9.0	-	-	8.0	1.6	3.0	1.4
	sd	-	-	-	-	-	-	5.5	1.5	-	-	9.7	1.0	4.5	2.2
Apherusa glacialis	$\bar{x}$	-	-	-	-	2.0	0.7	-	-	-	-	5.0	2.0	-	-
	sd	-	-	-	-	4.5	1.5	-	-	-	-	5.0	1.9	-	-
Gammarus setosus	$\bar{x}$	-	-	-	-	1.0	4.9	-	-	-	-	-	-	-	-
	sd	-	-	-	-	2.2	10.9	-	-	-	-	-	-	-	-
Parathemisto spp.	$\bar{x}$	-	-	-	-	-	-	-	-	1.0	1.0	-	-	1.0	14.3
	sd	-	-	-	-	-	-	-	-	2.2	2.2	-	-	2.2	32.0
Amphipod spp.	$\bar{x}$	4.0	1.4	10.0	5.9	23.0	17.1	19.0	13.9	13.0	8.9	9.0	5.0	29.0	12.1
	sd	8.9	3.0	7.1	1.7	20.8	10.3	4.2	12.1	9.7	9.9	9.6	6.4	10.2	7.3

Appendix 10 (continued).

		8 July		19 July		3 August		18 August		30 August		14 September		23 September	
		Abun.	Biomass	Abun.	Biomass	Abun.	Biomass	Abun.	Biomass	Abun.	Biomass	Abun.	Biomass	Abun.	Biomass
Station 4 Bottom															
Mysis litoralis	$\bar{x}$	-	-	398.0	587.3	65.0	51.2	47.0	49.0	19.0	19.1	3.0	4.2	22.6	36.5
	sd	-	-	264.9	950.9	47.2	35.1	11.5	21.3	5.5	6.8	2.7	4.0	18.9	34.1
Mysis relicta	$\bar{x}$	-	-	68.0	78.9	3.0	3.2	24.0	35.2	22.0	26.3	-	-	16.0	30.9
	sd	-	-	36.2	90.8	4.5	4.5	17.8	27.8	9.7	19.6	-	-	15.6	33.6
Mysid spp.	$\bar{x}$	-	-	11.0	2.5	2.0	1.0	6.0	2.9	1.0	0.3	2.0	1.9	1.0	0.8
	sd	-	-	6.5	2.5	2.7	1.4	8.9	4.7	2.2	0.8	2.7	2.8	2.2	1.8
Onisimus glacialis	$\bar{x}$	-	-	523.0	555.3	112.0	76.3	271.0	195.9	35.0	68.5	88.0	86.2	12.0	25.2
	sd	-	-	348.0	602.1	66.7	51.7	173.4	94.7	29.4	24.8	136.3	114.0	9.1	18.0
Pontoporeia affinis	$\bar{x}$	-	-	1.0	1.3	-	-	8.0	3.4	-	-	-	-	-	-
	sd	-	-	2.2	3.0	-	-	9.1	4.4	-	-	-	-	-	-
Halirages mixtus	$\bar{x}$	-	-	-	-	-	-	-	-	10.0	3.3	-	-	-	-
	sd	-	-	-	-	-	-	-	-	11.2	2.7	-	-	-	-
Apherusa glacialis	$\bar{x}$	-	-	4.0	2.2	-	-	-	-	-	-	-	-	-	-
	sd	-	-	4.2	2.5	-	-	-	-	-	-	-	-	-	-
Gammarus setosus	$\bar{x}$	-	-	4.0	1.3	-	-	6.0	2.7	15.0	16.7	-	-	1.0	0.1
	sd	-	-	4.2	1.3	-	-	8.2	4.0	20.0	20.4	-	-	2.2	0.2
Parathemisto spp.	$\bar{x}$	-	-	-	-	-	-	-	-	-	-	-	-	-	-
	sd	-	-	-	-	-	-	-	-	-	-	-	-	-	-
Amphipod spp.	$\bar{x}$	-	-	28.0	20.2	20.0	7.6	42.0	6.5	42.0	9.8	64.0	30.6	26.0	15.7
	sd	-	-	17.5	10.9	12.2	7.8	23.6	2.4	27.9	7.1	69.0	27.7	13.9	10.7

Appendix 10 (continued).

		8 July		19 July		3 August		18 August		30 August		14 September		23 September	
		Abun.	Biomass	Abun.	Biomass	Abun.	Biomass	Abun.	Biomass	Abun.	Biomass	Abun.	Biomass	Abun.	Biomass
Station 5 Bottom															
Mysis litoralis	$\bar{x}$	5.0	2.0	18.0	10.8	76.0	50.5	39.0	33.9	7.0	6.1	-	-	1.0	1.2
	sd	8.7	3.4	17.2	11.7	62.4	39.5	29.0	27.4	9.7	8.8	-	-	2.2	2.7
Mysis relicta	$\bar{x}$	16.6	5.9	4.0	1.6	5.0	3.0	22.0	17.4	2.0	1.6	1.0	0.8	-	-
	sd	11.5	6.6	4.2	1.9	3.5	3.0	8.4	6.9	2.7	2.2	2.2	1.8	-	-
Mysid spp.	$\bar{x}$	-	-	5.0	0.3	9.0	2.3	2.0	0.8	-	-	1.0	1.4	-	-
	sd	-	-	4.5	0.76	7.4	2.3	2.7	1.5	-	-	2.2	3.1	-	-
Onisimus glacialis	$\bar{x}$	8.3	15.4	167.0	106.0	69.0	25.7	47.0	195.9	11.0	22.9	25.0	36.8	7.0	7.3
	sd	14.4	26.7	137.6	75.0	22.5	7.2	25.4	94.7	11.4	23.2	16.6	33.3	8.4	9.1
Pontoporeia affinis	$\bar{x}$	-	-	1.0	2.9	-	-	-	-	-	-	-	-	-	-
	sd	-	-	2.2	6.6	-	-	-	-	-	-	-	-	-	-
Halirages mixtus	$\bar{x}$	-	-	-	-	-	-	2.0	0.7	-	-	-	-	-	-
	sd	-	-	-	-	-	-	4.5	1.5	-	-	-	-	-	-
Apherusa glacialis	$\bar{x}$	-	-	-	-	-	-	-	-	-	-	-	-	-	-
	sd	-	-	-	-	-	-	-	-	-	-	-	-	-	-
Gammarus setosus	$\bar{x}$	-	-	-	-	1.0	1.4	-	-	-	-	-	-	1.0	0.1
	sd	-	-	-	-	2.2	3.0	-	-	-	-	-	-	2.2	0.2
Parathemisto spp.	$\bar{x}$	-	-	-	-	-	-	-	-	-	-	1.0	11.2	-	-
	sd	-	-	-	-	-	-	-	-	-	-	2.2	25.0	-	-
Amphipod spp.	$\bar{x}$	1.7	0.27	1.0	0.5	51.0	16.5	89.0	13.9	20.0	10.3	15.0	8.6	6.0	1.7
	sd	2.9	0.5	2.2	1.0	32.1	22.0	57.5	8.3	7.9	7.2	11.2	9.8	5.5	1.7

Appendix 10 (continued).

		8 July		19 July		3 August		18 August		30 August		14		23 September	
		Abun.	Biomass	Abun.	Biomass	Abun.	Biomass	Abun.	Biomass	Abun.	Biomass	Abun.	Biomass	Abun.	Biomass
Station 6 Bottom															
Mysis litoralis	$\bar{x}$	497.0	395.2	1.0	0.4	379.0	267.4	6.4	58.7	4.0	3.5	-	-	1.0	1.2
	sd	487.0	563.1	2.2	0.8	287.0	215.0	9.6	7.3	4.2	4.98	-	-	2.2	2.7
Mysis relicta	$\bar{x}$	420.0	193.4	2.0	0.5	5.0	10.8	-	-	-	-	14.0	3.3	22.0	31.3
	sd	393.8	196.0	2.2	1.0	7.1	20.0	-	-	-	-	28.6	26.2	16.8	29.0
Mysid spp.	$\bar{x}$	-	-	-	-	44.0	13.1	8.0	5.6	-	-	4.0	3.0	-	-
	sd	-	-	-	-	51.9	16.6	4.5	7.6	-	-	8.9	6.7	-	-
Onisimus glacialis	$\bar{x}$	74.0	56.4	75.0	37.5	27.0	31.0	6.0	8.9	4.0	9.2	10.0	77.3	15.0	33.0
	sd	45.6	56.2	42.9	45.1	20.8	31.9	5.5	9.4	4.2	17.1	6.1	102.5	7.1	29.6
Pontoporeia affinis	$\bar{x}$	1.0	4.9	-	-	1.0	0.9	-	-	-	-	-	-	-	-
	sd	2.2	11.0	-	-	2.2	2.0	-	-	-	-	-	-	-	-
Halirages mixtus	$\bar{x}$	-	-	-	-	-	-	1.0	0.3	-	-	1.0	0.3	-	-
	sd	-	-	-	-	-	-	2.2	0.3	-	-	2.2	0.8	-	-
Apherusa glacialis	$\bar{x}$	-	-	4.0	2.2	-	-	-	-	-	-	-	-	-	-
	sd	-	-	4.2	2.5	-	-	-	-	-	-	-	-	-	-
Gammarus setosus	$\bar{x}$	4.0	18.1	-	-	-	-	1.0	-	-	-	-	-	-	-
	sd	8.9	40.6	-	-	-	-	2.2	-	-	-	-	-	-	-
Parathemisto spp.	$\bar{x}$	-	-	-	-	-	-	-	-	-	-	-	-	-	-
	sd	-	-	-	-	-	-	-	-	-	-	-	-	-	-
Amphipod spp.	$\bar{x}$	2.0	0.6	6.0	2.7	24.0	1.5	16.0	2.3	15.0	3.9	12.0	8.0	8.0	3.8
	sd	2.7	0.8	4.2	2.2	42.6	1.7	9.6	1.7	9.4	1.9	7.6	9.4	7.6	4.2

Appendix 10 (continued).

		8 July*		19 July*		3 August		18 August		30 August		14 September		23 September*	
		Abun.	Biomass	Abun.	Biomass	Abun.	Biomass	Abun.	Biomass	Abun.	Biomass	Abun.	Biomass	Abun.	Biomass
Station 7 Bottom															
Mysis litoralis	$\bar{x}$					57.0	46.5	430.0	683.4	147.0	204.5	66.0	7210.0		
	sd					27.1	22.8	237.8	335.5	30.5	158.6	19.8	23.3		
Mysis relicta	$\bar{x}$					1.0	0.8	6.0	23.8	4.0	13.4	4.0	9.2		
	sd					2.2	1.8	6.5	34.8	4.2	12.6	4.2	11.1		
Mysid spp.	$\bar{x}$					1.0	0.1	62.0	29.4	2.2	19.2	7.0	15.9		
	sd					2.2	0.3	66.0	22.6	10.2	12.4	5.7	17.7		
Onisimus glacialis	$\bar{x}$					-	-	-	-	1.6	0.2	-	-		
	sd					-	-	-	-	2.2	0.4	-	-		
Pontoporeia affinis	$\bar{x}$					-	-	-	-	-	-	-	-		
	sd					-	-	-	-	-	-	-	-		
Halirages mixtus	$\bar{x}$					-	-	1.0	0.3	-	-	-	-		
	sd					-	-	2.2	0.8	-	-	-	-		
Apherusa glacialis	$\bar{x}$					-	-	2.0	1.4	-	-	-	-		
	sd					-	-	4.5	3.0	-	-	-	-		
Gammarus setosus	$\bar{x}$					-	-	-	-	-	-	-	-		
	sd					-	-	-	-	-	-	-	-		
Parathemisto spp.	$\bar{x}$					-	-	-	-	25.0	62.8	2.0	22.4		
	sd					-	-	-	-	25.7	36.3	4.5	50.1		
Amphipod spp.	$\bar{x}$					76.0	9.8	7.0	3.0	5.0	2.7	37.0	24.8		
	sd					37.8	8.4	5.7	5.1	8.7	4.0	21.7	13.5		

*No sample was taken at station 7 due to ice conditions on 7 and 19 July and 23 September.

