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ENVIRONMENTAL ASSESSMENT PROGRAM

FINAL REPORTS OF PRINCIPAL INVESTIGATORS

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U.S. DEPARTMENT OF COMMERCE
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Outer Continental Shelf Environmental Assessment Program

Final Reports of Principal Investigators

VOLUME 53 DECEMBER 1986

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BAFFIN ISLAND EXPERIMENTAL OIL SPILL AND DISPERSANT STUDIES. HYDROCARBON BIOACCUMULATION AND HISTOPATHOLOGICAL AND BIOCHEMICAL RESPONSES IN MARINE BIVALVE MOLLUSCS

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SUMMARY

Infaunal bivalve molluscs from four bays at the BIOS experimental oil spill site became contaminated with petroleum hydrocarbons. Bay 7 was considered a reference bay (though it received some oil), Bays 9 and 10 received dispersed oil, and Bay 11 received oil alone. A Lagomedio crude oil and the dispersant, Corexit 9527, were used in these field experiments. Mya truncata and Serripes groenlandicus, which are filter-feeders, rapidly accumulated dispersed oil in Bays 7, 9 and 10 immediately after the spill, but released much of the hydrocarbons by the second post-spill sampling about two weeks after the spill. The deposit feeders, Macoma calcarea, Astarte borealis, and Nuculana minuta, accumulated more oil than did the filter-feeders (presumably from the sediments) and retained them longer in Bays 9 and 10. In Bay 11, all five species accumulated very little oil immediately after the spill but became heavily contaminated within about two weeks. Bay 7 received about 50-100 ppb dispersed oil in the first few days after the dispersed oil spill. This was about 1,000-fold less than the amount in the water of Bay 9. Nevertheless, the molluscs, especially Serripes, from Bay 7 became moderately heavily contaminated with oil.

Based on chemical data, both Mya and Serripes depurated oil during the two-week post-spill period, in part through an in vivo biodegradation presumably by microbial activity in the guts of the animals. However, Serripes preferentially retained the high molecular weight saturated hydrocarbon assemblage as well as the higher alkylated naphthalene, phenanthrene and dibenzothiophene compounds, whereas Mya depurated all hydrocarbon components although the water-soluble alkyl benzenes and naphthalenes were depurated somewhat faster. The filter-feeders depurated oil even though the sediments in which they resided still contained oil. However, the deposit feeders continued to accumulate oil from the sediments, at least for the two weeks after the spills.

Specimens of Mya truncata and Macoma calcarea for histopathologic examination were collected immediately before, immediately after, and one year after the experimental oil spills. Immediately after the spill, there was an increased incidence of gill and digestive tract necrosis in Mya from the bays receiving dispersed oil (Bays 7, 9 and 10). This was accompanied by an increase in the number of mucus cells in the digestive tract epithelium. After one year, a few clams had granulocytomas throughout

the tissues. Three clams from Bay 11 (receiving oil alone) collected one year after the spill had invasive neoplasias (probably cancer). One clam from Bay 7 immediately after the spill had a similar lesion.

There were few lesions in Macoma from Bays 7 and 9 immediately after or one year after the spill. One year after the spill, animals from Bay 11 had a high incidence of vacuolization of the digestive tubule epithelium. The incidence of parasitism and hemocytic infiltration also was higher in Macoma from Bay 11 than from the other bays. One specimen had a blood neoplasm.

Clams Mya truncata were collected immediately before, immediately after, and about two weeks after the simulated oil spills for biochemical analysis. Concentrations in the clam tissues of glucose, glycogen, trehalose, total lipid and free amino acids were measured. Concentrations and ratios of free amino acids in adductor muscle were the most useful indices of pollutant stress.

The results of the biochemical analyses indicate that Mya from the four bays were not severely stressed by either dispersed oil or oil alone. Immediately after the spill, clams from the two major dispersed oil bays, and particularly Bay 10, appeared to be more severely stressed than clams from Bay 11 (using clams from Bay 7 as reference). After two weeks, clams from the dispersed oil bays were nearly normal, while those from the bay receiving oil alone appeared stressed. These results seem to corroborate results from analytical chemistry and histopathology, that the acute effects of dispersed oil are greater than those of undispersed oil, but effects of undispersed oil on infaunal molluscs develop more slowly and persist longer than those from dispersed oil.

FINAL REPORT

on

BAFFIN ISLAND EXPERIMENTAL OIL SPILL AND DISPERSANT STUDIES. HYDROCARBON BIOACCUMULATION AND HISTOPATHOLOGICAL AND BIOCHEMICAL RESPONSES IN MARINE BIVALVE MOLLUSCS

to

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1. INTRODUCTION

More than 10,000 tons of chemical dispersant were used to clean the coast of Cornwall, England of Kuwait crude oil following the Torrey Canyon oil spill in 1967. It is now generally agreed that the dispersant caused more damage to the intertidal fauna and flora than did the oil itself (Southward and Southward, 1978). The most frequently used dispersant during the Torrey Canyon cleanup contained 12% nonionic surfactant and 3% stabilizer in a high aromatic solvent (kerosene extract). This mixture was highly toxic to nearly all forms of marine life. Because of the disasterous consequences of dispersant use in this and a few other spills, use of chemical dispersants for oil spill cleanup fell into disfavor. Relatively little dispersant was used after the Amoco Cadiz spill and none was used for shoreline cleaning.

Since the Torrey Canyon incident, considerable progress has been made in developing dispersants that have a very low toxicity to marine organisms. Since dispersal may be the method of choice in many cases for treating spilled oil, there is an urgent need for information about the toxicity and environmental impact of oil that has been dispersed with the new generation of "low-toxicity" dispersants (Sprague et al., 1982). The controlled experimental oil spill-dispersant study - The Baffin Island Oil Spill (BIOS) Project - being conducted by the Canadian Environmental Protection Service offers a unique opportunity to assess the biological effects of dispersed oil in a field situation. The primary objective of the BIOS Project was to determine if the use of dispersants in the Arctic nearshore will reduce or increase the environmental effects of spilled oil (Blackall, 1980).

1.1 Objectives of the Research Program

The primary objective of this research program was to assess and compare sublethal biological effects of chemically dispersed and non-dispersed spilled oil on benthic infaunal bivalve molluscs from the Arctic. The research project has three components: accumulation by three species of molluscs (Mya truncata, Serripes groenlandicus, and Astarte borealis) of hydrocarbons from dispersed and non-dispersed spilled crude petroleum; sublethal biochemical responses of Mya truncata to dispersed and non-dispersed spilled crude petroleum; histopathology of Mya truncata and Macoma calcarea up to one year after the simulated oil spills. The program was designed to determine if chemically dispersed oil is more or less bioavailable than undispersed oil to benthic infaunal bivalve molluscs, and whether dispersed oil is more harmful than undispersed oil to these animals.

1.2 Background

1.2.1 Hydrocarbon Accumulation. Marine animals readily accumulate petroleum hydrocarbons in their tissues from dispersion or solution in seawater and to a lesser extent from petroleum-contaminated sediments and food (Neff, Anderson, Cox, Laughlin, Rossi and Tatem 1976 ; Neff, Cox, Dixit and Anderson, 1976; Boehm and Quinn, 1977; Lee, 1977; Neff, 1979; Neff and Anderson, 1981; Boehm, Barak, Fiest and Elskus 1982). Bivalve molluscs, apparently because

they have little or no ability to metabolize aromatic hydrocarbons to water-soluble and easily excreted metabolites (Vandermeulen and Penrose, 1978; Lee, 1981), tend to accumulate petroleum hydrocarbons to higher concentrations and retain them longer than do other phyla of marine organisms (Neff, Cox, Dixit and Anderson 1976;Boehm and Quinn, 1977; Neff and Anderson, 1981; Elmgren et al., 1983). Dispersants favor the formation of micro oil droplets in the water column. The oil droplets are of a size that might be readily filtered from the water and ingested during normal filter feeding activity of bivalve molluscs. Thus, the use of dispersant could increase the bioavailability of petroleum hydrocarbons and, of particular importance, the poorly soluble medium molecular weight polycyclic aromatic hydrocarbons and heterocyclics (azaarenes, dibenzothiophenes, etc.) to bivalve molluscs.

1.2.2 Histopathology. Petroleum hydrocarbons, and particularly the more toxic aromatics and heterocyclics, accumulated by marine animals interact with cells and tissues to produce a variety of lesions. Aromatic hydrocarbons bind to the surface of cell membranes and interfere with cell membrane-mediated biological processes (Roubal, 1974; Roubal and Collier, 1975). Many hydrocarbons are irritants and cause localized inflammatory responses. In oysters Crassostrea gigas from the Amoco Cadiz oil spill site, the most common histopathology was leucocytosis (an inflammatory response) in mantle and gill tissues (Neff and Haensly, 1982). Cockles, Cerastoderma edule, and mussels, Mytilus edulis, transplanted to a bay that was heavily contaminated with oil from the Amoco Cadiz spill, developed accumulations of lipid droplets and lysosomal granules in the digestive diverticula (Wolfe et al., 1981). Stainken (1976) reported generalized leucocytosis in the mantle of soft-shell clams Mya arenaria exposed in the laboratory to oil. He also observed glycogen depletion and cellular vacuolization in several tissues of exposed clams. A wide variety of other histopathological lesions have been reported in invertebrates and fish exposed to petroleum in the laboratory or field (Malins, 1982).

Crude petroleum and heavy refined oils (e.g., bunker C residual oil) contain known carcinogens including benzo(a)pyrene, dimethylbenz(a)anthracene, and methyl chrysene (Neff, 1979). There are several reports in the literature of increased incidence of apparently cancerous tumors in populations of bivalve molluscs from oil spill sites (Barry and Yevich, 1975; Gardner et al., 1975; Farley, 1977; Yevich and Barszcz, 1977; Brown et al., 1979; Mix, 1982). However, in no case has it been unequivocally demonstrated that oil was the immediate cause of the cancerous lesions.

Immunosuppression and the resulting increased susceptibility to disease, including parasitism, has been observed in molluscs and other marine animals exposed to oil spills (Hodgins et al., 1977; Sindermann, 1982). Since some hyperplastic or neoplastic (cancer-like) lesions in molluscs are known or suspected of being caused by viruses, bacteria, or fungi (Couch and Winstead, 1979), similar cancer-like lesions in bivalves from oil spill sites may result from petroleum-mediated infection with pathogenic organisms.

1.2.3 Biochemistry/Physiology. Several physiological or biochemical measures of metabolic energy partitioning and nutritional status may be sensitive indices of sublethal pollutant stress in marine invertebrates. This conclusion is based on the hypothesis, supported by substantial experimental data, that a majority of pollutants at environmentally realistic concentrations, which are usually well below concentrations that are acutely lethal, act as loading stressors. Chronic exposure of the animal to these sublethal pollutant concentrations leads to an increase in the metabolic cost of basic biological maintenance and homeostatic functions. Less energy is available for growth and reproductive processes, and nutrient reserves are depleted. Recent reviews supporting this hypothesis include those of Rosenthal and Alderdice (1976) and Bayne et al. (1979; 1982).

Typical responses of bivalve molluscs to chronic exposure to sublethal concentrations of petroleum include alterations in respiration rate or ratio of oxygen consumed to nitrogen excreted (Capuzzo, 1981; Widdows et al., 1982), reduction in nutrient assimilation and scope for growth (Dow, 1975; Gilfillan et al., 1976; Gilfillan and Vandermeulen, 1978; Keck et al., 1978; Stekoll et al., 1980; Bayne et al., 1982; Mahoney and Noyes, 1982), reduced growth rate (Anderson et al., 1983), depletion of glycogen reserves (Stainken, 1976), changes in tissue free amino acid concentrations and ratios (Jeffries, 1972; Roesijadi and Anderson, 1979; Augenfeld et al., 1980), and decrease in condition index (Roesijadi and Anderson, 1979; Augenfeld et al., 1980). All these responses are indicative of a pollutant-mediated increase in metabolic load (loading stress) on the animals.

In oysters from the Amoco Cadiz oil spill site, we have observed statistically significant long-term (more than two years) changes in tissue free amino acid ratios, blood glucose concentration, and reserves of glycogen and ascorbic acid (Neff and Haensley, 1982).

2. HYDROCARBON BIOACCUMULATION

2.1 Materials and Methods

Specimens of Mya truncata, Serripes groenlandicus, and Astarte borealis were collected, when available in sufficient numbers, from the 3-meter and 7-meter transects in all four bays (Figure 2.1) at three sampling times, immediately pre-spill, immediately post-spill, and approximately two weeks after the experimental spills. Animals were wrapped in aluminum foil and frozen for air shipment to the laboratory.

Aromatic hydrocarbons and sulfur heterocyclics in tissues were analyzed by gas chromatography/mass spectrometry/data systems (GC/MS/DS). In order to investigate the polycyclic aromatic nitrogen heterocyclic (PANH) composition and content of the tissue, sample extracts from molluscs taken along the two depth strata were pooled and analyzed by GC/MS for PANH.

Very briefly, the analytical methods used were identical to those of Boehm, Barak, Fiest and Elskus (1982), a modification of the Warner (1976) alkaline digestion-extraction procedure. After fractionating the extract on an alumina-silica acid column, the saturated and aromatic hydrocarbons were analyzed by capillary GC and computer-assisted GC/MS (GD/MS/DS). GS/MS/DS analyses focused on the two- to five-ringed aromatic compounds. PANH analyses involved the GC/MS analysis of an aqueous acid extract of the total extractable (solvent) lipids, which had been neutralized and back extracted with solvent to recover the basic PANH compounds.

2.2 Results

Results from Boehm (1982) of analyses of total saturate and aromatic hydrocarbons in five species of bivalves, including the three species treated in detail in this report, are summarized in Table 2.1. The three filter-feeders, Mya truncata, Serripes groenlandicus, and Astarte borealis from the bays receiving dispersed oil (Bays 7, 9 and 10) rapidly accumulated petroleum hydrocarbons to high levels within a few days of the spills. In Bay 11 which received undispersed oil, these species accumulated petroleum hydrocarbons more slowly. Animals from the three bays receiving dispersed oil, released

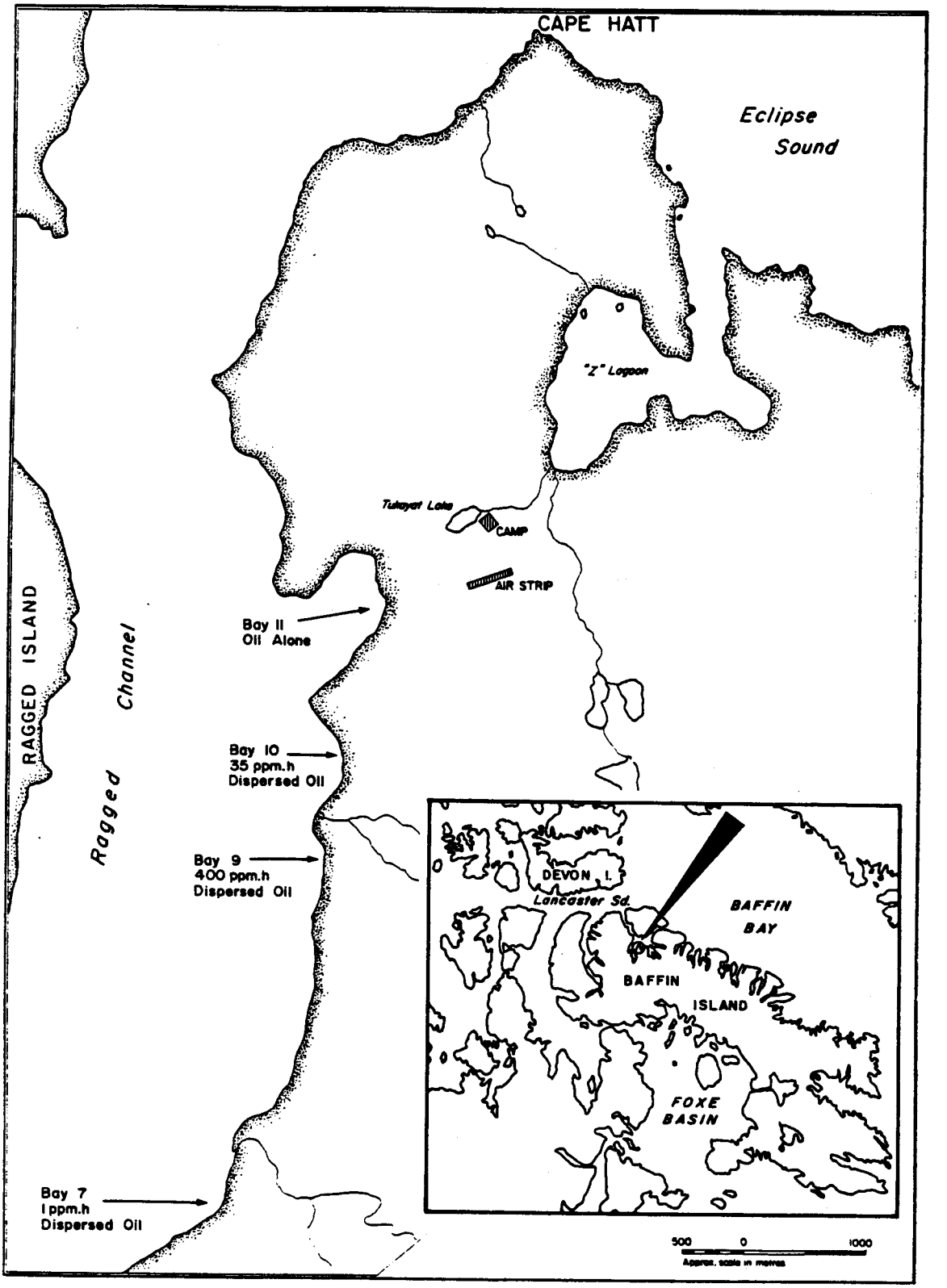

Figure 2.1. BIOS site at Cape Hatt, Baffin Island, showing the locations of study bays and oil treatments applied in August, 1981. Dispersed oil concentrations are maximum estimated exposures in ppm x hours (From Cross and Thompson, 1982).

Table 2.1. Summary of oil concentrations[a] in mollusc tissues by bay (in µg/g dry weight). (from Boehm 1982)

SPECIES	STRATUM	BAY 9 (DISPERSED OIL) PRE-SPILL	BAY 9 (DISPERSED OIL) FIRST POST-SPILL	BAY 9 (DISPERSED OIL) SECOND POST-SPILL	BAY 10 (DISPERSED OIL) PRE-SPILL	BAY 10 (DISPERSED OIL) FIRST POST-SPILL	BAY 10 (DISPERSED OIL) SECOND POST-SPILL
Mya truncata	7m	0.35 (.22, .49)	121 (51, 290)	114 (90, 140)	0.57 (.42, .74)	277 (180, 420)	157 (110, 230)
	3m	0.40 (.25, .56)	215 (130, 350)	135 (120, 150)	0.78 (.55, 1.0)	368 (290, 460)	131 (96, 178)
Serripes groenlandicus	7m	-	186 (110, 330)	97 (59, 160)	-	329 (240, 460)	141 (110, 180)
	3m airlift	-	-	160 (120, 210)	-	698 (500, 970)	177
	7m	0.68 (.02, 1.9)	482 (340, 680)	116 (69, 190)	1.4 (.40, 3.0)	278 (220, 350)	149 (130, 170)
Macoma calcarea	7m	0.73 (.33, 1.2)	75 (36, 150)	836 (610, 1140)	2.1 (1.0, 3.6)	406 (241, 680)	440 (250, 760)
	3m	-	-	-	-	-	-
Astarte borealis	7m	0.81 (0.41, 1.3)	463 (270, 800)	171 (88, 330)	1.4	441.5	336.7
	3m	-	-	-	-	-	-
Nuculana minuta	7m	1.3	33.0	615.6	1.4	441.5	336.7
	3m	-	-	-	-	-	-

Table 2.1. (Continued)

SPECIES	STRATUM	BAY 7 (REFERENCE) PRE-SPILL	BAY 7 (REFERENCE) FIRST POST-SPILL	BAY 7 (REFERENCE) SECOND POST-SPILL	BAY 11 (OIL ALONE) PRE-SPILL	BAY 11 (OIL ALONE) FIRST POST-SPILL	BAY 11 (OIL ALONE) SECOND POST-SPILL
Mya truncata	7m	0.34 (.21, 4.8)	114 (64, 210)	47 (31, 70)	0.43 (.33, .53)	2.0 (1.2, 3.1)	93 (73, 120)
	3m	-	-	-	-	-	-
Serripes groenlandicus	7m	-	-	-	-	-	-
	3m airlift	-	-	-	-	-	-
	7m	1.2 (1.2, 1.3)	517 (360, 750)	73 (31, 170)	1.6 -	6.0 (.19, 41)	394 (200, 780)
Macoma calcarea	7m	1.0 (.88, 1.2)	82 (60, 112)	85 (39, 190)	2.5 (.05, 10)	24 (14, 42)	246 (76, 790)
	3m	-	-	-	-	-	-
Astarte borealis	7m	2.2 (.38, 6.4)	51 (12, 210)	56 (31, 140)	0.47 (.31, .92)	2.7 (2.2, 3.4)	140 (50, 390)
	3m	-	-	-	-	-	-
Nuculana minuta	7m	1.2	41.2	87.3	1.1	11.3	428.9
	3m	-	-	-	-	-	-

[a]Geometric mean (lower 95% confidence limit, upper 95% confidence limit).

some of the oil during the period between the first and second post-spill sampling (about 2 weeks). A different pattern of hydrocarbon bioaccumulation was evident in the two deposit-feeding bivalves, Macoma calcarea and Nuculana minuta. In these species, uptake of petroleum hydrocarbons in all four bays was more gradual and maximum body burdens were reached in the second post-spill samples.

Although Bay 7 was considered a reference bay, 50-100 ppb dispersed and soluble petroleum hydrocarbons were measured in the water column of the bay after the dispersed oil spill. The benthic bivalves from this bay, in particular Serripes groenlandicus and Mya truncata, became contaminated with petroleum hydrocarbons immediately after the spill.

2.2.1. Mya truncata. The analytical results from 20 samples of Mya truncata are summarized in Figures 2.2-2.15. Results correspond to one GC/MS/DS analysis of a pooled extract of five stations along a depth stratum. For example, the 1-day post-spill sample from Bay 9 (7m) represents a result of a pooling of five samples (1 sample = 10 animals) along the 7-meter depth stratum in this bay. Pre-spill, 1-day post-spill, and 2-week post-spill analyses are presented for each bay. A set of samples from the inshore (3-meter) transect was analyzed from Bays 9 and 10. In addition to the pooled 5-station sample, analyses were conducted on animals from two individual stations in Bay 9. Total petroleum (by UV) values for samples from each station and selected capillary GC traces are presented as well.

There were differences in the patterns of accumulation of different aromatic and sulfur heterocyclic hydrocarbons in M. truncata from different water depths in the same bay (e.g., Figure 2.2) and from different stations along the same depth transect (Figure 2.3), perhaps indicating an uneven distribution of hydrocarbons in the bays. In M. truncata from Bays 9 and 10 which received dispersed oil, the compound accumulated to the greatest extent from each of the three homologous series examined in detail was C_3-naphthalenes, C_2-phenanthrenes and C_2-dibenzothiophenes (Figures 2.2 and 2.7). Only very small amounts of higher molecular weight polycyclic aromatic hydrocarbons were accumulated (Σ PAH in figures). On the other hand, M. truncata from Bay 11 which received undispersed oil, preferentially accumulated C_4-naphthalenes, C_3-phenanthrenes and C_3-dibenzothiophenes. These clams also accumulated proportionately much smaller amounts of naphthalene and alkyl naphthalenes than did clams from Bays 9 and 10. M. truncata from Bay 11 undoubtedly were exposed to more highly weathered oil than clams in Bays 9 and 10.

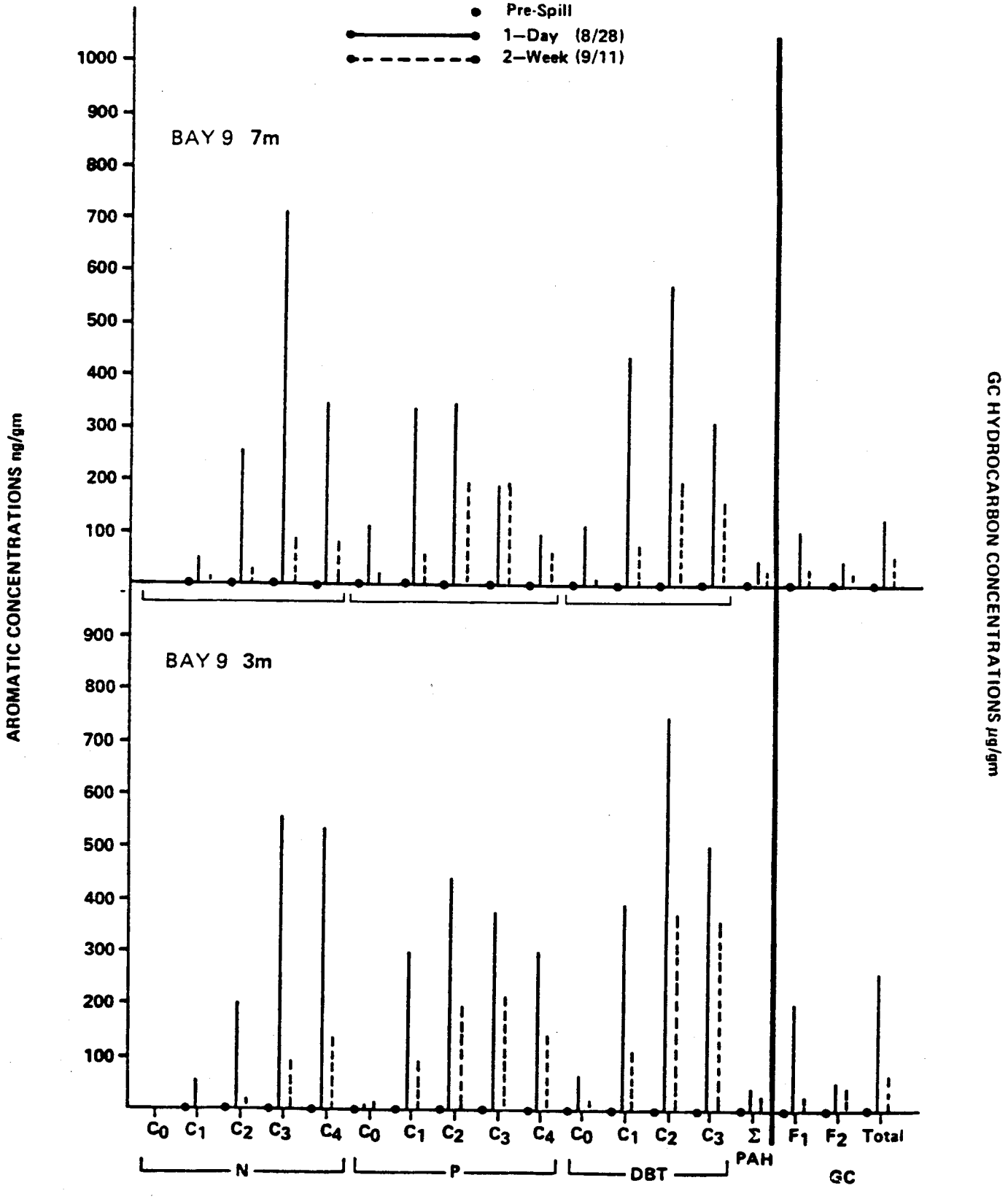

Figure 2.2. Mya aromatic profiles (by GC2/MS), (Bay 9).