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BEAUFORT SEA BARRIER ISLAND-LAGOON ECOLOGICAL PROCESS STUDIES

OCEANOGRAPHIC AND GEOLOGIC PROCESSES- A SYNTHESIS OF ECOLOGICALLY IMPORTANT INFORMATION

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1 April 1979

TABLE OF CONTENTS

Page
SUMMARY iii
ACKNOWLEDGEMENTS vi
INTRODUCTION.. 1
  Perspective and Data Sources.................................. 1
  Objectives and Rationale.................................. 2
STUDY AREA AND THE REGIONAL ENVIRONMENT.................................. 5
WATER CIRCULATION AND EXCHANGE.................................. 8
  Seasonal Characterization.................................. 9
    Winter Ice Season.................................. 9
    Spring Thaw.................................. 10
    Open-water Season.................................. 12
  Coastal Flushing.................................. 12
  Lagoon-Offshore Water Exchange.................................. 15
    Magnitudes of Exchange.................................. 16
    Mechanisms of Exchange.................................. 16
  Effects of Topography on Circulation.................................. 19
  Currents Near the Bottom.................................. 22
DETRITUS - SOURCES AND TRANSPORT.................................. 23
  Detritus Sources and Delivery Mechanisms.................................. 23
    Detritus from Stream Discharge.................................. 24
    Detritus from Shoreline Erosion.................................. 25
    Marine-Derived Detritus.................................. 26
    Relative Contributions--Riverine, Coastal, Marine......... 28
  Detritus Flux--Is The Nearshore Area a Trap?................ 28
    Detritus vs Inorganic Sediments.................................. 29
    Deposition of Terrigenous Detritus.................................. 30
    Detritus Flux Between Marine and Nearshore Areas.......... 31
    Effects of Topography.................................. 32
    Depositional Evidence.................................. 33

TABLE OF CONTENTS (continued)

Page

GEOMORPHIC FEATURES AND THEIR EVOLUTION........................ 35

Formative Processes.. 35

Barrier Islands, Lagoons and Estuaries - General Considerations.. 36

Barrier Islands and Lagoons - Beaufort Sea................ 39

Time Scales of Change...................................... 42

Barrier Islands... 43

Lagoon Basins... 44

Mainland Coasts... 46

CONCLUSIONS... 47

RECOMMENDED FURTHER RESEARCH.................................. 48

SUMMARY OF 4th QUARTER OPERATIONS............................. 48

LITERATURE CITED.. 49

SUMMARY

This report synthesizes and interprets, from reports of Barrier Island-Lagoon Program participants and from the general literature, data about selected oceanographic and geologic processes in coastal regions. Processes discussed are water circulation and exchange; detritus sources, transport mechanisms and sinks; and the origin and evolution of coastal landforms. The purpose of the synthesis has been to provide a more realistic assessment of the ecological consequences of man's alteration of these processes in the Beaufort Sea.

Circulation regimes change seasonally. During winter, circulation is greatly restricted because of the ice cover, and exchange rates between lagoons and adjacent environments may be a small fraction of what they are in summer. Spring thaw and break-up (late May-early July) freshen nearshore waters and clear them of ice. Water exchange rates increase greatly in the open-water season that follows because there is no ice cover to hinder the effects of wind in driving the circulation.

In summer, lagoon waters are freely exchanged with adjacent nearshore waters, but mix relatively less with offshore waters. Circumstantial evidence suggests that lagoon-offshore exchange may be characterized by a net seaward movement of surface waters and landward movement of bottom waters, as is found in most estuarine situations. Coastal upwelling, which brings offshore waters from the bottom to the surface at the coast, may also augment lagoon-marine exchange. Barrier islands retard rates of lagoon/marine exchange. Barrier islands, submerged bars, inlets, and other topographic features are both molded by and influence water movement, and some (e.g., inlets) develop characteristic locations and features in response to the existing coastal circulation patterns.

Currents near the bottom in coastal areas may be more important than currents at other levels from an ecological standpoint, because many of the biologically important materials and organisms

(detritus, epibenthos) are concentrated on or near the bottom. Water movement near the bottom is characteristically retarded by the friction imposed by the substrate. In shallow coastal areas, effects of this friction are overcome most effectively by oscillatory, wave-generated motion in the water column. This turbulence tends to resuspend benthic materials, which then are easily transported by unidirectional currents.

Two major documented sources of detritus to the nearshore Beaufort Sea are terrestrial--delivered by streams and eroded from coastlines--and these two sources are believed to provide similar volumes of organic detritus. Almost nothing is known about offshore waters as a potential third detritus source, although some evidence suggests that this source may be important. What is generally known about sediments and detritus transport in coastal regions suggests that the nearshore region of the Beaufort Sea, because of its topographic configuration and postulated shelf circulation patterns, may serve as a trap for detritus from all three sources. Processes acting to cause the nearshore area to selectively accumulate detritus are the slowing of currents as detritus-laden streams enter the lagoons, the theorized presence of landward-flowing currents near the bottom, and the effects of barrier islands in blocking seaward transport of detritus.

Most barrier islands of the world are thought to have been formed during the currently-existing post-glacial rise in the sea level by one or more of three mechanisms--(1) sand thrown up by waves from the continental shelf, (2) elongation of sand spits by longshore transport, and their subsequent separation from the mainland, and (3) submergence of low-lying areas behind coastal ridges. Most Beaufort Sea barriers appear to have originated primarily through the third process (coastal submergence), but to have been extensively modified in many cases by longshore transport of mainland- and island-derived sand.

The expected persistence of topographic features on the Beaufort coast in their present form is short by geological time standards. On an annual basis, islands and shorelines may change shape considerably and migrate up to several meters. The tundra cover of most existing islands will probably persist for at most a few centuries. Existing barrier island-lagoon systems, although expected to last more than several centuries, may naturally disappear within tens of centuries and be replaced by others as the sea advances onto the land.

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Much of the data for this section was provided by Chris Mungall, Brian Matthews, Sathy Naidu, Jan Cannon, Stu Rawlinson and Don Schell, to whom I am very grateful. John Richardson provided valuable editorial comments.

INTRODUCTION

The ways in which physical processes influence the population processes of animals and plants are too numerous to study in a project of this sort. However, each species of organism is significantly affected by only a few of the many processes occurring in an area, and since the emphasis of this study is on a few selected species of organisms, the array of processes with which we must be concerned is correspondingly limited. Furthermore, the fact that not all processes important to these selected organisms are affected by development limits our scope of interest even more. Our purpose in this section of the report is to investigate processes which (1) strongly influence populations of selected key species of animals in the coastal environment, and (2) are affected by oil and gas exploration and development activities on the continental shelf.

Perspective and Data Sources

This section of the report will synthesize and interpret data from new oceanographic and geologic research conducted under the auspices of the Barrier Island-Lagoon Program, as well as from other studies conducted in the Beaufort Sea and elsewhere. The research conducted by the oceanographers and geologists participating in the Barrier Island-Lagoon Program was influenced by the Program biologists; therefore most of their research is useful for this synthesis. But because the funds and time available to these scientists were limited and their research could consequently not address the entire array of physical process data needs, additional information is needed.

Given these limitations of the research conducted as part of this program, my approach in discussing physical processes will be to (1) use the research carried out under the auspices of this program to the extent that it is relevant, and (2) rely on outside literature to supplement and complement these data as deemed appropriate. Reference to the reported research of Barrier Island-Lagoon Program participants will be by conventional citation. Program Principal Investigators and their disciplines of study are as follows:

Dr. Brian Matthews	Oceanography (RU 526)
Dr. Chris Mungall	Oceanography (RU 531)
Dr. Sathy Naidu	Sedimentology (RU 529)
Dr. P. Jan Cannon Mr. Stuart Rawlinson	Geomorphology (RU 530)
Dr. Donald Schell	Nutrient Dynamics (RU 537)
Dr. Stephen Johnson	Avian Ecology (RU 467)
Dr. Peter Craig	Ecology of Fish (RU 467)
Mr. William Griffiths	Invertebrate Ecology (RU 467)

Objectives and Rationale

Three general objectives for physical process studies were established during the early planning stages of the program:

1. to characterize vertical and horizontal circulation patterns and water mass exchange characteristics in and near the barrier island-lagoon system,
2. to determine the sources and sinks of detritus and describe its transport mechanisms in the nearshore region, and

3. to determine the origins and evolutionary characteristics of the geomorphic features (barrier islands, lagoon basins, etc.) of the coastal region.

Some of these objectives were addressed by more than one person, each investigator using a different research approach but coordinating his effort with his co-investigators.

Objective #1. To characterize water circulation and exchange.

Circulation and exchange of water are ecologically important as a transport mechanism for detritus, dissolved nutrients, and many invertebrates. The ways in which these materials and organisms are suspended, transported, and deposited are governed by water circulation which, in turn, is a function of wind speed and direction, water depth and bottom topography. Likewise, circulation and exchange patterns between the lagoon and offshore water masses significantly influence the chemical and physical environments. During the open-water season existing circulation regimes maintain relatively low salinities and high temperatures in the coastal waters, relative to those in the open ocean. This phenomenon appears to provide a favorable environment for certain invertebrates and fish.

Development may be accompanied by extensive alterations of nearshore topography through construction of solid-fill causeways and shipping channels, removal and/or connection of existing barrier islands, etc. Information about currents, water exchange characteristics (and associated patterns of material transport and temperature/salinity regimes) is required for assessment of the short- and long-term effects of such activities.

Objective #2. To document detritus sources and sinks and describe detrital transport mechanisms.

Organic detritus is an important energy source in the nearshore environment. It is replenished periodically from both terrestrial and marine sources. It is also moved about in nearshore lagoons and bays from time to time, and is transported to and from nearshore systems. Because fish and birds habitually congregate in the lagoons and bays (as opposed to the adjacent marine system) to feed, it is important that the supply and maintenance of the detrital food base in these areas be continued.

Certain kinds of development structures may interfere with detritus transport to nearshore bays and lagoons. It becomes important, therefore, to document *which* detritus sources are critical, and to isolate *which* features of existing nearshore topography, circulation and water exchange are important factors in detritus accumulation. With such information, it would be possible to identify the kinds of development activities that would intercept vital sources of detritus or alter nearshore topography to adversely affect detritus asscumulation.

Objective #3. To determine the origins and evolution of nearshore landforms.

A basic hypothesis being tested by this study is that lagoons provide important habitats for selected species and that these habitats are not replicated in adjacent marine waters. Evidence collected to date supports this hypothesis, and indicates that the difference between lagoon and marine ecosystems is influenced by the topographic configurations of the nearshore region. Maintenance of barrier islands and lagoon basins as topographic entities is thus probably important as an environmental protection measure.

In order to determine the long-term impacts of development activities (such as removal of island material, stabilization of islands, and construction of shipping channels and causeways) to the integrity of the lagoon-barrier island system, the capabilities of the system to "mend" or regenerate itself must be known. For example, in terms of the barrier islands, we are faced with consideration of two alternate hypotheses regarding their origin and maintenance:

1. Barrier islands are persistent "constructional" entities that are maintained by nearshore oceanographic processes and their associated patterns of sediment transport and deposition.
2. Barrier islands are remnants of the former mainland shoreline that are constantly reshaped by erosion.

These hypotheses are not mutually exclusive; some islands may be remnants whereas others may be constructionally maintained. Similarly, individual islands may be partly mainland remnants and partly constructional. In any case, definition of the factors involved in the origin and maintenance of the barrier islands has important implications with respect to the regenerative tendency of the barrier islands. In other words, if historical evidence indicates that the magnitude of natural changes over short time periods exceeds the level of changes expected to be caused by development, then it is likely that the system can absorb the impacts of man's activities and still retain its functional role as an ecosystem.