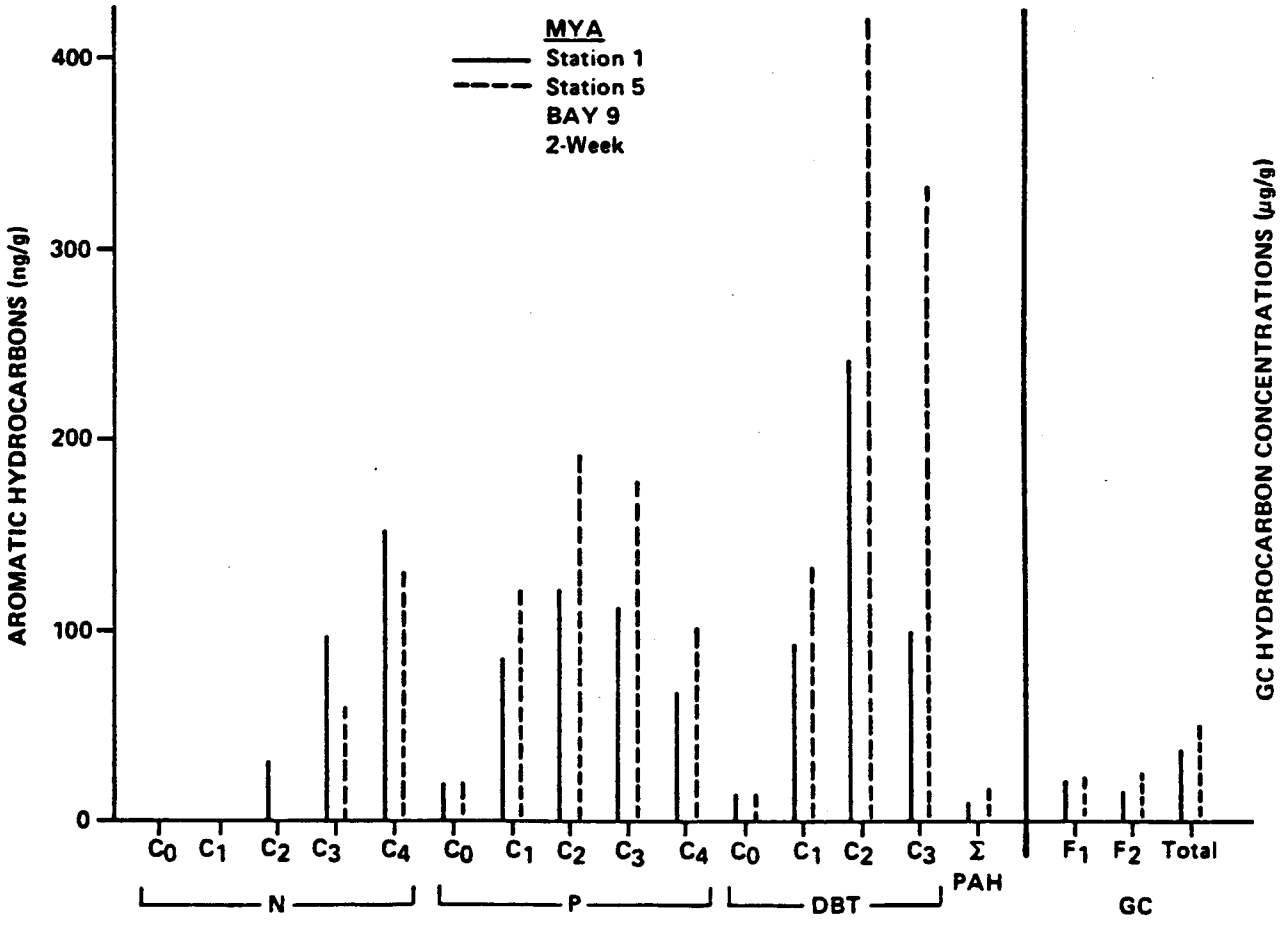

Figure 2.3. Variation of aromatic hydrocarbon levels in Mya along 7 meter depth stratum (Bay 9).

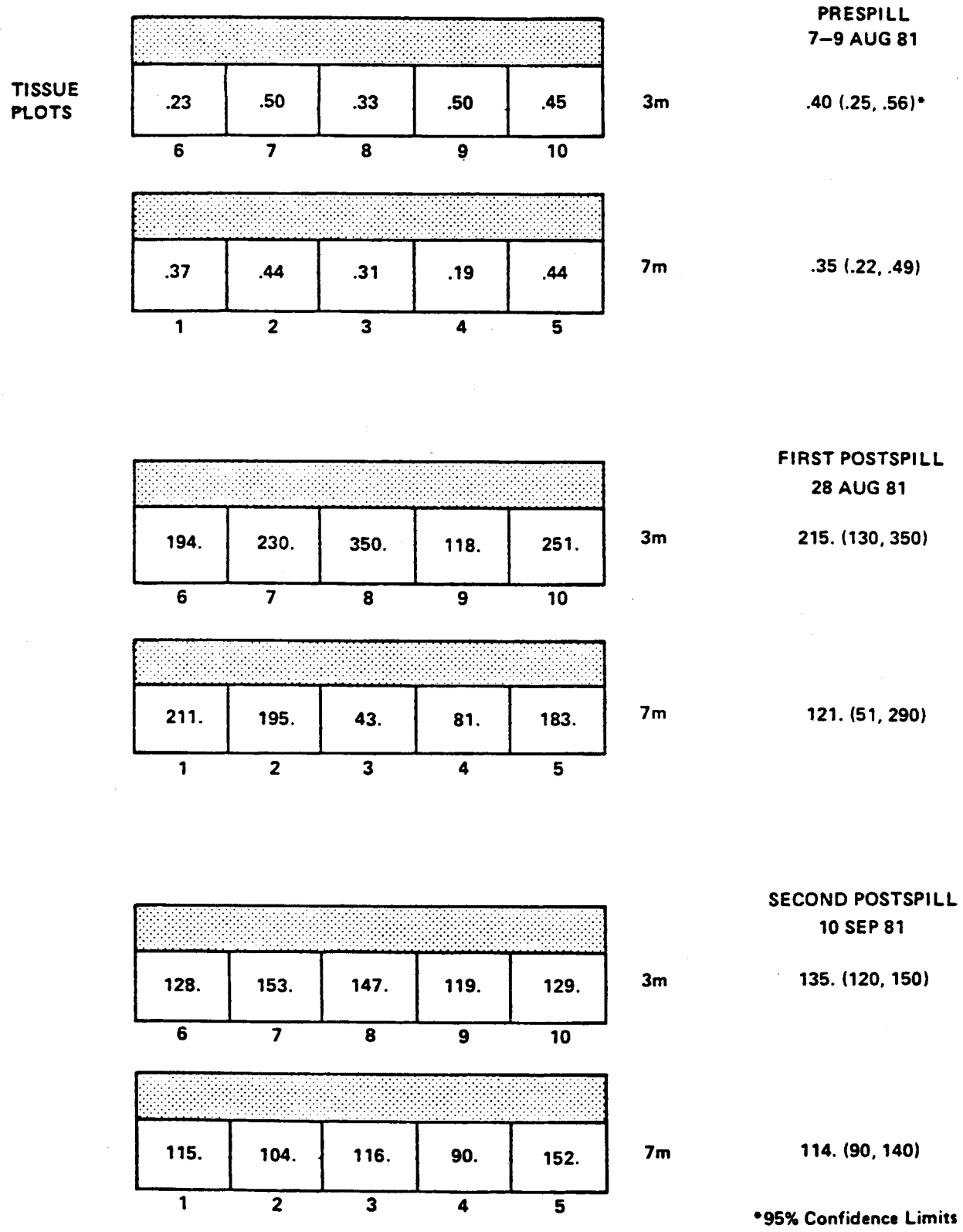

Figure 2.4. Concentrations of oil in Mya truncata, Bay 9 by UV/F (µg/g).

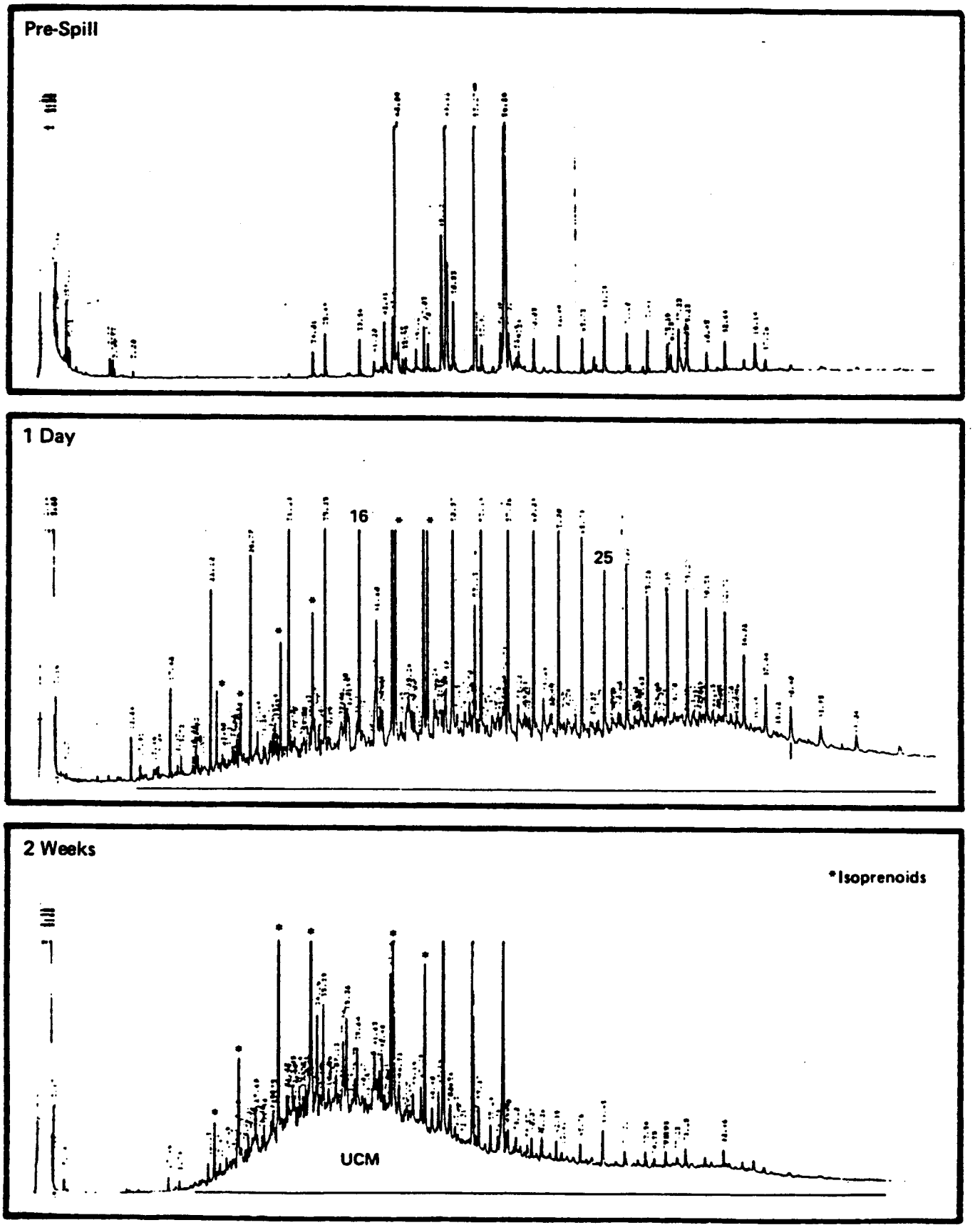

Figure 2.5. Mya truncata-GC2 profiles of Bay 9 animals (saturated hydrocarbons).

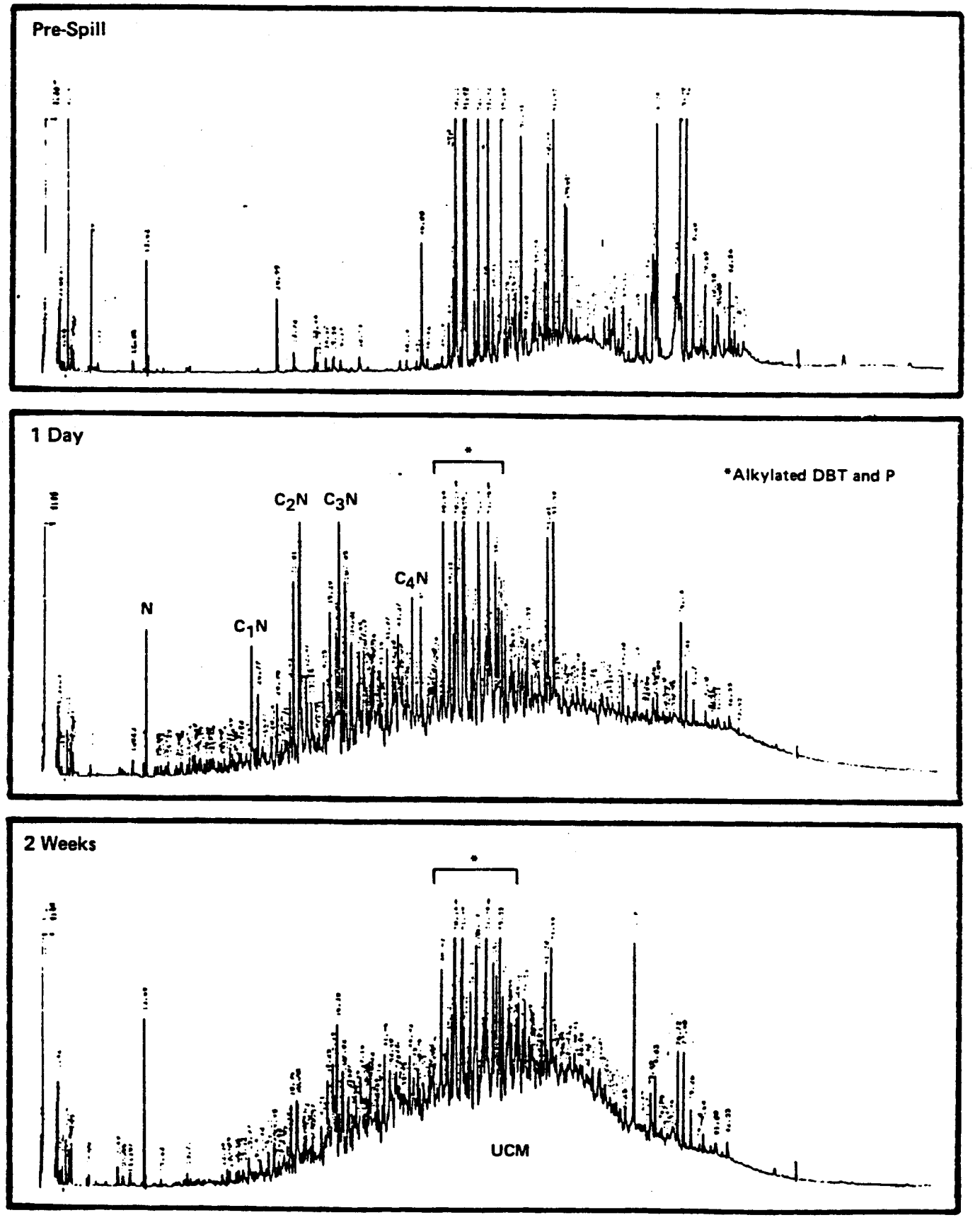

Figure 2.6. Mya truncata-GC2 profiles of Bay 9 animals (aromatics).

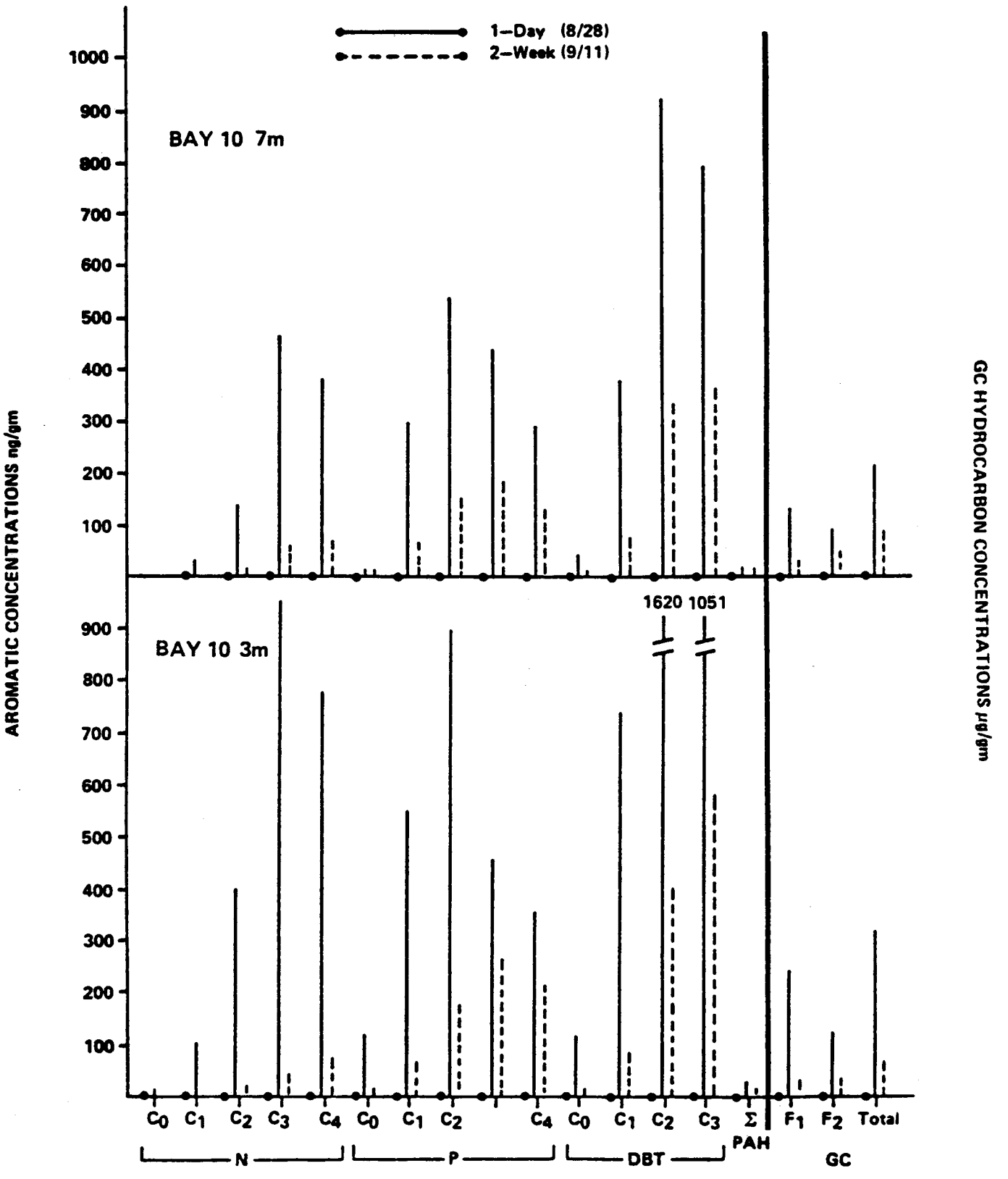

Figure 2.7. Aromatic profiles from Mya exposed to oil, illustrating changes in concentrations over 2 weeks, (Bay 10).

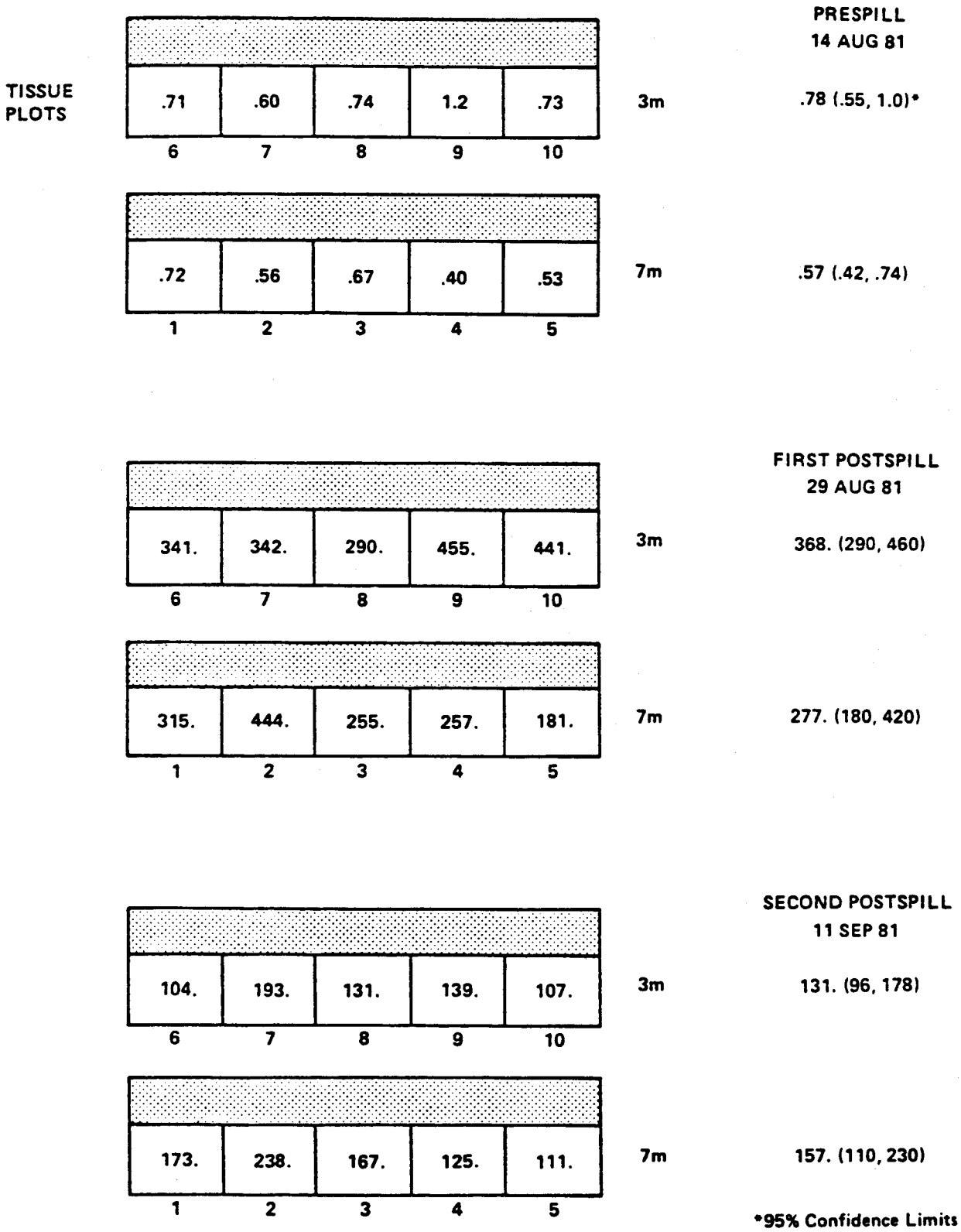

Figure 2.8. Concentrations of oil in Mya truncata, Bay 10 by UV/F (µg/g).

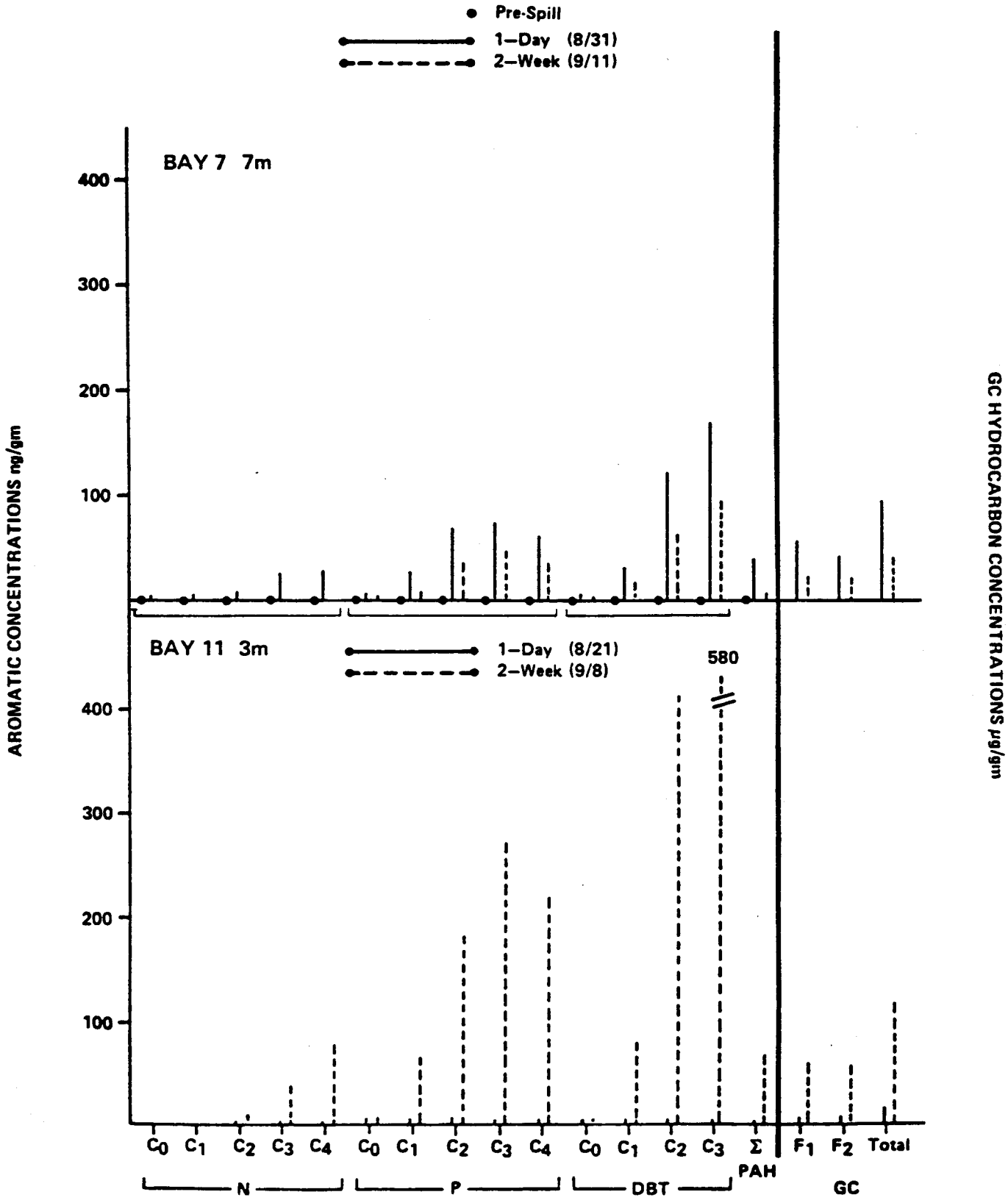

Figure 2.9. Mya truncata; aromatic profiles of Bays 7 & 11 by GC^2/MS.

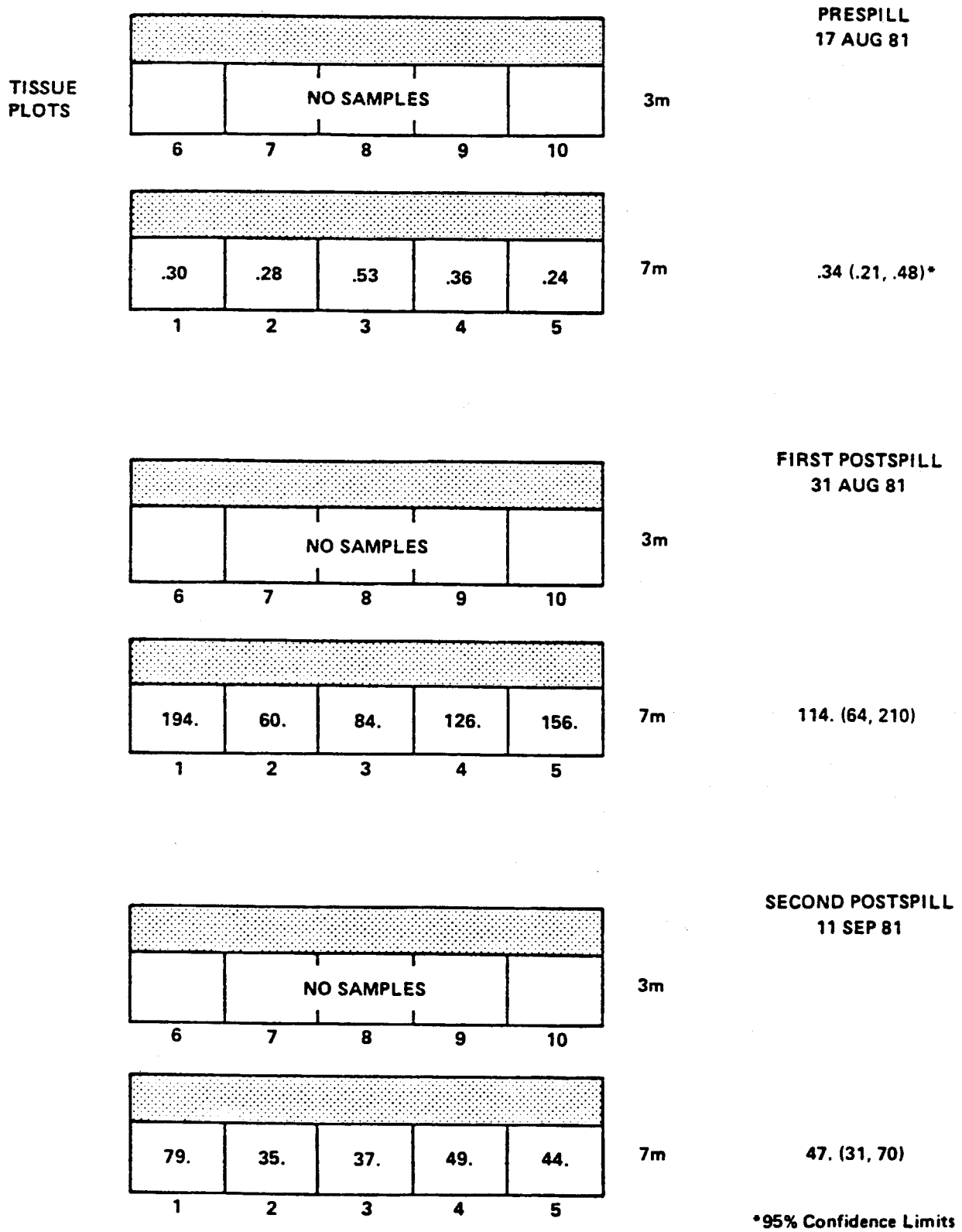

Figure 2.10. Concentrations of oil in Mya truncata, Bay 7 UV/F (µg/g).