STUDY AREA AND THE REGIONAL ENVIRONMENT

The field research of the Barrier Island-Lagoon Program has focused on a relatively short section of the Beaufort Sea coast, Simpson Lagoon and vicinity (Fig. 1). It was assumed that the ecological processes in this area are also operating at other coastal locations. Generally, this has been observed to be the case (Wiseman *et al.* 1974; LGL 1978; Weller *et al.* 1978:76). That is, the processes which determine the biological characteristics of Simpson Lagoon appear to dominate most of the Alaskan Beaufort Sea coast. A brief description of the coastal region of the Beaufort Sea follows.

The nearshore waters are shallow, and irregular, discontinuous chains of barrier islands skirt about 50% of the coastline. The island chains, which are generally parallel to the mainland, consist of islands that are characteristically low (1-1.5 m above sea level)

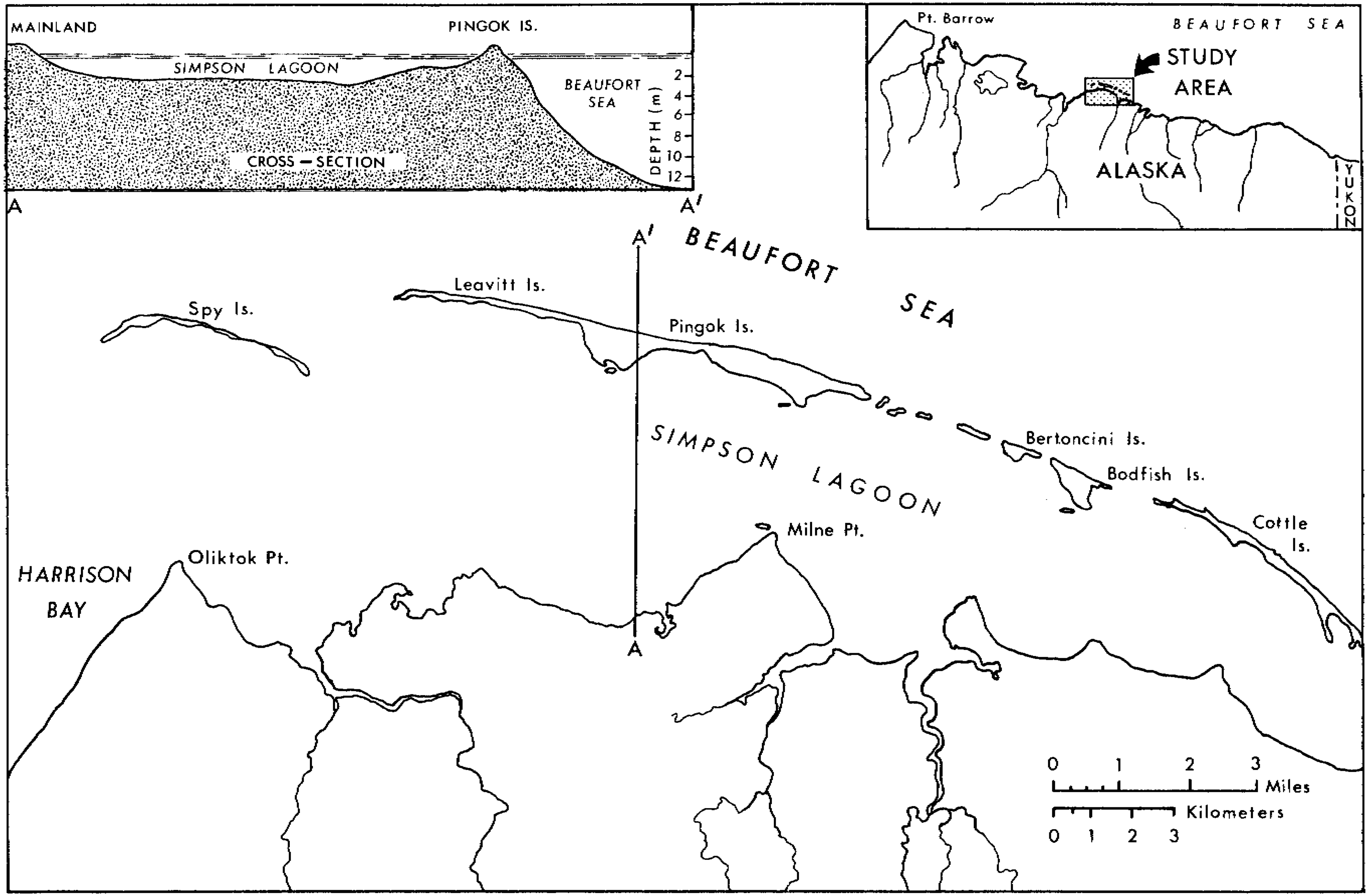

Fig. 1. Simpson Lagoon Study Area on the Beaufort Sea Coast of Alaska.

and narrow (0.1-2.0 km wide); the islands range in length from a few hundred meters to 15 km. Offshore bars exist on the seaward sides of the barrier islands and along some stretches of exposed mainland coasts. The bottoms of unprotected nearshore areas are roughened by the gouging action of ice floes and icebergs.

Freezing of coastal waters begins in late September or October. Ice forms on lagoons first because they are more sheltered and brackish, and cool faster than the nearby ocean. During late fall and early winter, surface ice is still relatively thin and may be moved about considerably by wind; consequently, large areas of open water may periodically appear during this time. Ice thickens by about 1 cm per day throughout winter so that by April it is about 2 m thick. The ice begins to melt in May, and its rate of melt is soon accelerated near river deltas by river discharge.

In late May or early June waters from melting streams reach the coast; these streams carry large amounts of silt and detritus which they discharge into the nearshore environment. Sixty to 80 percent of the annual discharge of most streams occurs within several weeks after flooding begins, during which time nearshore waters are still ice-covered. The water that reaches the coast first is discharged over the sea ice; most of this water eventually drains through cracks and holes to the water beneath. Within a few days, however, much of the ice adjacent to stream mouths has melted, allowing the river water to flow directly into coastal waters and thence under the ice. Discharges rapidly decrease during the course of the summer and are minimal by freeze-up.

During the open-water period the nearshore currents of the region are extremely variable and wind-dependent; astronomical tides are of secondary importance in affecting currents. Complex current patterns occur in nearshore circulation; these patterns are related to bottom topography, coastal configuration and presence of islands. Current speeds decrease as the winter ice cover forms and thickens.

During severe summer storms, high waters (storm surges) can inundate considerable portions of both the barrier islands and the nearshore mainland. The barrier islands limit the wind and wave action in the lagoon system, but the effects of wind and waves in exposed coastal waters are limited only by distant points of land, by the distance to the edge of the ice pack, or by concentrations of ice floes.

Because of wave, tidal and ice action and a gradual historical rise in sea level relative to the mainland, the mainland coastline retreates on an average of 1-2 m annually, and the island margins are also eroded away and reworked. This erosion is episodic in nature; most occurs during intense storms. At such times large amounts of organic material (tundra mat and underlying peat) and inorganic sediments are transported from mainland and island shores to lagoon and marine environments.

Most inorganic sediment particles in the lagoons and other nearshore basins are the size of sand or silt; gravels occur sparingly. Sediments are poorly sorted because sediment resuspension and transport by currents and wave action is extremely variable. Sediments are continually being introduced to nearshore areas via river floodwaters and coastal erosion. Wind-generated waves and currents produce a net westerly longshore sediment transport.

WATER CIRCULATION AND EXCHANGE

The important questions related to water circulation and exchange are listed below; the ecological significance of each question is explored in the paragraphs that follow.

1. What are the nature and timing of seasonal changes in the nearshore circulation regime?

2. What are the flushing rates of a typical coastal lagoon system under a range of expected conditions?

3. What are the magnitude and nature of exchange between coastal and marine waters?

4. How are circulation and water mass exchange affected by topographic features?

5. What are the magnitudes of the currents affecting coastal benthic environments?

Seasonal Characterization

In high-latitude environments, organisms have life histories that are structured around seasonal environmental phenomena. Because circulation and water mass movement strongly influence animal consumers and their supporting food chains in the study area, it is important to accurately define the seasonal nature of these processes in order to assess the ecological implications of oceanographic processes in general.

Winter Ice Season

Ice usually begins forming on the lagoon surfaces in late September or early October. The sheltered lagoon water begins to freeze earlier than the nearshore ocean because the shallow waters cool more quickly and, because they are brackish, freeze at a higher temperature (Wiseman and Short 1976). From this time until the following April, ice increases in thickness at an average rate of about 1 cm per day. During October, November and December, the nearshore circulation beneath the ice is relatively unimpeded, although it progressively decreases as ice thickness increases. Severe storms that occur during this period can move the ice about freely, causing large ice-free leads to form and ice to move offshore or to pile up on the shore (Barnes and Reimnitz 1977; Weller *et al.* 1978:60).

As the ice thickens, the effects of winds on the underlying waters are damped, but under-ice movement otherwise remains relatively unrestricted until channels and passes begin to be blocked by ice.

In Simpson Lagoon this occurs when ice reaches 1.2-1.5 m in thickness (Schell and Hall 1972). Even when unimpeded by ice blockage, the rates of water movement and associated sediment suspension and transport under ice are much smaller than during summer (Drake 1977).

During late winter (March, April, early May) when the ice is thickest, sub-ice water flow is at a minimum (Schell and Hall 1972; Weller *et al.* 1977:41). At this time lagoons and bays may experience little or no flow, and currents in nearshore areas are generally less than 5 cm per second. Circulation in these areas may be enhanced at this time by thermohaline convection, a seaward-landward water exchange generated by the production of high-salinity water in shallow areas by salt exclusion during freezing (Weller *et al.* 1977:151; Schell 1978). Under such conditions, the highly saline water produced at the water-ice surface sinks and flows seaward at the bottom, and is placed by a landward flow of lower salinity water near the top of the water column.

Spring Thaw

The relatively steady state of low to zero circulation in coastal waters from March to May is quickly and drastically altered by spring flooding of rivers, which usually begins during the last week in May or the first week in June. Since the interaction of river discharge with coastal waters is ecologically important in a number of respects, I will discuss it in detail. Although variable in magnitude, characteristics of spring thaw are similar among North Slope rivers and coastal segments; the following descriptions are from Barnes and Reimnitz (1972), Reimnitz and Bruder (1972), Walker (1974), Wiseman and Short (1976), and Weller *et al.* (1978:110).

When spring floodwaters from Alaskan arctic rivers reach the coast, if river delta channels are shallow and consequently frozen throughout, all the initial flow goes over the river delta and then onto the coastal ice. In rivers such as the Colville that have deep delta channels some of the initial flow goes under the river delta ice and the sea ice.

As the initial discharge moves seaward, it fans out rapidly over the nearshore ice, reaching depths of a meter or so and depositing much silt and detritus. This flood lasts for only a few days; much of the water finally drains through holes and cracks into lagoon and nearshore marine waters. Also, sea ice immediately adjacent to the deltas is soon melted, allowing the river water to flow directly into the sub-ice water.

The floodwater injected beneath the ice advances seaward as a freshwater wedge or lens between the ice and the more saline waters beneath, to the approximate extent of the over-ice discharge. (The sub-ice lagoon and river delta waters are highly saline immediately preceding flooding because the solutes have been excluded and concentrated under the ice during the freezing process.) Little mixing of the fresh and saline waters occurs immediately, although some of the material suspended in the river water settles through to the bottom.

Typically the over-ice floodwaters quickly cover large portions of the surfaces of the lagoons or bays at the river mouths, and a small portion of the over-ice floodwaters extend beyond to the marine environment. The water on the ice generally flows westward; the river water that flows under the ice presumably goes the same direction.

Intense flooding normally lasts less than two weeks, after which the under-ice water in some of the lagoons and bays is almost completely fresh except for pockets of saline water in bottom depressions. As the surface ice melts in the following weeks, the fresh water gradually mixes with incoming cold marine water to create the brackish water systems that prevail along the coast throughout the summer.