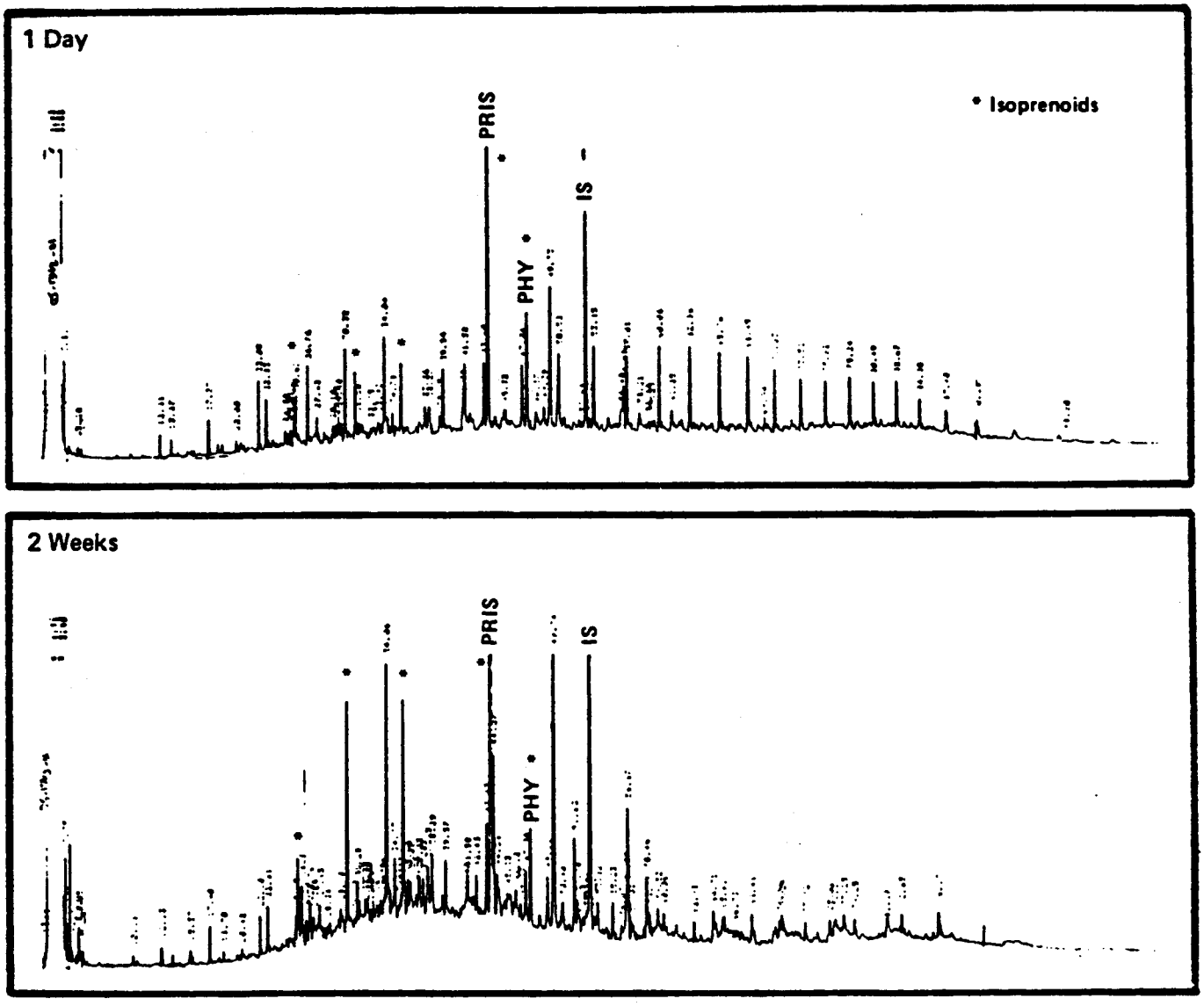

Figure 2.11. Mya truncata-GC^2 profiles of Bay 7 animals (saturates).

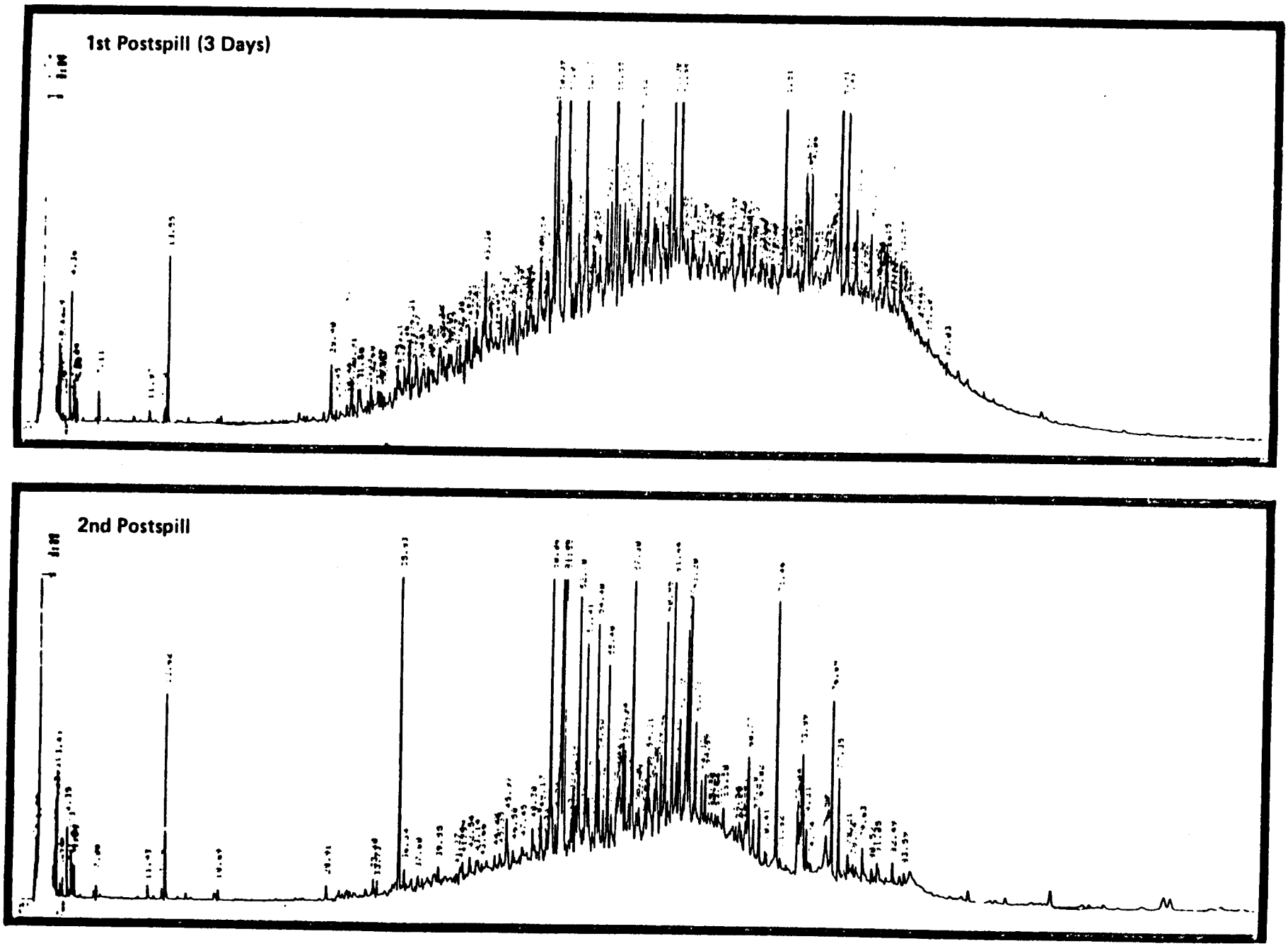

Figure 2.12. Mya truncata-GC^2 profiles of Bay 7 animals (aromatics).

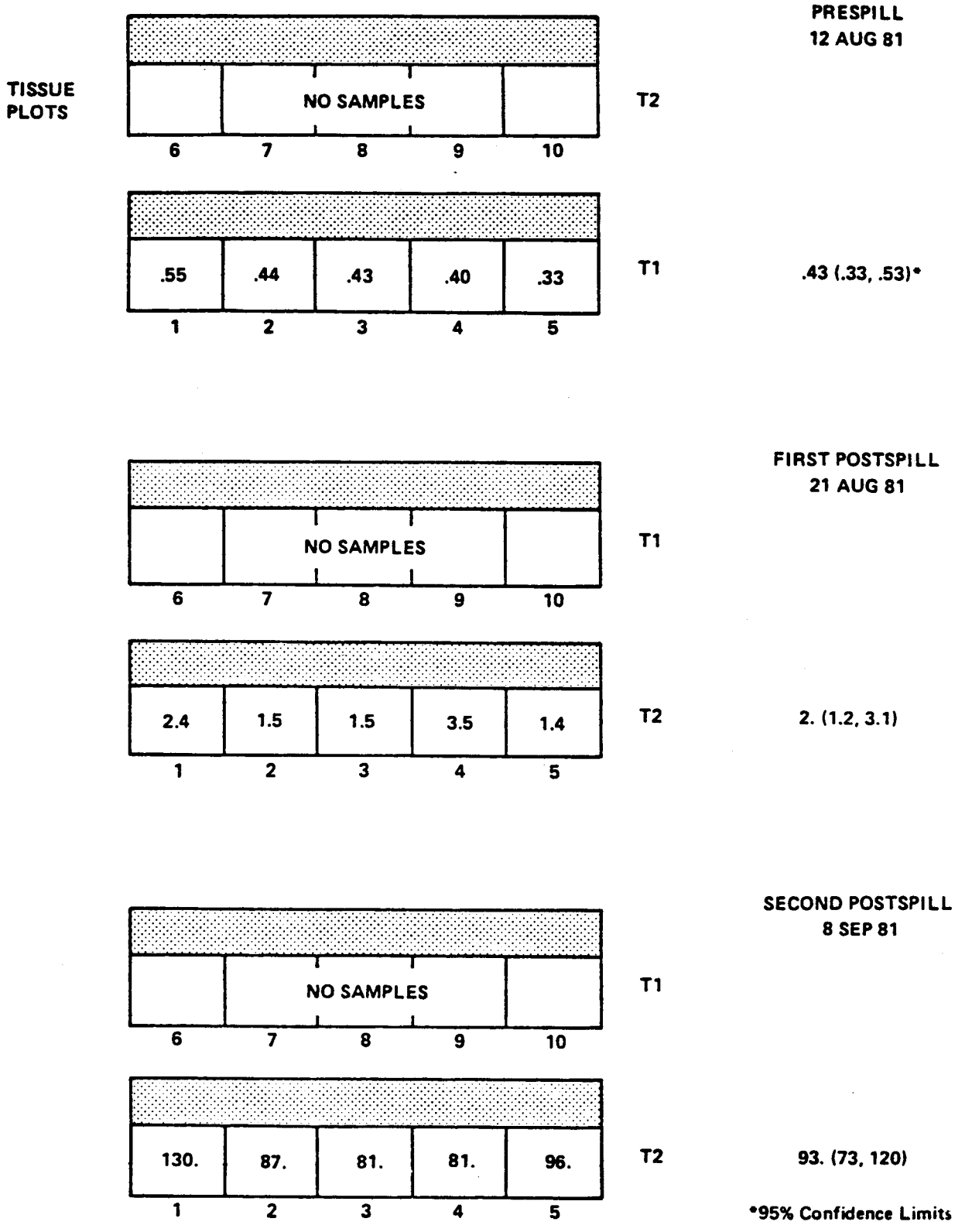

Figure 2.13. Concentrations of oil in Mya truncata, Bay 11 by UV/F (µg/g).