During the month following initial over-ice flooding, bay and lagoon ice typically thins in place, melting first where deposits of silt and detritus have darkened the surface. Because of this differential melting, most of these deposits are probably dropped in place rather than being rafted away (Reimnitz and Bruder 1972). In early June the thin ice finally begins to break apart and move; by mid-July the ice remnants have normally moved out with the winds and currents, leaving the lagoons and bays open.

Open-water Season

The open-water season is the period during which surface ice offers little obstruction to the action of wind on coastal waters. Although annually variable, this period normally lasts about three months, from early July to early October.

Nearshore currents in the open-water season are primarily wind-driven (Wiseman *et al.* 1974; Callaway and Koblinsky 1976; Dygas and Burrell 1976; Matthews 1978; Mungall 1978; and others). Winds are predominantly from the northeast and secondarily from the west. Currents in the nearshore move parallel to the coast and in the same general direction as the wind.

The most intense storms come from the west, at irregular intervals, but primarily late in the open-water season (sometimes well into the early winter). These late-season storms are responsible for the largest storm surges and for the majority of coastal erosion (Short *et al.* 1974; Weller *et al.* 1978).

Freshwater input from most rivers decreases by the beginning of the open-water season, and remains relatively low throughout the open-water season (Barnes and Reimnitz 1972; Reimnitz and Bruder 1972; Walker 1974; and others), although the pattern varies somewhat among rivers (Fig. 2).

Coastal Flushing

The flushing rate or 'residency time' of waters in nearshore environments needs to be evaluated because it is an index of the integrity of the nearshore system. If water and its entrained

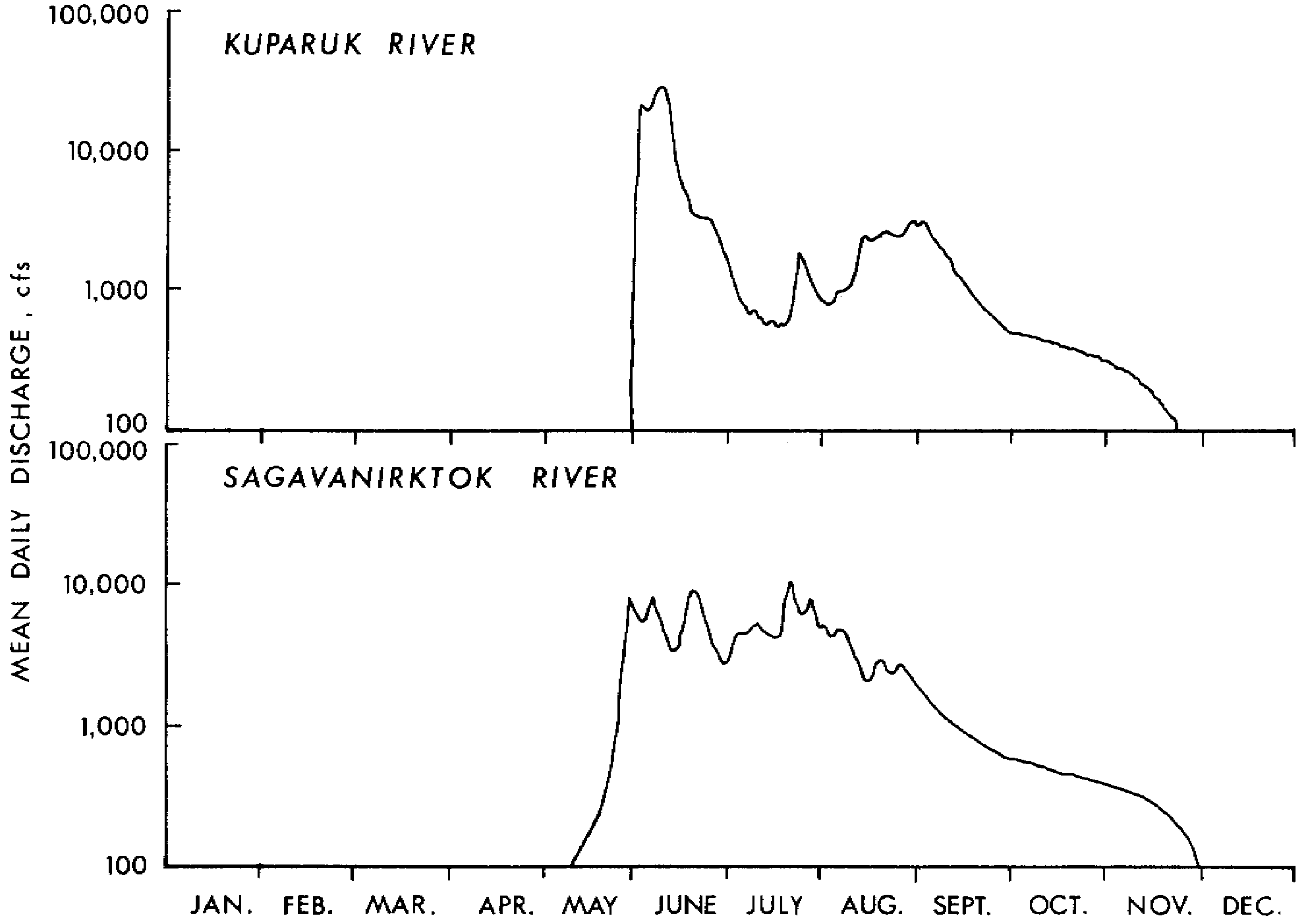

Fig. 2. Annual Hydrographic Regimes of Two Rivers Discharging Into the Alaskan Beaufort Sea. (Adapted from Carlson *et al.* 1977).

organisms and materials are rapidly transported through a coastal segment, then the integrity and distinctness of that area, *in terms of the water and its load*, are low. This is an important consideration when extrapolating information from one part of the coastal system to another. Effects of flushing rates and characteristics on the transport of suspended materials are especially important; the rate of supply of food-chain materials to sites where food may have been depleted depends on the rates and nature of transport processes. Similarly, the rate of flushing determines the rapidity with which coastal sites are exposed to changing arrays of physical and chemical water conditions.

In summer, currents in shallow coastal waters generally move parallel to the coast at about 3 to 4% of the speed of the wind and in the same direction as the wind (Callaway and Koblinsky 1976; Mungall 1978). Summer winds are usually from the northeast and average about 5 m per sec. The coastal waters will move westward under these conditions at about 15 cm/s, causing a coastal area the size of Simpson Lagoon (about 35 km long) to flush in about five days. Under the influence of strong winds, the same system could flush in one day (Mungall 1978). Since wind-driven currents in such shallow waters are normally uniform throughout the water column except very near the bottom (Komar 1976a), such flushing may be virtually complete except for bottom waters and those affected by coastline irregularities. However, as I will describe later, the ecologically important currents may be those at the bottom that are resistant to flushing.

Currents under ice apparently also move parallel to the coast, but at rates much reduced from those of summer (Schell and Hall 1972; Barnes and Reimnitz 1977). Flushing rates for winter have not been calculated, except that they are presumably reduced to essentially zero in lagoons when inlets become sealed by ice (e.g. Schell and Hall 1972).

Lagoon-Offshore Water Exchange

It is implied above that rapid coastal flushing is caused mainly by water mass exchange parallel to the coast. However, it has not been established what proportion of the water that flushes coastal systems comes from adjacent offshore marine areas. The following discussion addresses the ecological importance of the difference between movement of water along the coast and coastal-marine exchanges, and documents what is known about water exchange between nearshore lagoon and offshore marine areas.

Water exchange between coastal and marine environments appears to be extremely important to animals in the coastal region; whether the exchange is ecologically beneficial or harmful may depend largely on its nature and rate. First, for selected species, the nearshore water appears to offer beneficial conditions (presumably related at least partly to water quality or entrained materials) in comparison with waters in the marine system (Griffiths and Dillinger 1979, Craig and Haldorson 1979). Therefore, for the benefit of these species, exchange rates between nearshore and marine water needs to be low enough to prevent excessive dilution of coastal waters by marine waters. Second, exchanges of transported materials (invertebrates, detritus, nutrients) between the coastal and marine environments may be vital to the well-being of coastal biota. From this point of view, water exchanges need to remain sufficiently great to maintain these vital transport processes. It is important, then, that the magnitudes and mechanisms of coastal-offshore water exchange be examined, especially since proposed development activities (construction of causeways, etc.) may affect exchange characteristics in ecologically important ways.

Magnitudes of Exchange

Partially enclosed bays and lagoons become progressively more isolated and different from the marine environment as the surface ice thickens in winter (Schell and Hall 1972; Weller *et al.* 1978). The waters of the two environments may actually become physically separated by ice barriers, and salinities in the lagoons and bays may exceed the physiological tolerances of some of the animals that utilize the lagoons in summer (Griffiths and Craig 1978).

The exchange rate (and the resulting integrity of the nearshore system) during the summer appears to be a more critical issue. Biologists participating in this study (P. Craig, W. Griffiths) report that during summer lagoon water temperatures are higher and salinities lower than they are in the adjacent ocean. Matthews (1978) shows that the temperatures of the coastal waters remain distinctly higher in summer than do the temperatures of the adjacent marine system. Mungall (1978) documented that salinities and temperatures within the lagoon, although variable, remain generally higher and lower, respectively, than those in offshore areas. These temperature and salinity differences have also been reported by Hufford (1974), Wiseman *et al.* (1974), Herlinveaux and de Lange Boom (1975), Schell (1975), and others. Matthews (1978) and Mungall (1978) thought that they could trace the coastwise movement of water boluses. Matthews concluded that mixing between the nearshore and marine water masses was minimal, since the temperature and salinity differences between the two areas persisted throughout the open-water season. Callaway and Koblinsky (1976) also implied that exchange between the nearshore and marine systems was very much less than exchange between nearshore subsystems.

Mechanisms of Exchange

The evidence cited above indicates that coastal waters normally do not mix with offshore marine waters to a great extent. However, some exchange between the two systems does occur. The mechanisms of exchange are important to transport of entrained materials (to be discussed later) as well as to the maintenance of the characteristic warm, brackish waters in nearshore areas.

Exchange processes characteristic of shallow lagoons and estuaries in more temperate zones presumably also occur along the Beaufort coast in summer when waters are ice-free. It should be noted that most lagoons and bays in northern Alaska are by definition estuaries, i.e. "semi-enclosed coastal bodies of water which have free connections with the open sea and within which sea water is measurably diluted with fresh water derived from land drainage" (Cameron and Pritchard 1963). The following paragraphs discuss important aspects of estuarine-marine exchanges.

The dominant mode of exchange between estuarine and marine environments, even in the case of partially- to well-mixed estuaries (as are most of the Beaufort lagoons and bays), involves seaward flow of brackish water in the surface layers and landward flow of saline water in lower layers (Conomos and Peterson 1976; Dyer 1978; Officer 1978; Pritchard 1978; and others). In the Beaufort Sea this phenomenon apparently occurs even under the nearshore ice during spring runoff, as described earlier. However, during and for some time following the peak runoff period the interface between the overlying freshwater wedge and the underlying salt water wedge may be seaward of some of the very shallow lagoons, judging from salinity measurements reported by LGL biologists (RU 467) in Simpson Lagoon in June 1978. Consequently, waters of some Beaufort Sea lagoons at this time may be almost completely fresh because of the tremendous under-ice flushing action from major rivers. During the open-water season in the nearshore Beaufort, the mixing effect of winds obscures this two-directional stratified flow in the shallow lagoons. However, sensors monitored by Barnes *et al.* (1977a) showed that under prevailing easterly winds in Stefansson Sound, cold saline waters entered the sound on the bottom of passes as the warm brackish water exited at the surface. Similarly, Schell (1975) found that pronounced stratification developed in Simpson Lagoon during calm weather in late summer, apparently because of the intrusion of sea water at the bottom. Herlinveaux and de Lange Boom (1975) noted characteristic intrusions of high-salinity waters in summer at the bottoms of southern Beaufort Sea lagoons in Canada. Furthermore, steep salinity gradients (differences of 6‰ per m depth) have been noted at relatively deep entrances to Simpson Lagoon at the same time that the lagoon waters themselves were fairly well mixed (Weller *et al.* 1978:67). Stratification caused by surface freshwater outflow is more evident in the deeper waters outside the lagoons than within the lagoons (Hufford 1974).

Related to this layering phenomenon is the process of coastal upwelling, whereby deep, cold marine waters are brought to the surface near the land margin. Upwelling is a common occurrence in many coastal areas of the world (Johnson 1957; Segerstrale 1957; Conomos and Peterson 1976; and others) and may occur simultaneously with the estuarine-marine mixing processes described above. Upwelling apparently is common along the southern Beaufort Sea coast; the postulated causes and characteristics are described below from Hufford (1974), Wiseman *et al.* (1974), Herlinveaux and de Lange Boom (1975), Barnes *et al.* (1977 a,b), and Drake (1977).

Upwelling along the Beaufort coast typically occurs when winds are from the east during the open-water period. Under these conditions, the sea level is lowered, and the warm, brackish coastal waters tend to be pulled seaward as a surface lens, and the cold, saline marine waters intrude landward at the bottom. This type of circulation pattern should be expected to occur commonly since the summer winds are predominantly from the east (Barnes *et al.* 1977b). (It should be noted that winds from the west typically raise coastal water levels by pushing water into the coastal bays and lagoons; the warm brackish coastal waters under these westerly wind conditions are held against the coast where they are warmed by the sun and freshened by runoff [Wiseman *et al.* 1974].)

It is likely that the presence of barrier islands tends to retard both the seaward transport of the coastal waters and the landward transport of marine waters, and that stratified flows would be more observable along exposed coasts. The fact that the coastal bay and lagoon waters tend to remain relatively warm and brackish throughout the open-water season indicates that the exchange processes are not sufficient to thoroughly mix lagoon waters with marine waters. However, as discussed later, both the typical estuarine flows and upwelling may cause significant shoreward transport of materials entrained in the water near the bottom.

In winter, normal advective exchange between marine and nearshore areas is assumed to be slow, although there is little conclusive information. However, Schell has postulated (in Weller *et al.* 1977:151; Schell 1978) a sub-ice convective exchange mechanism, the magnitude of which is uncertain but the importance of which in supplying nutrients may be significant.

Effects of Topography on Circulation

Topography appears to affect nearshore water motion in several ways that are potentially important to biota. As indicated above, the presence of barrier islands may be important to the maintenance of physically warm, brackish waters in biologically active coastal regions. Some water birds (e.g., phalaropes and arctic terns) appear to congregate to feed in the lagoon near lagoon entrances (Johnson 1978, 1979); it is hypothesized that currents may selectively deliver and/or affect availability of entrained food organisms to birds, as well as other organisms, at these sites. The configuration of the nearshore bottom and emergent landforms may determine the effectiveness of coastal areas as detritus and sediment traps.

It is well known that all anomalies in the topography of the nearshore bottom and of the coastline have an influence on nearshore circulation (Mooers 1976). Islands, coastal capes, and submarine banks form barriers to flow. Coastal embayments, depressions and submarine canyons may form channels for flow. Since the interactions of flow with topography are governed by predictable physical laws, extrapolations and comparisons among coastal regions are possible and desirable (Mooers 1976).

Barrier island chains have characteristic inlet features, or passes, that are maintained by water movement, and that, in turn, control water movement (Emery and Stevenson 1957; Riggs 1976). These passes form or change in direct response to the basic hydraulic pressures within the coastal system; they open by erosion and close by shoaling of sediments to fit the hydraulic pressures at any given time. Passes in the vicinity of rivers are generally larger and more stable than other passes because they carry much of the freshwater discharge. Inlets that are predominantly tidal tend to be more ephemeral; they are generally formed by storm waves, kept open by tidal currents, and closed or moved by storms or longshore currents. If closed, they will tend to recur within the same general area, when needed to accomodate discharge. Because inlets must periodically accomodate rapid water discharge, they are usually the deepest part of a lagoon or estuary area.

Inlets in the barrier island chain skirting Simpson Lagoon and Gwydyr Bay appear similar in structure and function to those reported for other systems. The tidal inlets are generally shallow compared to the major inlet (Egg Island Channel) which accomodates the Kuparuk River discharge (Matthews 1978; Mungall 1978). Some of these tidal inlets have been observed to close and reopen (Cannon and Rawlinson 1978; W. Griffiths, pers. comm.). Inlet depth in the Simpson Lagoon area, particularly of the major inlets, is usually greater than that of the adjacent lagoon, and water flow through the inlets is often rapid.

It has been found that inlet position and condition are critical to the circulation and the ecology of lagoon systems in temperate regions (Copeland 1974; Mooers 1976; Warme *et al.* 1976; and others); the same has been implied for the Alaskan arctic coast (Schell and Hall 1972; Faas 1974; Matthews 1978; Mungall 1978; and others). The nature and magnitude of lagoon flushing in winter depends on the locations and depths of major inlets; under-ice flows decrease or cease as inlets are sealed by thickening ice, and water salinities increase rapidly thereafter (Schell and Hall 1972; Weller *et al.* 1978:110). Introduction of cold, saline marine water to lagoons in summer by landward intrusion and upwelling processes may be regulated by inlet depth, since these waters must enter at the bottom beneath the exiting brackish water. Longshore flushing rates of lagoons in summer also depend on the flow capacities of lagoon entrances, and the effectiveness of transport of entrained organic and inorganic materials into and out of lagoons may depend on inlet location and depth, as will be discussed later.

The barrier islands have both direct and indirect effects on circulation. They physically obstruct water movement and exchange so that the discreteness of the lagoon from the sea is enhanced. They also obstruct wind motion so that the effect of wind on adjacent waters is altered. However, the changes in general circulation patterns as a consequence of such effects is not well known (Bowden 1978; Hamilton and Rattray 1978; Hsu 1978).

The effects of changing depth on water motion in wind-driven, shallow lagoons are most pronounced at the bottom. Wind-driven currents in shallow waters behave similarly regardless of depth except immediately above the bottom, where gradients in current speeds are very sharp because of frictional drag that retards the water motion (Carriker 1967; Komar 1976 a,b; and others). The retardation of wind-driven currents in bottom waters is less in shallow water than in slightly deeper water. The theoretical considerations and consequences related to currents in benthic environments are discussed in the next section.

Currents Near the Bottom

Water motion near the bottom is biologically important for several reasons. The topographic conformation of nearshore areas is strongly affected at critical sites (e.g., inlets) by the erosive action of bottom currents. Also, the resuspension and deposition of organic detritus, and perhaps dissolved nutrients, depends on bottom currents. Furthermore, some of the important epibenthic organisms (e.g., mysids, amphipods) may make behavioral adjustments to bottom currents in order to accomplish critical movements to, from, and within the nearshore lagoons.

Because of drag effects and retardation of flow near the bottom, considerable motion must be present in the mid-water zone before there will be movement of particles or organisms on the bottom. Three kinds of processes result in significant water motion near the bottom in the nearshore Beaufort Sea--unidirectional currents, oscillatory motion associated with waves, and localized scouring (caused by a focusing of unidirectional flow). There is some disagreement as to whether unidirectional currents or wave motions are most important to resuspension and transport of materials (Komar 1976b). However, there is general agreement that in shallow shelf waters under a given wind regime, the shear stress exerted on the bottom by oscillatory wave motion is several times larger than the shear stress associated with the unidirectional current (Komar 1976b; Madsen 1976). It appears that wave action is most important in resuspending bottom materials, whereas unidirectional currents are more important in causing net transport of already-suspended materials (Komar 1976b). Focused bottom scouring is a local phenomenon associated with rapid water motion through holes or cracks in ice (Reimnitz and Bruder 1972) and at narrow inlets or passes (Emery and Stevenson 1957; Riggs 1976; and others). The importance of scouring appears to be more in shaping *local* benthic environments than in contributing to the total resuspension and transport over a large area.

Because of the extreme difficulty in measuring currents at the bottom (Carriker 1967), few empirical data are available about the relationships of winds, waves and surface currents to bottom currents. The effects of these interactions on the vertical resuspension of bottom materials are especially poorly known (Komar 1976b; Kjerfve *et al.* 1978; Schubel *et al.* 1978). During storms on Alaska's arctic coast, high sediment and detrital loads suspended in the water indicate that considerable water motion occurs on lagoon bottoms, but there is no knowledge of the magnitude of this motion at varying bottom depths, current speeds, wave periods, and wind speeds.

DETRITUS - SOURCES AND TRANSPORT

From the viewpoint of ecosystem functioning, there are two important questions about dynamics of detritus movement in the nearshore environment:

1. What are the sources and mechanisms of delivery of detritus to the nearshore?
2. Is the nearshore environment a detritus trap, and if so, what physical processes and environmental features are involved?

Detritus Sources and Delivery Mechanisms

Detritus may be an important energy source for key invertebrate species in the nearshore environment (Schell 1978). Most of the detritus found in the nearshore is not produced *in situ* but delivered there from external sources. It is important, therefore, to document where the detritus comes from and what processes deliver it to the coastal regions.

Three potentially important detritus sources and delivery mechanisms have been identified:

1. terrestrially-derived detritus from the drainage systems of the larger streams that discharge into nearshore areas,
2. terrestrially-derived detritus from coastal erosion, and
3. marine-derived detritus transported landward.

Detritus from Stream Discharge

River discharge has been found to be a major source of detritus to nearshore lagoons and estuaries in many temperate areas (Fox 1957; Hedgpeth 1957; Segerstrale 1957; Copeland 1974; and others); it has also been reported to contribute large amounts of organic materials to the nearshore Beaufort Sea (Reimnitz and Bruder 1972; Walker 1974; Pelletier 1975; Cannon and Rawlinson 1978; and others). The general characteristics of stream-borne detritus and sediment discharge into the Alaskan Beaufort Sea have been documented (Barnes and Reimnitz 1972; Reimnitz and Bruder 1972; Walker 1974; Pelletier 1975; Cannon and Rawlinson 1978). Almost the entire annual increment of river-supplied detritus is brought to the coast in June, carried by the rivers during the peak runoff period. The organic and inorganic suspended materials are mixed; the organics range in size from very small particles to peat shreds to driftwood. The percentage of organic material in the suspended load is estimated (for the Kuparuk River) to be about 1% (Cannon and Rawlinson 1978, quoting D. Schell pers. comm.). (Schell [RU 537] and Cannon and Rawlinson [RU 530] are currently developing more precise estimates.) The suspended load is deposited in part on the nearshore ice surface and discharged in part beneath the ice (Walker 1974); Cannon and Rawlinson (1978) believe that the majority of the organic fraction is carried in the early overflow and deposited on top of the ice, at least in the case of the Kuparuk River.

It appears likely that the majority of the detritus, even though a large portion is initially discharged above the ice, reaches the water column in or near the coastal lagoons and bays. Most of the water which initially flows over the ice quickly finds its way, via cracks and holes, to the underice environment within and near the bays and lagoons (Barnes and Reimnitz 1972; Cannon and Rawlinson 1978). The sediments remaining on the ice in the lagoons are not moved appreciable distances until the ice breaks up and leaves the lagoons in late June and early July. By this time most of the ice underlying the deposits of detritus (which are darker than exposed ice and thus heat more rapidly) has melted in place, releasing the detrital materials to the water beneath.

Quantities of organic particulate detritus supplied to the nearshore areas by terrestrial runoff have been roughly estimated by Cannon and Rawlinson (1978) and Schell (1978). Cannon and Rawlinson estimated that about 1.19×10^7 kg of peat was flushed into Simpson Lagoon annually from the Kuparuk River. Schell, apparently using the data of Cannon and Rawlinson, estimated that Simpson Lagoon received about 5.6×10^5 kg carbon per year from stream discharge, mainly from the Kuparuk. These three authors are currently working together to refine their estimates and to resolve discrepancies between estimates.