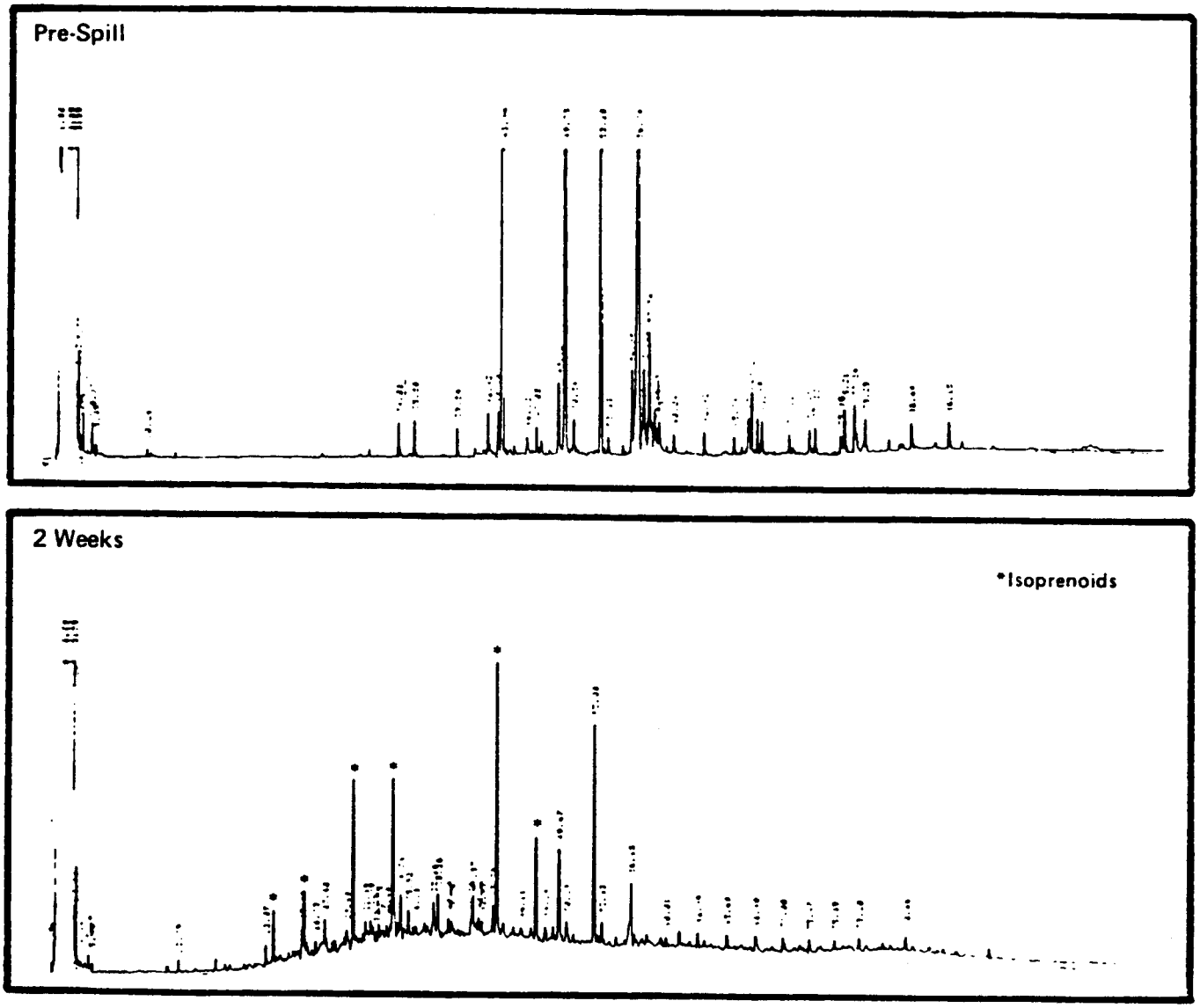

Figure 2.14. Mya truncata-Bay 11 (saturates).

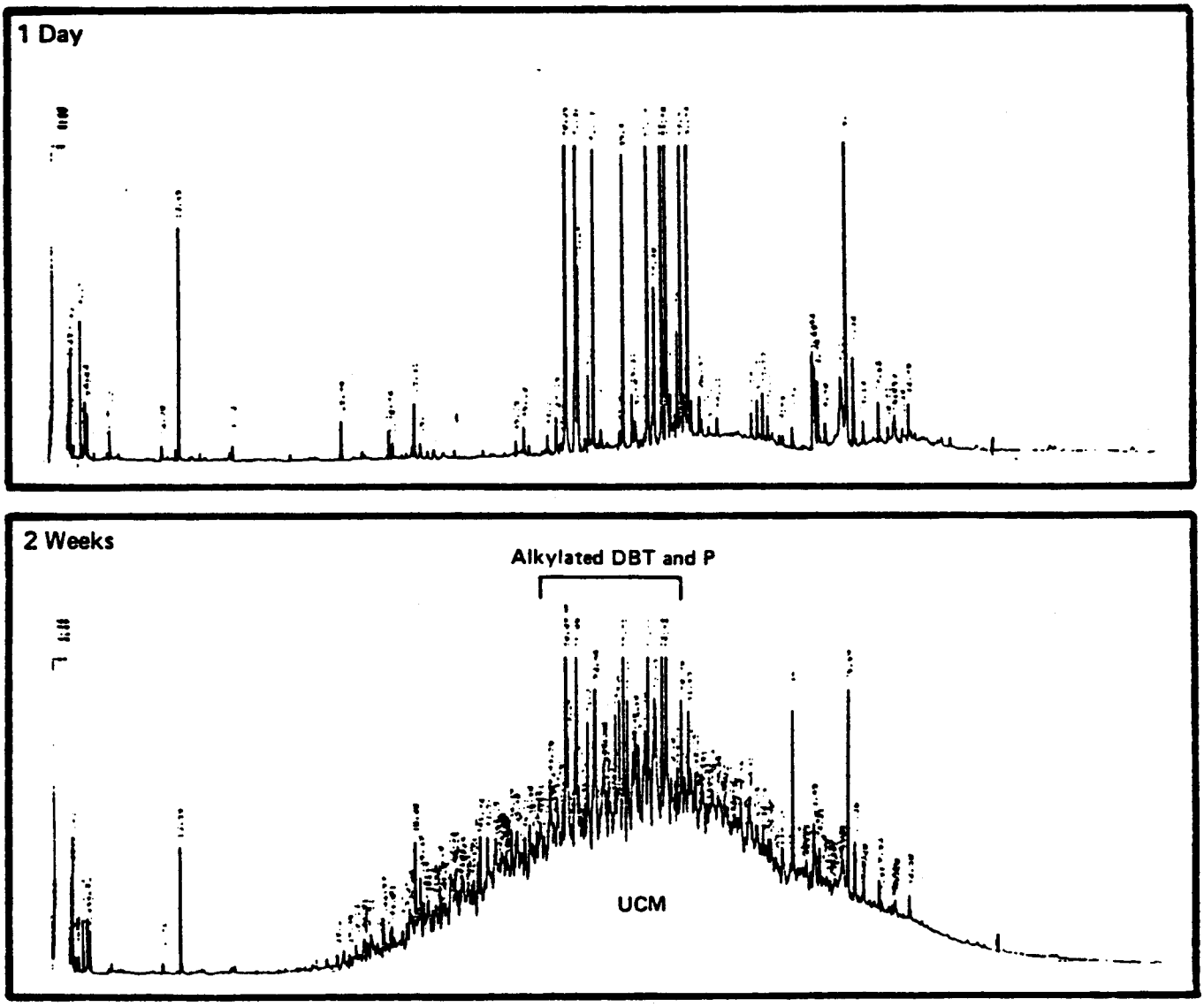

Figure 2.15. Mya truncata-Bay 11 (aromatics).

In all cases but one (Bay 10, second post-spill sample) where comparisons could be made, clams from the 3-meter water depth contained higher concentrations of total hydrocarbons than clams collected at the same time from the 7-meter water depth.

2.2.2. Serripes groenlandicus. Seventeen samples of Serripes groenlandicus were analyzed. These include the pre-spill, 1-day post-spill, and 2-week post-spill samples from Bays 7, 9, and 10 (7 meters), the 1-day and 2-week post-spill samples from Bay 11 (7 meters), the 3-meter sample set from Bay 9, and the analyses of two individual stations along the 7-meter depth stratum in Bay 9. Additionally, we had the opportunity to analyze the gut of a 1-day post-spill Serripes collection separately from the remaining tissue to examine chemical differences within the animals. Results of GC/MS/DS analyses of aromatic and sulfur heterocyclic hydrocarbons, total petroleum (by UV) values, and capillary GC traces are presented in Figures 2.16-2.29.

In general, the aromatic/heterocyclic hydrocarbon profiles in tissues of S. groenlandicus are quantitatively similar to those in Mya truncata. In a sample of S. groenlandicus collected from Bay 10 immediately after the spill, concentrations of alkyl benzenes were higher in muscle tissue than in gut tissue (Figure 2.24). Concentrations of phenanthrenes, dibenzothiophenes and total higher molecular weight polycyclic aromatic hydrocarbons were higher in gut tissue than in muscle tissue.

2.2.3. Astarte borealis. Eight samples of Astarte borealis were analyzed. These include samples from the 7-meter depth stratum from Bays 9, 10, 11, and 7 during the first and second post-spill samplings (i.e., 1-day, 2-weeks). Results of GC/MS/DS analysis of aromatic/heterocyclic hydrocarbons, total petroleum concentration information, and representative GC traces are summarized in Figures 2.30-2.37.

A. borealis from Bays 9 and 10 accumulated much higher concentrations of aromatic and heterocyclic hydrocarbons, particularly immediately after the oil spill, than did Mya truncata and Serripes groenlandicus. The dominant hydrocarbons in tissues of A. borealis from these two bays were C_3-C_4-naphthalenes, C_1-C_3-phenanthrenes and C_1-C_3-dibenzothiophenes (Figure 2.30). A. borealis from Bay 11 contained proportionately lower concentrations of C_1-phenanthrenes and C_1-dibenzothiophenes than did animals from Bays 9 and 10.

2.2.4. Nitrogen heterocyclics. Four pooled sample extracts were processed and analyzed by GC/MS/DS to determine the presence, identity, and concentration of the basic PANH compounds. Samples analyzed were:

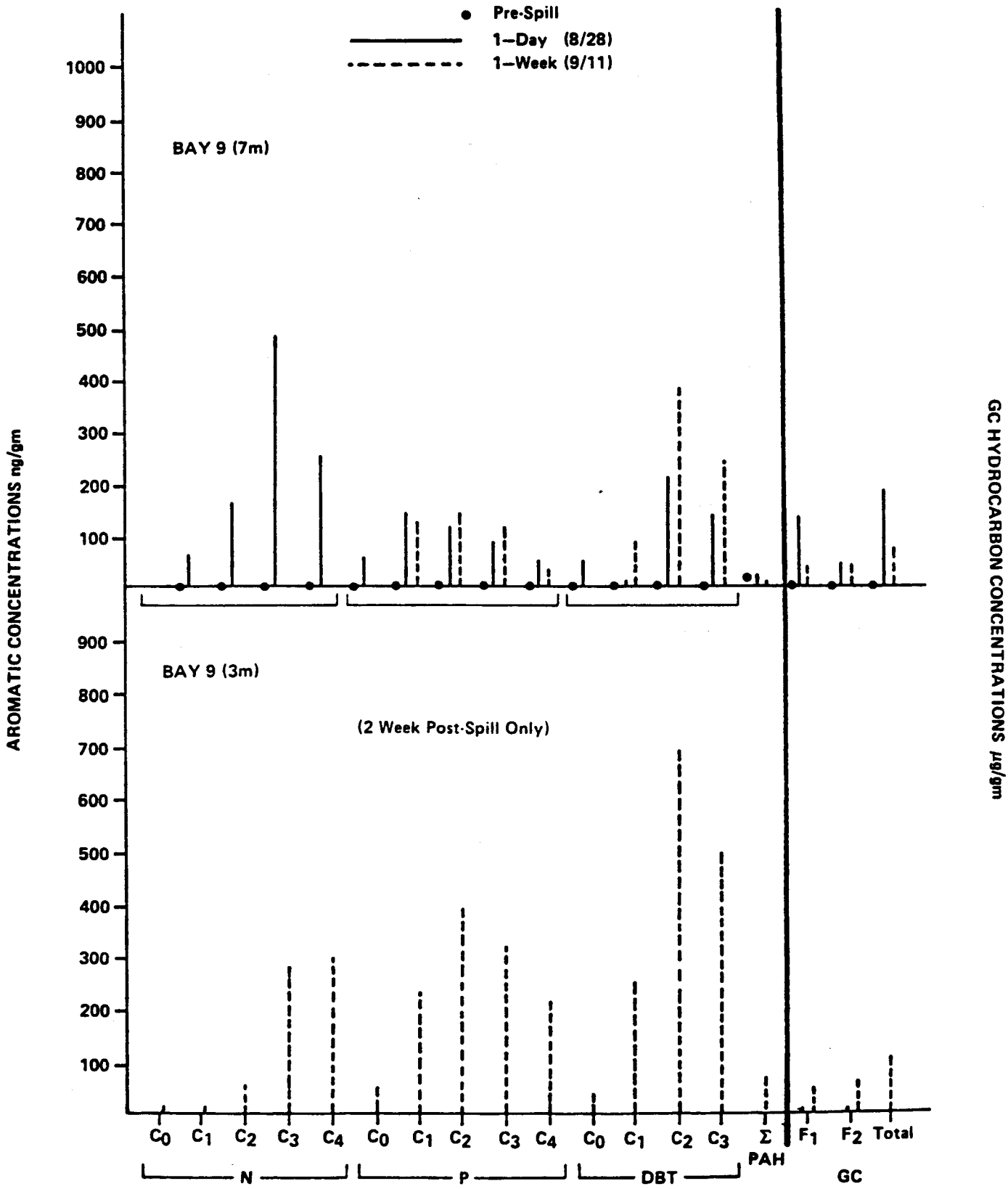

Figure 2.16. Serripes aromatic profiles (by GC^2/MS), (Bay 9).

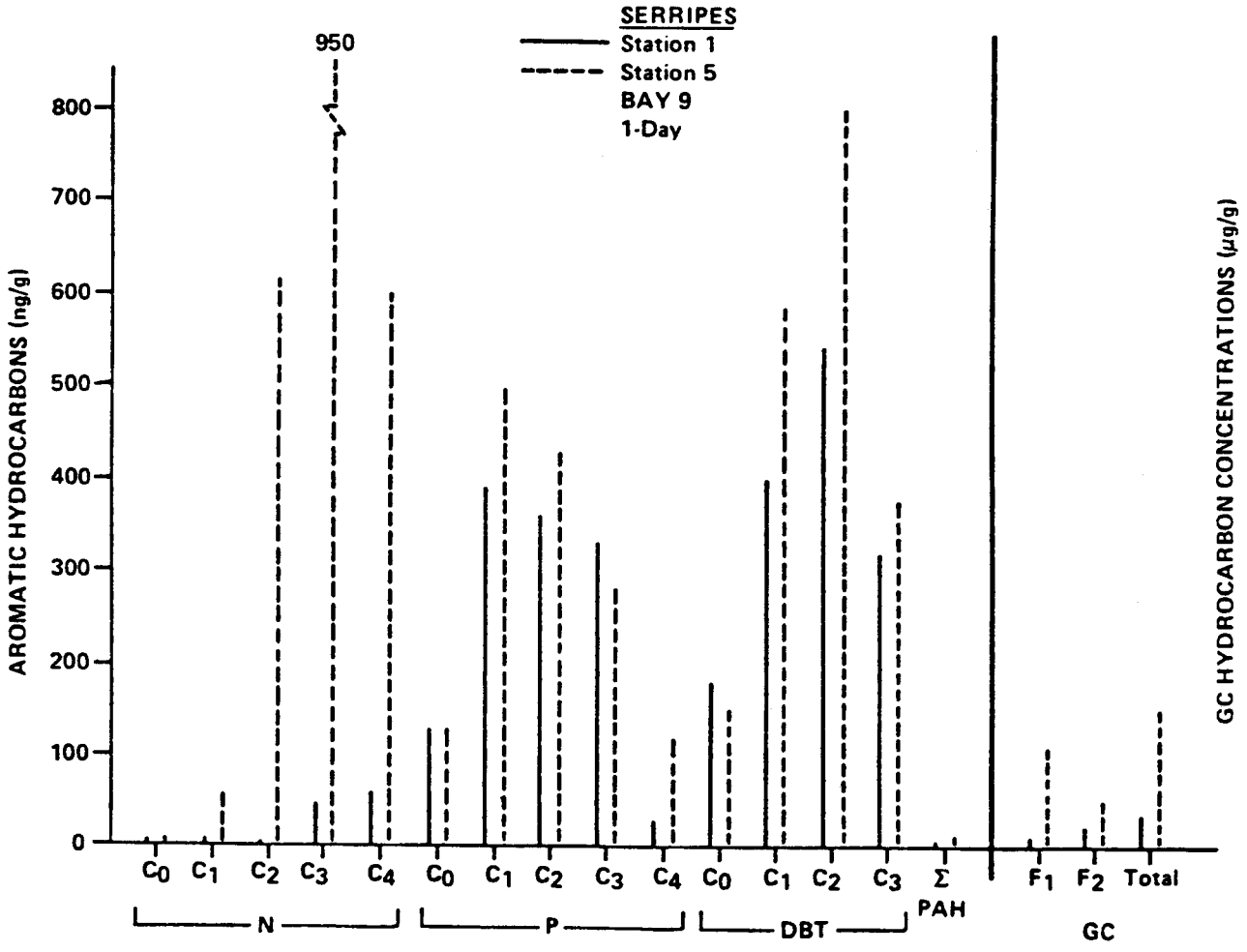

Figure 2.17. Variation of aromatic hydrocarbon levels in Serripes along 7 meter depth stratum (Bay 9).