Detritus from Shoreline Erosion

It has been known for many years that coastal erosion accounts for large amounts of detritus in nearshore waters of the Alaskan arctic. MacGinitie (1955) reported that tundra vegetation and peat were eroded into the nearshore Beaufort Sea at Barrow. More recently, Short *et al.* (1974), Schell (1975, 1978), Lewis and Forbes (1975), and Cannon and Rawlinson (1978) have described coastal erosion as a detritus source in the southern Beaufort Sea.

The organic material released to nearshore waters by coastal erosion is largely peat, which underlies the tundra vegetation in thicknesses up to a meter or more. This peat is eroded primarily during storms, when wave action reaches across the beaches to the peat-capped bluffs on the mainland and islands. The major inputs probably occur in late summer and early fall under the action of winds from the west.

Indirect evidence indicates that seaward transport of detritus from coastal erosion is relatively slow. Large lumps of tundra mat are commonly encountered on the beaches fronting bluffs and in shallow waters near these beaches, but not in deeper waters in mid-lagoon. Naidu (1978) found organic carbon levels in sediments to decrease with distance from mainland shores. Westerly storms, which cause the most severe coastal erosion, also tend to hold the coastal water masses against the shore, thereby impeding seaward transport of suspended particulates.

The magnitude of detrital input from coastal erosion is considerable. MacGinitie (1955) estimated that near Barrow 0.3 to 1.5 metric tons (300 to 1500 kg) of plant material (dry weight) per mile (1.6 km) of shoreline reached the ocean annually via coastal erosion. Cannon and Rawlinson (1978) and Schell (1978) estimated that the annual amount introduced to Simpson Lagoon was considerably greater (6.8 x 10^5 kg/yr per km of coastline). These estimates are currently being refined.

Marine-Derived Detritus

Whether a significant portion of marine-produced detritus (e.g., dead plant and animal remains) finds its way to the coastal estuaries and lagoons along the Beaufort coast is unknown. Schell (1978) implied that in nearshore areas marine sources of detritus (sinking plankton, etc.) may be ecologically significant, but indicates that supportive data are not yet available.

The major components of detritus produced within coastal and marine waters are sinking phytoplankton, dead animals, animal parts, and metabolic products. The importance of sinking plankton in shallow, turbulent coastal waters is uncertain; the plankton may remain suspended because of their low specific gravity (Bellis 1974; Kremer and Nixon 1978:56). However, in winter, settling under ice, even in shallow water, should not be affected by excessive turbulence. Settling rates also become significant in the open ocean where waters are deeper and, below the surface layer, less turbulent (Kremer and Nixon 1978:56).

Little information about the landward-seaward flux of organic detritus is available; descriptions of how inorganic sediments behave in coastal waters are more common. Bellis (1974), Hatcher and Segar (1976) and Naidu (1978) have assumed that organic detritus is similar to inorganic fines (clay, silt) in response to current action. If this is true, then we may gain insight about detritus transport by examining information about interactions between inorganic sediments and water along coasts. Johnson (1957) and Drake (1976) noted that current patterns over the inner continental shelves of the world typically concentrate resuspended sediment in the nearshore zone. Dyer (1978) showed that the mechanism that drives sea water toward land near the bottom in typical estuarine circulation systems also returns the sediments to the coastal waters; he found a net landward dispersion of sediments in two well- to partially-mixed estuaries in France and the United Kingdom. In San Francisco Bay, Conomos and Peterson (1976) found that significant portions of sediments dispersed seaward in the water column were returned to the bay in bottom, landward-flowing currents.

To conclude, it is not known if much marine-derived detrital material is transported to the nearshore lagoons and estuaries of the Beaufort Sea. However, it would appear that coastal circulation and transport processes may generate such a landward transport of marine organic detritus. The likelihood that the nearshore will act as a sink for such material will be discussed later.

Relative Contributions--Riverine, Coastal, Marine

It is important to know the relative amounts of detritus supplied to the nearshore from each of the three potential sources. (It is also important to evaluate the utilization by higher organisms of material from each of the sources; this problem is currently under investigation by Schell [RU 537] and others.) As indicated above, no firm estimates of the amounts of marine-derived materials supplied to the lagoons and bays are available. Schell (1978) and Cannon and Rawlinson (1978) have estimated that riverine and coastal erosional inputs are of the same order of magnitude. These estimates are currently being refined by those investigators, and more precise estimates of contributions from at least these two sources should soon be available.

Detritus Flux--Is The Nearshore Area a Trap?

It is important to determine whether shallow coastal environments are critically important for the maintenance of fish and bird populations that have been found to selectively use nearshore habitats. Since detritus may provide the energy that maintains the prey of these animals, it is important to compare the relative rates of accumulation of detritus in nearshore areas and adjacent marine environments. If the habitat quality of nearshore areas is enhanced by the accumulation of detritus, we can then recommend protective measures to guarantee the integrity of these areas.

Coastal estuaries and lagoons function as detritus traps in many parts of the world. Meade (1969, 1972) believed that, at most, only about 10% of the riverborne suspended solids entering estuaries ever reach the sea. Drake (1976) stated that the evidence for nearly perfect retention of fluvial suspensoids in many estuaries is incontestable. Hedgpeth (1957) maintained that the rate of deposition of land-derived detritus is far greater in lagoons and estuaries than in the open sea. Conomos and Peterson (1976) found San Francisco Bay to be an effective sediment (and also presumably detritus) trap during normal river discharge conditions. The processes that regulate the behavior of detritus in coastal areas are reviewed below, with particular reference to the southern Beaufort Sea coast, to examine if and how the nearshore Beaufort is likely to collect detritus.

Detritus vs Inorganic Sediments

The behavioral relationships between organic suspensoids (detritus) and inorganic particles (sediments) are germane to this discussion for several interrelated reasons. First, a great deal more is known about sediment resuspension, transport and deposition than is known about detritus behavior. Second, organic materials appear to behave similarly to some inorganic sediments. Third, certain organic and inorganic materials may, by the process of flocculation, be bound together and thereby forced to share the same depositional fate.

Organic materials in the water are reported to have transport properties similar to those of inorganic fines (clay, silt). Generally, organic matter is associated with fines in depositional environments (Bordovskiiy 1965; Froelich *et al.* 1971). High organic carbon concentrations on continental shelves are generally encountered in mud (as opposed to sand) bottoms (Hatcher and Segar 1976). The reason for the co-deposition of organics with fines is presumed to be that the two behave similarly in water (Naidu 1978).

Suspended clay and organic particles may adhere to each other to form larger particles via the process of flocculation (Copeland *et al.* 1974; Pelletier 1975; Krone 1978). Co-deposition of the two thus becomes obligatory; flocculation may therefore augment the extent to which organics are to be found with inorganic fines in depositional sites. The influence of flocculation in determining the sites of deposition of detritus is discussed at greater length below.

Deposition of Terrigenous Detritus

The majority of eroded coastline materials and organic and inorganic materials carried by rivers are deposited in nearshore areas. It has been a common observation that particles suspended in streams discharging into coastal basins tend to settle there due to the sudden reduction of current speed (Hedgpeth 1957). The same is true for the Beaufort Coast. The larger, denser particles are dropped from suspension first, near the river mouths, and silt and clay are deposited farther away (Burrell *et al.* 1975). Most organic materials, similarly to the inorganic fines, are probably not deposited immediately, but carried some distance prior to settling out. However, it is likely that the process of flocculation (see below) affects the depositional behavior of these clays and organics.

Flocculation is the physicochemical process whereby fine silt, clay, and organic particles in the water form aggregations because of the mutually attractive forces of their charged surfaces. Flocculation is minimal in waters having low salt concentrations (such as most streams), but increases markedly with salinity (Copeland and Dickons 1974; Krone 1978). For this reason its effects are most dramatic where particulate-rich fresh waters impinge upon high-salinity coastal waters. At present the data suggest that flocculation increases the settling rate in marine waters by up to one order of magnitude (Drake 1976).

Conditions under which rivers discharge the major portions of their organics into the nearshore Beaufort are ideal for extensive flocculation. The first several days of flood discharge in the spring may carry most of the annual detritus load (Cannon and Rawlinson 1978). At this time the nearshore lagoons are highly saline because of salt exclusion during the freezing of lagoon water. As the river waters spread seaward under the ice, with the highly saline waters beneath, the freshwater/saltwater interface becomes extensive. Walker (1974) notes that, although little mixing occurs initially across this interface, suspended material nevertheless settles through to the bottom. In the Canadian Beaufort, Pelletier (1975) noted that flocculation of clay and organic particles occurred extensively within and on the periphery of the Mackenzie River plume.

Flocculation also causes aggregation of organics introduced via coastal erosion, which occurs almost entirely during late summer and autumn storms. Although salinities of coastal waters at this time are normally lower than when river discharge begins, the turbulent mixing accompanying the storms acts to promote increased particle collision, which promotes flocculation (Krone 1978).

Although it is clear that there are higher deposition rates of terrigenous detritus in nearshore lagoons and bays than in offshore waters, a portion of the detritus is undoubtedly deposited seaward of lagoons and embayments. MacGinitie (1955) maintained that fresh vegetation and peat from freshwater discharge were deposited as far out to sea as 40 km (near Elson Lagoon). Barnes and Reimnitz (1972) and S. Johnson (pers. comm.) noted that some of the over-ice discharge from the Kuparuk River in spring proceeded seaward of Simpson Lagoon to discharge through the ice into marine waters.

Detritus Flux Between Marine and Nearshore Areas

Is the detritus that is preferentially deposited in nearshore areas from terrestrial sources gradually lost to the ocean, or is it supplemented by net landward transport of marine- and/or terrestrially-derived organics from the marine environment? The transport of organic matter under ice on the Beaufort Shelf is probably inconsequential (Drake 1977), so the main consideration is detritus movement during the open-water period.

Current patterns over the inner continental shelves of most areas of the world tend to concentrate re-suspended shelf sediment (and presumably also detritus) in the nearshore zone; if estuaries are present, much of this material will be funneled into estuaries and deposited (Drake 1976). There is evidence that a major force contributing to this landward transport is the characteristic landward-flowing bottom currents (Conomos and Peterson 1976; Schubel and Carter 1976). Dyer (1978) shows that well-mixed estuaries have a turbidity maximum near the landward margin of the salt water intrusion at the bottom; this indicates that the mechanism driving salt water landward must also affect suspended sediment. Dyer found a net landward dispersion of sediment and correspondingly more sediment entrained during the flood (landward-moving) tide than on the ebb (seaward-moving) tide.

Whether Beaufort Sea marine sediments that are resuspended have a net landward transport is not known, but circumstantial evidence suggests that they do. Landward-flowing bottom currents (and probably associated sediment transport) caused by the predominant easterly winds and/or by characteristic estuarine-marine water exchange should be common, based on evidence provided by Hufford (1974), Herlinveaux and de Lange Boom (1975), Schell (1975), Wiseman and Short (1976), Barnes and Reimnitz (1977), and Barnes *et al.* (1977a). Shoreward-flowing bottom currents may not exist when winds are westerly, but coastal waters are generally held against the coast at these times (Wiseman and Short 1976) and extensive seaward transport is thereby prevented. However, C. Mungall (pers. comm., RU 531) cautions that westerly winds might also cause down-welling in nearshore areas, with a consequent seaward transport of bottom water and materials.

In summary, available evidence suggests that the coastal lagoons and bays may be sites to which marine-derived detritus (as well as terrestrially-derived organics) is delivered and deposited.

Effects of Topography

The topographic characteristics of nearshore environments may locally affect the ability of these environments to catch and hold detritus. Studies along the northeastern U.S. coast indicate that organic matter accumulates in depressions in the bottom (Hatcher and Segar 1976). Hedgpeth (1957) notes that troughs between submerged bars parallel to the shore may serve as traps for silt (and presumably detritus as well). Models show an entrapment of suspended material within shoreline irregularities, because of the predicted effects of these irregularities on current speed (Dyer 1978). It is presumed that topographic troughs and shoreline irregularities in the nearshore Beaufort would also cause detritus accumulation. The lagoons themselves are troughs behind the barrier islands and spits; submerged spits and bars parallel to shore are characteristic of areas both with islands and exposed shores (Faas 1974; Short *et al.* 1974; Burrell *et al.* 1975). These emergent and submerged features undoubtedly enhance the effectiveness of the nearshore Beaufort as a detritus trap.

Depositional Evidence

The quantities of organic materials in sediment samples taken in various locations on the shelf may indicate recent as well as historical patterns of detritus deposition, since the nonliving (detrital) organic material in such samples is likely to be the predominant portion of the total organic matter (Fox 1957). Unfortunately, normal methods of collecting sediments for analysis (grab, dredge, etc.) do not accurately measure recent deposits of detritus, which normally rest on top of the substrate. However, if the same sampling device is used, sampling effectiveness should be roughly comparable among sites. Naidu and Mowatt (1975b) found the levels of organic carbon in sediments to be similar in Simpson Lagoon and adjacent Harrison Bay (0.79% and 0.77%, respectively), but lower (0.58%) in the nearby marine environment. In the Canadian Beaufort, Pelletier (1975) found higher organic carbon levels in sediments of deltaic and coastal areas than in the marine environment. Within the nearshore, Naidu (1978) found that organic carbon in sediments decreased from the mainland to the barrier islands across Simpson Lagoon. (The high levels near the mainland were postulated to be related to the nearness of these samples to the source of input, e.g., coastal erosion.) Because of inadequate sampling methods, it is not definite that these seaward decreases in carbon content reflect corresponding decreases in the surface deposits of detritus, although such is suspected.

Other depositional evidence for sites of detritus accumulation is based on the assumption that organic matter normally co-deposits with inorganic fines. Several investigators have described deposition sites for fine silts and clays in the nearshore Beaufort Sea; some have noted the co-deposition of these sediment sizes with organics. Naidu and Mowatt (1975b) point out that the sorting of sediments (and presumably also resuspension and transport of detritus) in the coastal waters of the Beaufort Sea occurs during storms. The ultimate depositional sites of fines are, therefore, the relatively "quiet" localities partially protected from wave action by a combination of topographic features and water depth. Emery and Stevenson (1957) note that mud substrates are usually characteristic of the quiet reaches of estuaries, where turbulence and current action are reduced. Burrell *et al.* (1975) and Naidu (1978) found an inverse correlation between mean particle size and water depth in Simpson Lagoon despite the fact that the Beaufort coastal sediments in general are poorly sorted (Naidu and Mowatt 1975a,b; Weller *et al.* 1978:106). This indicates that the central lagoon basin acts to selectively accumulate fine sediments (Naidu 1978), and perhaps (by inference) detritus.

Lewis and McDonald (1974) maintain that in the Canadian Beaufort Sea, three main sediment sinks exist along the southern coast--between Herschel Island and the mainland, in Phillips Bay, and in Shoalwater Bay. They present no evidence to imply that these are also detritus sinks, but the possibility may be presumed. No data documenting specific sites in the Alaskan Beaufort Sea as sediment or detritus sinks have been published.

GEOMORPHIC FEATURES AND THEIR EVOLUTION

The ecologically important geomorphic features along the Alaskan coast of the Beaufort Sea include

1. The barrier islands which provide nesting sites for certain birds. (The sand and gravel substrates on islands are more important as nesting areas than the tundra-covered portions.)

2. The island chains, which act as barriers to winds and waves and restrict water exchange between coastal and marine systems.

3. The inlets and passes, which connect lagoons with the ocean and with other lagoons, and allow transport of suspended materials and migration of aquatic organisms.

4. The shallow basins of lagoons, which promote rapid warming of coastal waters and provide ready access by birds to bottom-dwelling prey.

Two questions about these features must be answered before it will be possible to assess long-term consequences of some of man's activities.

1. What are the formative processes of the ecologically important features?

2. What time scales are involved in the natural formation and disappearance of these features?

Formative Processes

A knowledge of the processes that have caused the geomorphic substrates of the Beaufort Sea coast to assume their present configuration is very important to assessing the ecological consequences of development because (1) key species make use of some of the features of the barrier islands and sheltered basins along the coast, and (2) development of the nearshore region may entail modification of some of these features. The processes that have given rise to the ecologically important features must be understood in order to decide whether the consequences of particular development activities are likely to be naturally mended. For example, if island materials are now supplied by processes that will no longer function after some development activity, or if islands were formed by processes not currently functioning, then removal of islands or portions of islands may be an irreversible change.

Barrier Islands, Lagoons and Estuaries - General Considerations

The formative mechanisms for coastal barrier islands and their associated estuaries and lagoons have been the focus of controversy over the past century (Schwartz 1973; Wanless 1976). Recent evidence suggests that several processes may act jointly or independently to generate barrier islands in various areas of the world (Zeigler 1959; Otvos 1970; Schwartz 1971). These processes are closely tied to sea level fluctuations (Gill 1967).

Most coastal geologists agree that there has been a general worldwide rise in sea level since the last glaciation (LeBlanc and Hodgson 1959; Shepard 1960; Schwartz 1965; Godfrey 1976; Riggs 1976; Wanless 1976). Many of these workers think that the general rise is continuing, although some (Leontyev 1965; Leontyev and Nikiforov 1965) maintain that a drop in sea level occurred during a brief interlude several thousand years ago. A few investigators (LeBlanc and Hodgson 1959) have found local evidence that the post-glacial rise stopped a few thousand years ago and that the sea level has since remained constant.

Assuming a continued gradual rise in sea level, I will consider three mechanisms that have been proposed for the formation of present-day barriers and the shallow coastal areas behind them: (1) building of barriers by sand thrown up from the continental shelf, (2) elongation of sand spits built from headlands by longshore drift, and their eventual breaching by tidal action, and (3) gradual submergence of low-lying coastal areas behind topographic highs (Schwartz 1971; Wanless 1976).

Evidence from some coasts indicates that barrier islands have been formed and/or enlarged by the accretion of submerged shelf materials onto nearshore submarine or emergent features. LeBlanc and Hodgson (1959) and Shepard (1960) found evidence that materials for many of the barriers along the Gulf of Mexico were derived from shelf sediments that presumably built upon existing emergent islands, or upon submerged bars. The latter are characteristic of shallows immediately off sandy beaches (Hedgpeth 1957). Otvos (1970), working in the same area, and Leontyev (1965), studying barriers in the U.S.S.R., reached similar conclusions about barrier island formation.

Pierce and Colquhoun (1971) doubted that emergent barriers could be built by wave action from submerged bars, particularly at a time when the sea level is rising. They quote Kuelegan (1948), King (1960:337) and McKee and Sterrett (1960) to the effect that breaking orbital waves have questionable ability, in most circumstances, to build an emergent barrier upon a submerged feature. Submarine bars are built by waves but, instead of emerging, the bars usually migrate landward and eventually become part of a pre-existing feature. Under these assumptions, the generation of a barrier by shelf sediments thrown up by waves appears to depend on the existence of an already-emergent feature upon which to build. Regardless of whether submerged bars can emerge during a rise in sea level, once emergent barriers exist, they commonly grow by upward aggradation and remain emergent in spite of a rise in sea level (Shepard 1960).

The generation of sand spits from the mainland or from existing islands is sometimes implicated in barrier island and lagoon formation. These barrier spits are nourished by longshore transport of materials (usually sand) derived from erosion of headlands or from river discharge (Pierce and Colquhoun 1970; Wanless 1976). Eventually, segments of the spits become islands as the spits are breached by wave action during storms. Examples of barriers formed in this way may be seen in such locations as the Atlantic coast of the

United States (Pierce and Colquhoun 1970) and coastal Australia (Bird 1973).

Isolation of coastal headlands by inundation of coastal lowlands behind the headlands may be an important formative mechanism for barrier systems in some areas. Coastal subsidence as a consequence of the rising sea level is the ultimate causative phenomenon. That sea level rise caused coastal lowland submergence was noted early (McGee 1890) along the east coast of the United States. Zeigler (1959) postulated that barrier islands and associated estuaries along the southeastern United States originated by coastal submergence. Hoyt (1967) precipitated more recent controversy in proposing that barrier islands form by gradual submergence of coastal lowlands behind beach-dune ridges (Wanless 1976). Since then, coastal submergence and consequent isolation of mainland features have been commonly postulated as generating mechanisms for island-lagoon systems along the coast of the southeastern United States (Pierce and Colquhoun 1970; Godfrey 1976).

It is now conceded that a combination of mechanisms can form and maintain barrier/lagoon systems (Zeigler 1959; Schwartz 1971). Pierce and Colquhoun (1970) propose that both primary barriers (built on or derived from relict mainland features) and secondary barriers (built from spit extensions of mainland or primary barriers) are common along the North Carolina coast. They maintain that the two different formative processes are not mutually exclusive, but commonly interact. Zeigler (1959) also recognized along the South Carolina coast both mainland-derived emergent features ("erosion remnant" islands) and barriers formed from spit accretion off headlands and islands ("beach-ridge" islands). He proposed that the former were built upon relict features and the latter accreted over submarine deposits by longshore transport and deposition of sediments.

Barrier Islands and Lagoons - Beaufort Sea

There also appears to be a continuing rise in sea level relative to coastal substrates along the southern coast of the Beaufort Sea. Weller *et al.* (1978:103, 105), using data compiled by D.M. Hopkins, showed that 20,000 years ago the surface of the Beaufort Sea was about 80 m below its present level. The increase in sea level, then, has averaged about 40 cm/century for this period. Because of this rise in sea level, the process dominating the formation of barrier island-lagoon systems is probably marine impingement into coastal regions. Two types of barriers (relict and constructional) appear to have been formed as a consequence.

Relict Barriers. It is generally accepted that those Beaufort Sea coastal islands capped with tundra vegetation and peat are remnant mainland features (Cannon and Rawlinson 1978; Weller *et al.* 1978:127). The biological evidence of this is clear--islands have a vegetative covering that is identical with that of the mainland and that overlies undisturbed peat deposits several thousand years old. The geological evidence is also unmistakeable; Cannon and Rawlinson (1978) show that the lake basins on the islands are similar in form and orientation to mainland lake basins and that mainland and island substrates have similar stratigraphies and lithologies.

A feature that has promoted the isolation of coastal bluffs and the associated formation of lagoons is the abundance of lakes in the relatively flat landscape of the coastal plain. Evidence that these lakes have coalesced behind coastal highs, thus hastening the formation of lagoons, has been presented by Faas (1974) and Cannon and Rawlinson (1978) for the Alaskan Beaufort and by Lewis and Forbes (1975:4) for the Canadian Beaufort.

Constructional Barriers. Most of the coastal barrier islands are surfaced with sand and gravel and are, according to conventional definition, constructional (Weller *et al.* 1978:127), notwithstanding that their constituent gravel and sand may have come from relict features (Naidu 1978). The knowledge that they are constructional (at least in part) is insufficient for evaluation of the potential consequences of development; the constructional processes and source materials must also be known.

Clastics (gravels, boulders) larger than sand comprise a significant portion of the constructional materials of Beaufort Sea barrier islands. These gravels are thought to have been very local in origin, because wave and current energies capable of transporting them from elsewhere do not presently exist along the Beaufort coast (Naidu and Mowatt 1975a; Cannon and Rawlinson 1978). Naidu and Mowatt (1974) postulated that some of the large boulders found sparingly on these barriers might have been ice-rafted from elsewhere, but Cannon and Rawlinson (1978) and Weller *et al.* (1978:111) disagreed with that view. Cannon and Rawlinson (1978) believed the coarse clastics to be lag deposits from eroded remnant islands.