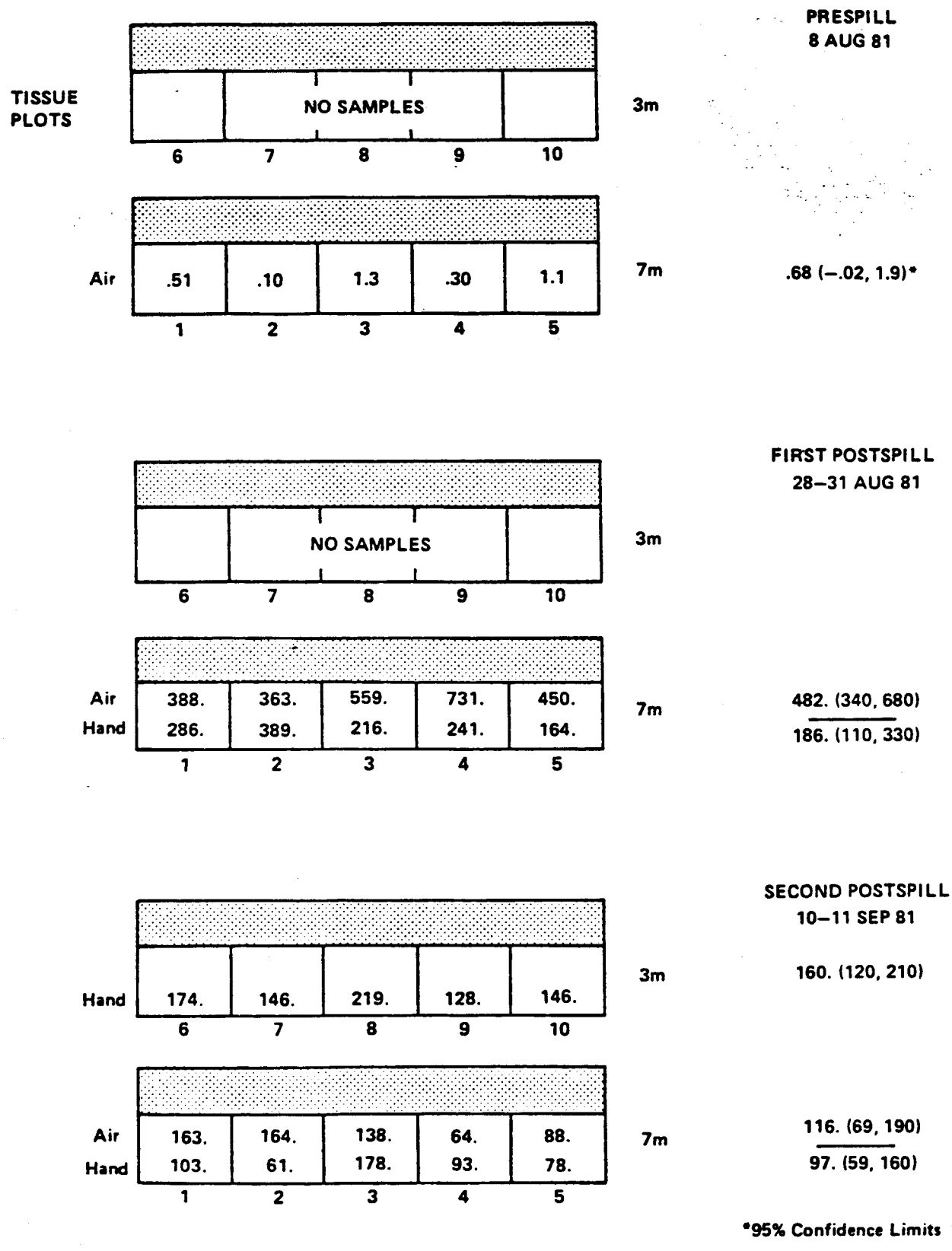

Figure 2.18. Concentrations of oil in Serripes, Bay 9 by UV/F (µg/g).

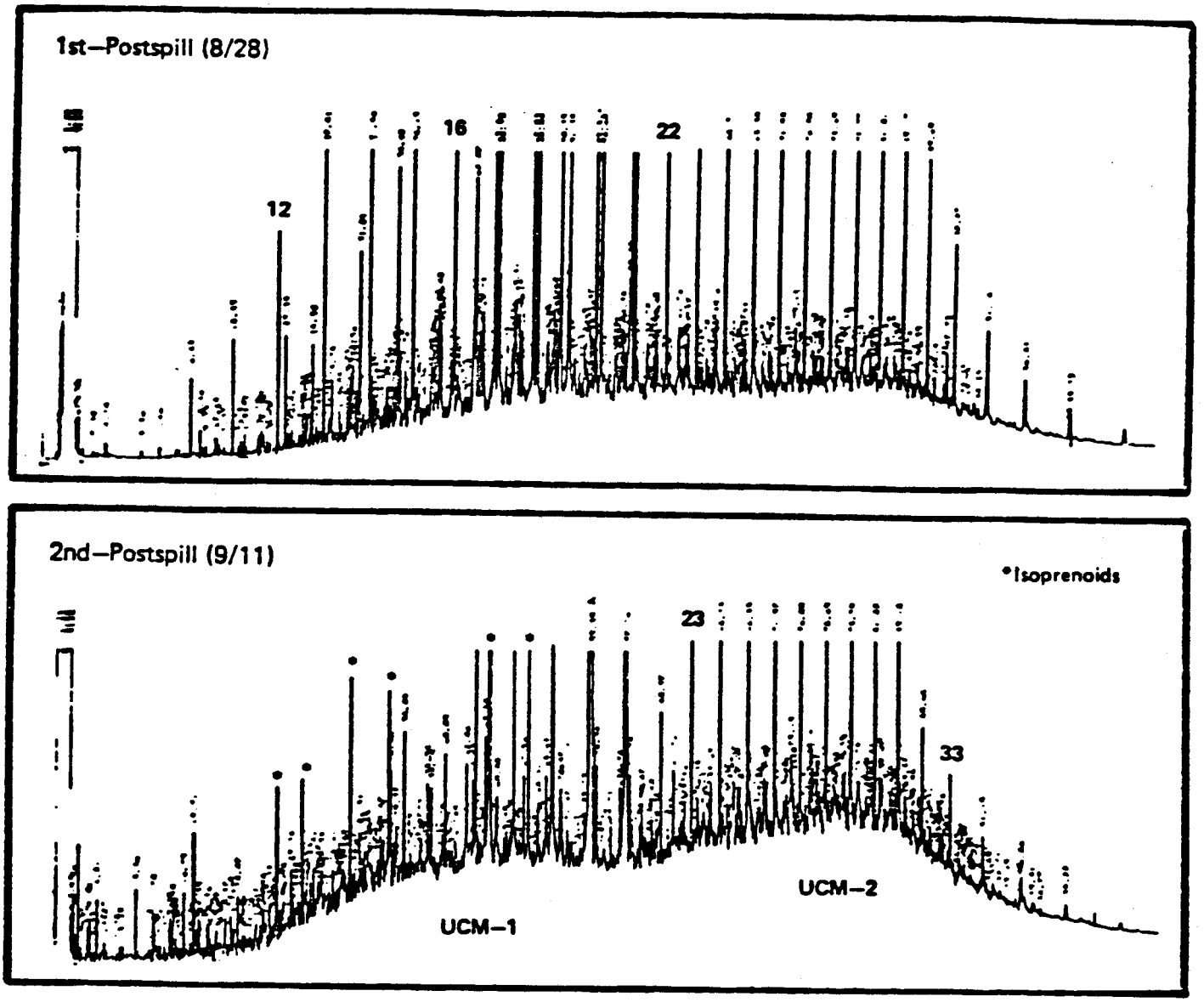

Figure 2.19. Serripes groenlandicus-GC2 profiles of Bay 9 animals (saturates).

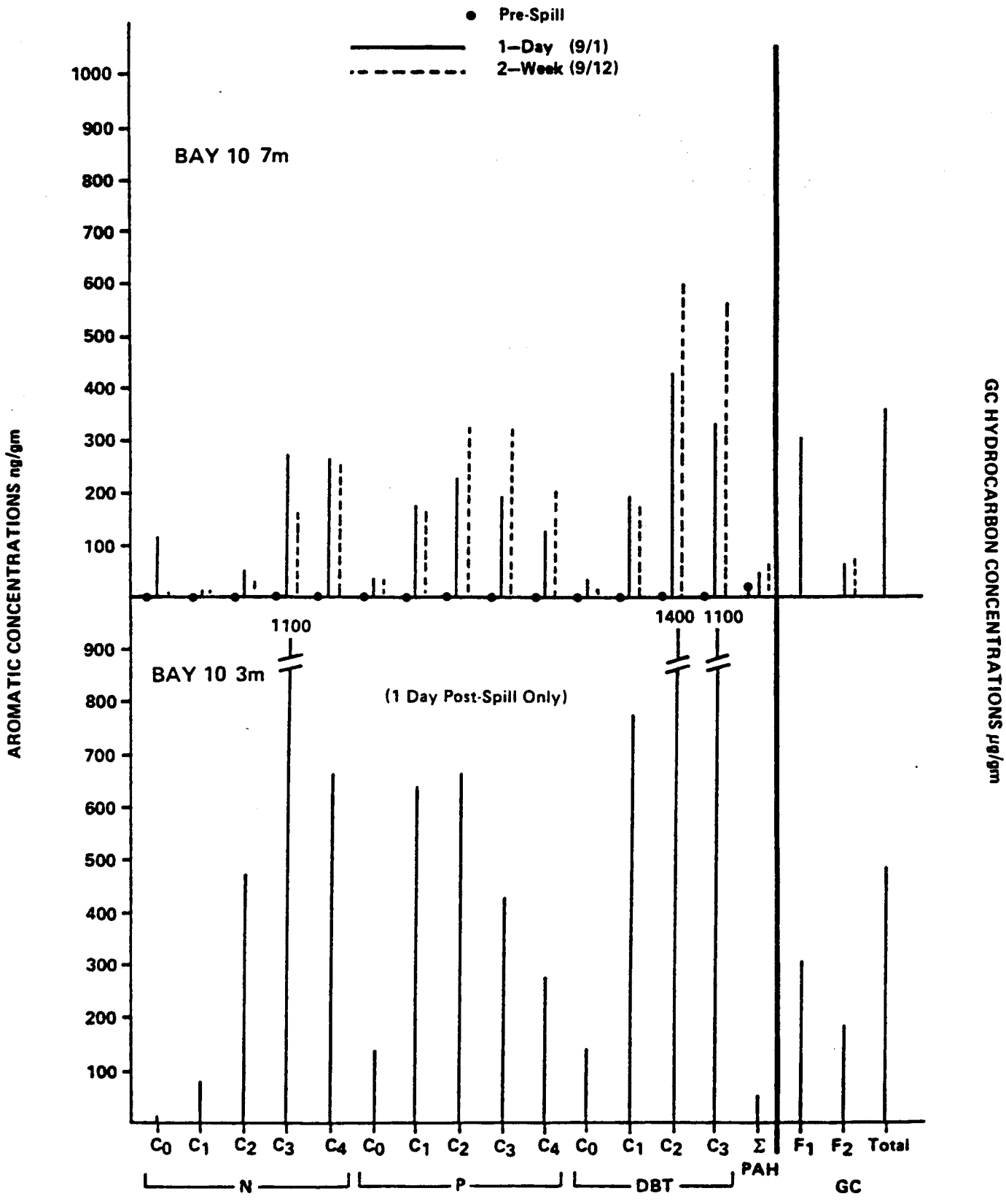

Figure 2.20. Serripes aromatic profiles, (Bay 10).