The specific mechanisms and magnitudes of transport of the gravel-sized clastics are not completely known. Faas (1974), Reimnitz *et al.* (1977), Cannon and Rawlinson (1978), and Weller *et al.* (1978:124) think that they are transported very short distances, and are only locally reworked by ice shove and wave action. Weller *et al.* (1978:124, 129) imply that transport of gravel may be restricted to the island where the gravel originated, especially if islands are separated by relatively deep inlets. Rex (1964) working in the western Beaufort near Barrow, and Lewis and Forbes (1975) working in the eastern Beaufort, found that gravels may be transported considerable distances along spits. Nevertheless there is general agreement that present-day transport of gravel on the Beaufort Sea shelf by natural processes is very limited (Reimnitz *et al.* 1977; Weller *et al.* 1978:129; and others).

Sand-sized and finer sediments may be moved through the nearshore system by longshore transport and thereby supplied to barrier islands and spits from relatively distant sources (Lewis and Forbes 1975:3; Cannon and Rawlinson 1978; Naidu 1978). (Of these sub-gravel sized particles, those comprising constructional spits and barriers are mostly sand, so silts and clays are not of significant concern.) The primary sources of sand for barrier and spit accretion along the coast of the Beaufort Sea are presumed to be river discharge and erosion of coastal headlands; landward transport of continental shelf sands has not been postulated to be significant. As might be suspected, sand discharged into the nearshore by rivers appears to settle near the deltas, whereas clays and silts tend to travel farther (Burrell *et al.* 1975). Similarly, sand released from eroded coastal headlands is initially deposited near its source (Schwartz 1965).

Once the sand is deposited, it is not easily resuspended by waves and transported by currents unless it remains in very shallow water (Burrell *et al.* 1975; Swift 1976; Naidu 1978). The fact that sand at depth is not readily resuspended and transported suggests that a shallow-water "corridor" must exist between a sand source (e.g., river depositional site, mainland or island depot) and an emergent feature in order for the feature to be significantly nourished by sand from such sources. Maximum depths at which sand is readily resuspended and transported along low-energy coasts such as along the southern Beaufort Sea are not known. However, sedimentologists working along the Beaufort Sea coast (e.g., Burrell *et al.* 1975; Naidu 1978) have found that lagoons with depths of only a few meters selectively accumulate fine-grained (silt, clay) particles, suggesting that sand from terrestrial sources is not readily transported into and across such depths to the barriers beyond. This is supported by observations that most sand transport from mainlands and barriers seems to be along emergent or slightly submerged spits extending from headlands or existing islands (e.g., Pierce and Colquhoun 1970; Burrell *et al.* 1975; Wanless 1976), or along the beaches of chains of emergent barriers. Even the transport of sand along barrier chains may be hindered by the presence of inlets between islands (Weller *et al.* 1978:129).

In the final analysis, then, most constructional barrier islands along the Beaufort Sea coast are probably relict features that have been eroded and reshaped by wave action and ice push. Their large clastics are probably lag deposits dropped in place as the islands have eroded, and are not being currently supplemented from elsewhere. The islands may be nourished by sands from more distant river discharges or erosion of coastal headlands if they are separated from such sand sources by relatively shallow depths, but deep lagoons and inlets may partially or completely block such supplies of sand.

Whether sand from the deeper marine areas of the continental shelf also accretes in significant quantities to the nearshore barriers is not known, but such has not been postulated to be the case.

Time Scales of Change

The impacts of development activities on biological communities persist only when the habitat changes exceed the capacities of organisms within the communities to adjust. If the development activities do not persist, most (but not all, see Holling 1978:30-32) ecological impacts are temporary in the sense that populations can resume their original status and function once the habitat is "repaired". Thus an important question in assessing long-term ecological impacts is "How long will habitat changes caused by man persist?"

This question is especially important in assessing the impacts of landscape changes in coastal regions of the Beaufort Sea because the effectiveness of physical processes in molding some geomorphic substrates suggests that some changes in these substrates would eventually be mended by natural forces. The critical questions relate to how fast the natural changes will obscure the man-caused changes.

In this section we will address rates of natural geomorphic change in the barrier islands, the lagoonal and estuarine basins, and the mainland coasts, with a view to estimating the permanence of man-caused changes in these features. It should be remembered that natural changes in all these features will be influenced greatly by coastal subsidence.

Barrier Islands

Storm surge events rapidly erode the tundra and peat covers of mainland relict islands. Cannon and Rawlinson (1978) estimated that the margins of tundra caps on islands enclosing Simpson Lagoon erode at an average rate of 1.6 m per year. They also estimated that these islands will retain their tundra/peat caps for lengths of time varying between 35 and 270 years (depending on island size), given the present rates of erosion.

Likewise, both sand-and-gravel islands and the sand-and-grável portions of tundra-capped islands change shape and move rapidly. Sand and gravel from the eastward and seaward extremes of islands appear to be eroded and transported to accrete to the westward and landward portions of the islands; consequently the direction of island migration is predominantly westward (in the direction of the dominant longshore transport) and southward (landward). Islands migrate at annual rates estimated variously to be 6-25 m (Short *et al.* 1974), 6-72 m (Reimnitz *et al.* 1977), and 13-30 m westward and 3-7 m landward (Weller *et al.* 1978:12).

The tenure of Beaufort Sea barrier islands as emergent features is not known. Presumably it must be a matter of centuries, since all the major islands in existence at the time the arctic coastal islands were first mapped in the early 20th century are still in existence, and no major new islands have formed since then. Reimnitz *et al.* (1977) state that Cross Island northeast of Prudhoe

Bay has apparently not changed greatly in emergent area since it was mapped by the U.S. Geological Survey in the early 1900's (Leffingwell 1919). Considering that most of the islands presently extend at least 1-2 m above sea level, it would take several centuries for them to be submerged at the estimated present rate of sea level rise if no erosional degradation in height occurred in the interim. Evidence from other areas suggests that such degradation would not occur, for emergent features frequently tend to build upon themselves to remain emergent as the sea rises (Shepard 1960).

Lagoon Basins

Since the lagoons depend on the existence of barriers, a lagoon and its barrier islands have similar durations. However, during the lifetime of a barrier island-lagoon system, the geomorphic boundaries of lagoons may change in important ways. Lagoon depth, inlet characteristics, and lateral extent are all ecologically significant attributes that may change with time.

Change in depth of nearshore waters is a function of the balance between sediment deposition (which causes shoaling) and subsidence and/or sediment removal (which deepens coastal basins). Emery and Stevenson (1957) and Hedgpeth (1957) observed that deposition (largely of stream-derived sediments) caused depths of Texas bays to decrease by about 23 cm in 65 years, despite a general coastal subsidence of about 30 cm during the same period. Schwartz (1965), in a laboratory study of rise in sea level and shore erosion, suggested that the rise of nearshore bottoms simply as a result of deposition of beach-eroded materials should equal the rise in sea level, thus maintaining a constant nearshore water depth despite regional subsidence.

In sheltered waters along the Beaufort coast of Alaska, measured net sedimentation rates are 5 cm/century off the Colville delta, 10 cm/century in many nearshore areas (both inside and outside barrier islands), and as much as 60 cm/century in Prudhoe Bay (Weller *et al.* 1978:106). These sedimentation rates are of the same order of magnitude as the average 40 cm/century rate of increase in sea level estimated for the last several thousand years (calculated from data of Weller *et al.* 1978:105). The implications are that regional subsidence may compensate for much or all of the potential shoaling caused by deposition, and that, as a consequence, lagoon depths may remain fairly constant for long periods. However, since the estimates of both subsidence and deposition rates are very imprecise, the rate of change in water depths in coastal regions of the Beaufort Sea is uncertain.

Inlet characteristics and locations, as we have seen, are primarily a function of the hydraulic forces impinging on a barrier island chain (Emery and Stevenson 1957; Riggs 1976). Short-term changes, particularly in inlet shape and size, may be very rapid in direct response to hydraulic pressures, but over the long term inlets with the same general characteristics will recur to accomodate discharge forced by the regional oceanographic circulation patterns. Therefore, as the depth and lateral conformity of a lagoon change with time, inlets will correspondingly change in size and location. Weller *et al.* (1978:129) imply that inlets in Beaufort Sea barrier island chains migrate westward with the individual islands. However, inlets opposite river mouths (for example, Egg Island Channel off the Kuparuk River delta) must remain in the same general locality to accomodate the annual river discharge.

Weller *et al.* (1978:127) report that constructional islands along the Beaufort coast migrate landward at an annual rate of about 3-7 m. This rate is similar to, and in the same direction as, the coastal erosion rates estimated by various researchers (see following section). Given, then, that both the island/lagoon margins and the mainland/lagoon margins are moving southward at similar rates, lagoon width should remain fairly constant for long periods.

Mainland Coasts

As noted earlier, the mainland along the Beaufort Sea coast is receding, eroded mostly by storm surge action. There is extreme short-term variability in erosion rates because erosion is significant only during storms. Estimates of annual rates of coastal recession vary. Schell (1975) calculated annual rates of 1.4 m/year over 22-23 years for a stretch of mainland bordering Simpson Lagoon, and Cannon and Rawlinson (1978) estimated retreat rates of about 1.2 m/year for the mainland in the Simpson Lagoon area. Hume and Schalk (1967) reported a beach retreat of about 9 m during the course of one storm near Barrow, and Leffingwell (1919) reported short-term erosion rates of up to 30 m/year at Drew Point and Cape Simpson. Lewis and Forbes (1975:3) report sea cliff retreat of up to 90 m in 16-18 years along the Canadian Beaufort coast. Weller *et al.* (1978:126) estimate that coastal retreat averages 1 m per year in the Canadian Beaufort west of the MacKenzie Delta, 1.6 m per year in the Alaskan Beaufort east of the Colville delta, and 4.7 m per year in the Alaskan Beaufort west of the Colville delta.

CONCLUSIONS

A summary of important conclusions follows.

In summer along the Beaufort Sea coast, prevailing wind regimes cause water to rapidly exchange between adjacent coastal water bodies. Exchange between coastal and offshore waters is, on the other hand, sufficiently restricted that the two systems remain measurably different in their temperatures and salinities, and presumably in other attributes as well. In winter, coastal circulation and exchange rates are much reduced from those of summer.

The water exchange that occurs between the relatively warm and brackish nearshore waters and the colder, more saline ocean waters is probably dominated by an exchange pattern characteristic of many estuarine areas--landward intrusion of ocean water near the bottom and seaward movement of nearshore water at the surface. It appears that this process along the Beaufort coast may commonly be augmented by coastal upwelling. The rates of such exchanges are retarded by barrier island chains.

Currents near the bottom are more important in transporting ecologically significant materials than are currents higher in the water column. Existing data suggest that there is a dominant landward component in the bottom currents in summer that may promote net landward delivery of materials and organisms entrained in the lower part of the water column.

The amounts of detritus delivered to the nearshore waters by river discharge and by coastal erosion are about equal; amounts delivered from offshore environments have not been quantified. Several lines of evidence suggest that nearshore basins behind barrier islands and submerged bars are traps for detritus from all three sources.

Major barrier islands along the Beaufort Sea coast are of two related kinds--relict mainland features and constructional barriers built upon or from relict features. They were originally formed as the sea rose and inundated areas behind coastal highs. Most of these islands are apparently not presently being nourished significantly by materials transported from distant sources.

Lateral shifts in coastal landforms are rapid--margins of coasts, islands, and lagoon basins annually move several meters landward and/or westward. Large-scale vertical changes in topographic features are much slower, and seem to be controlled over the long term by the tendency of the rising sea to inundate features and the opposing tendency of bottoms of lagoon basins and surfaces of islands to rise because sand and silt slowly accrete to them. Tens of centuries may pass before the sea drowns the existing barrier island-lagoon systems and intrudes landward to form new systems from lake beds and other low places behind coastal ridges.

RECOMMENDED FURTHER RESEARCH

This part of the Barrier Island-Lagoon Program will be updated and revised during the next few months using new data that will be forthcoming from the oceanographers and geologists participating in the program. This revised version will be included as a chapter in the Final Report, which is scheduled for completion by 30 September 1979.

SUMMARY OF 4th QUARTER OPERATIONS

The fourth quarter was spent preparing the Annual Report.

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