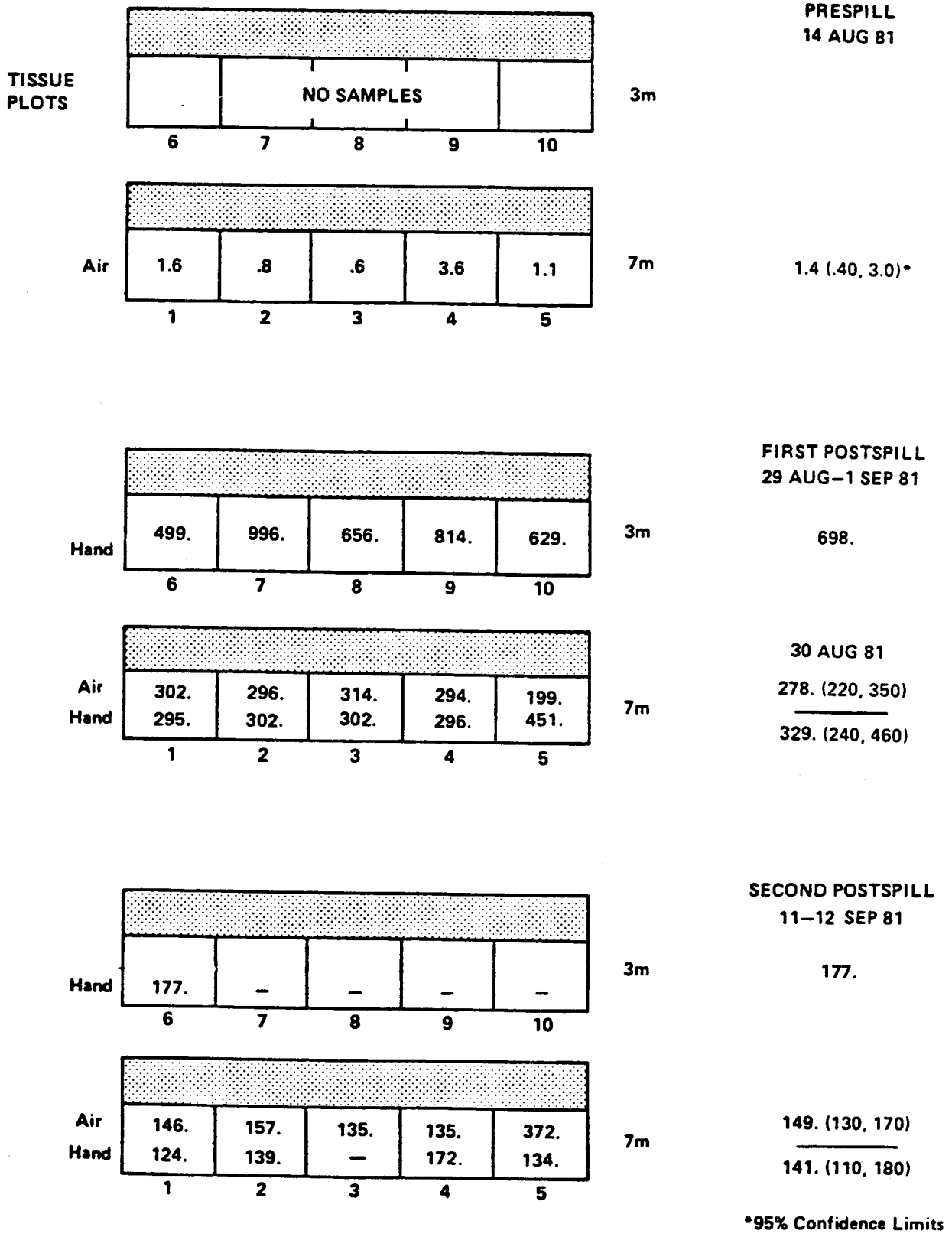

Figure 2.21. Concentrations of oil in Serripes, Bay 10 by UV/F (µg/g).

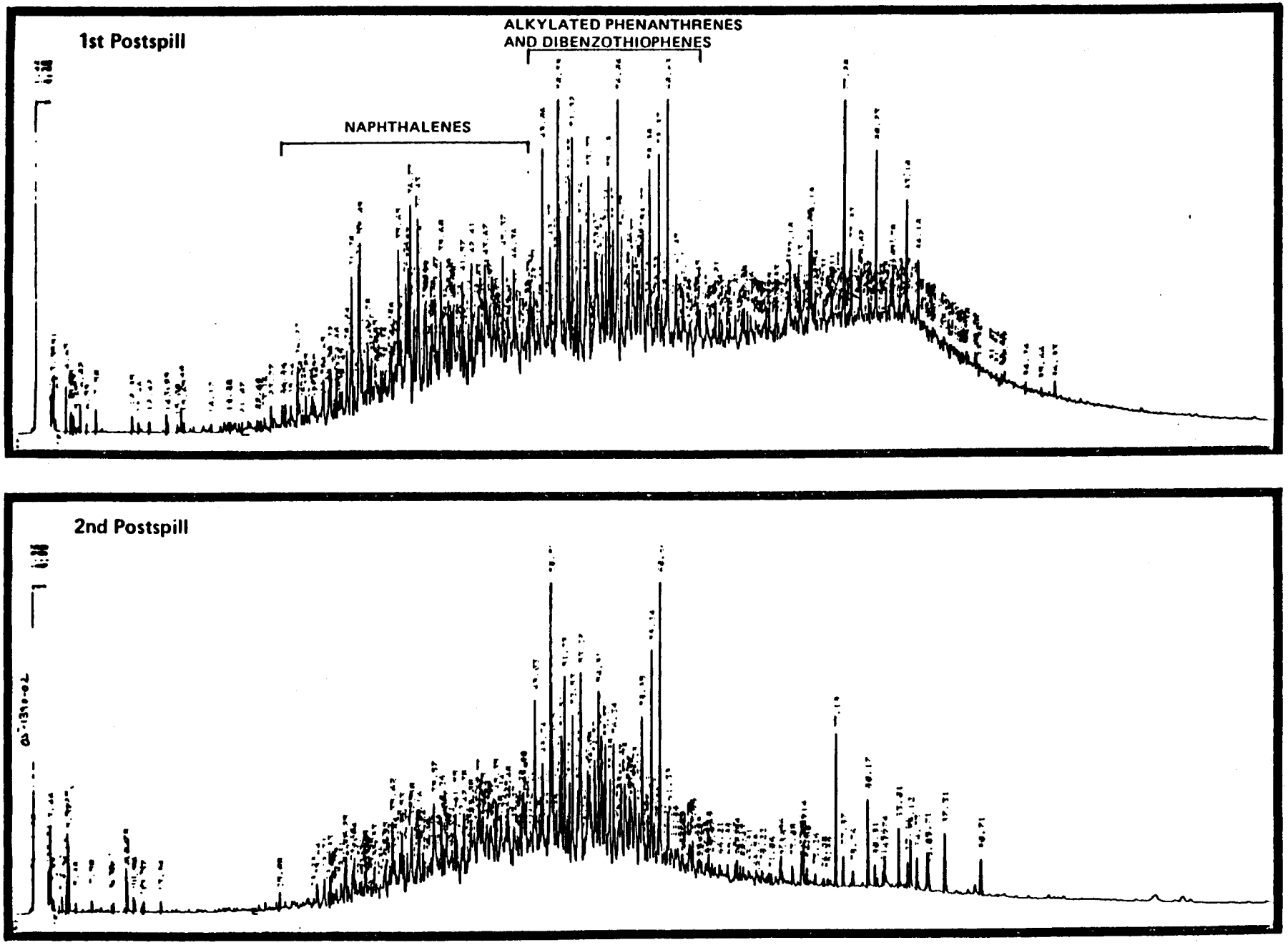

Figure 2.22. Aromatic hydrocarbons in Serripes-Bay 10, (3 meters).

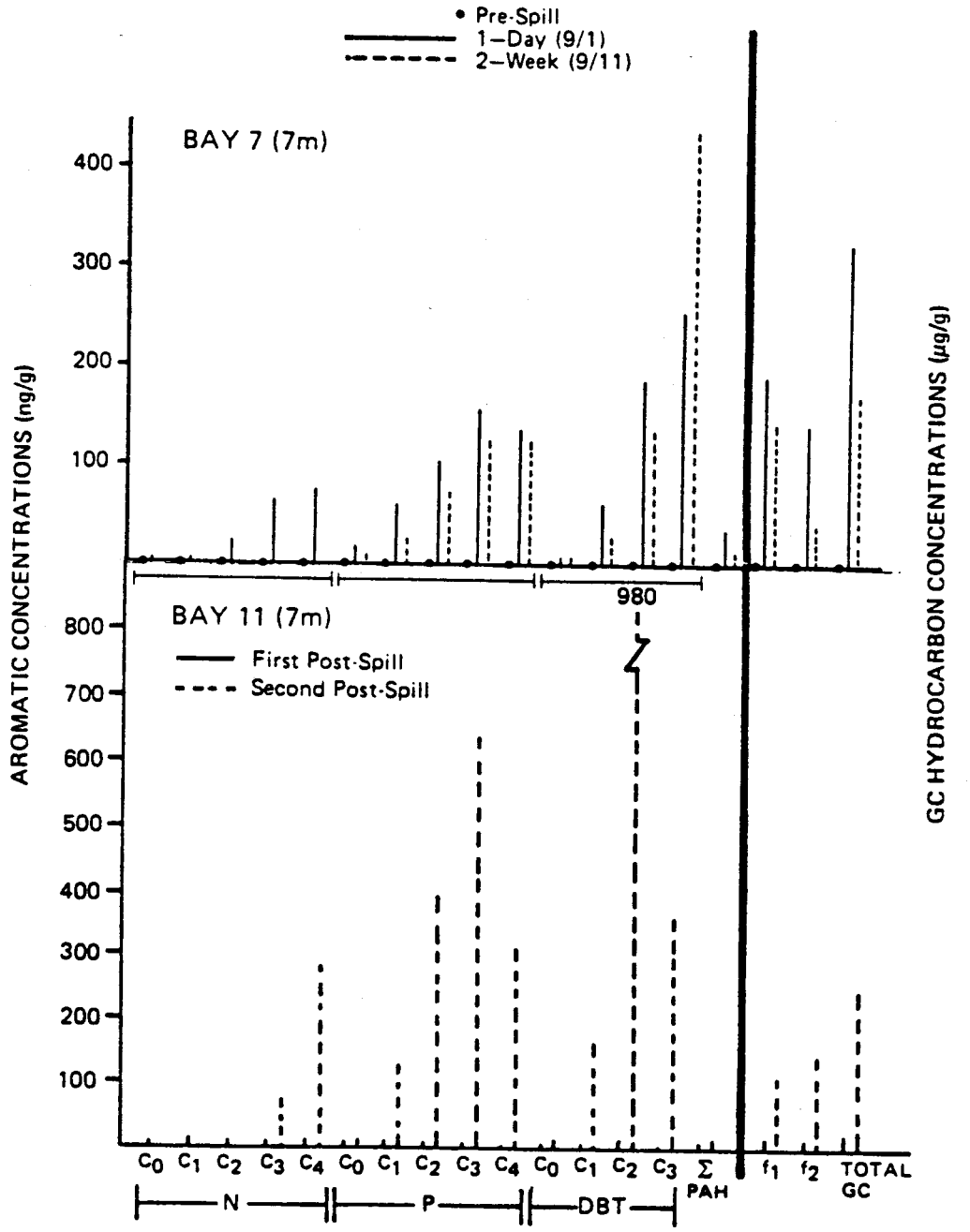

Figure 2.23. Aromatic hydrocarbon profiles in Serripes by GC²/MS (Bay 7 and 11).

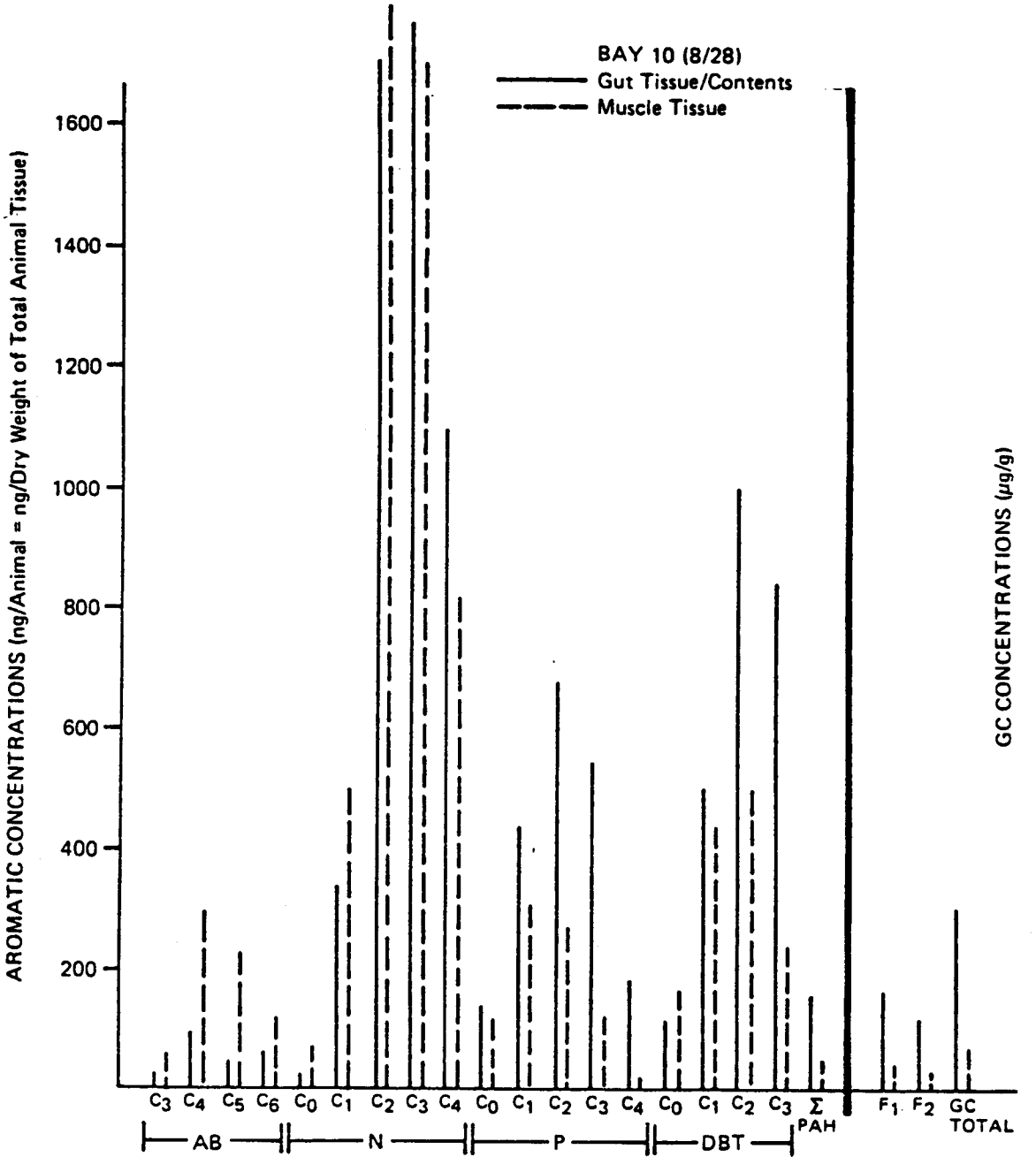

Figure 2.24. Aromatic hydrocarbon profiles of Serripes parts.

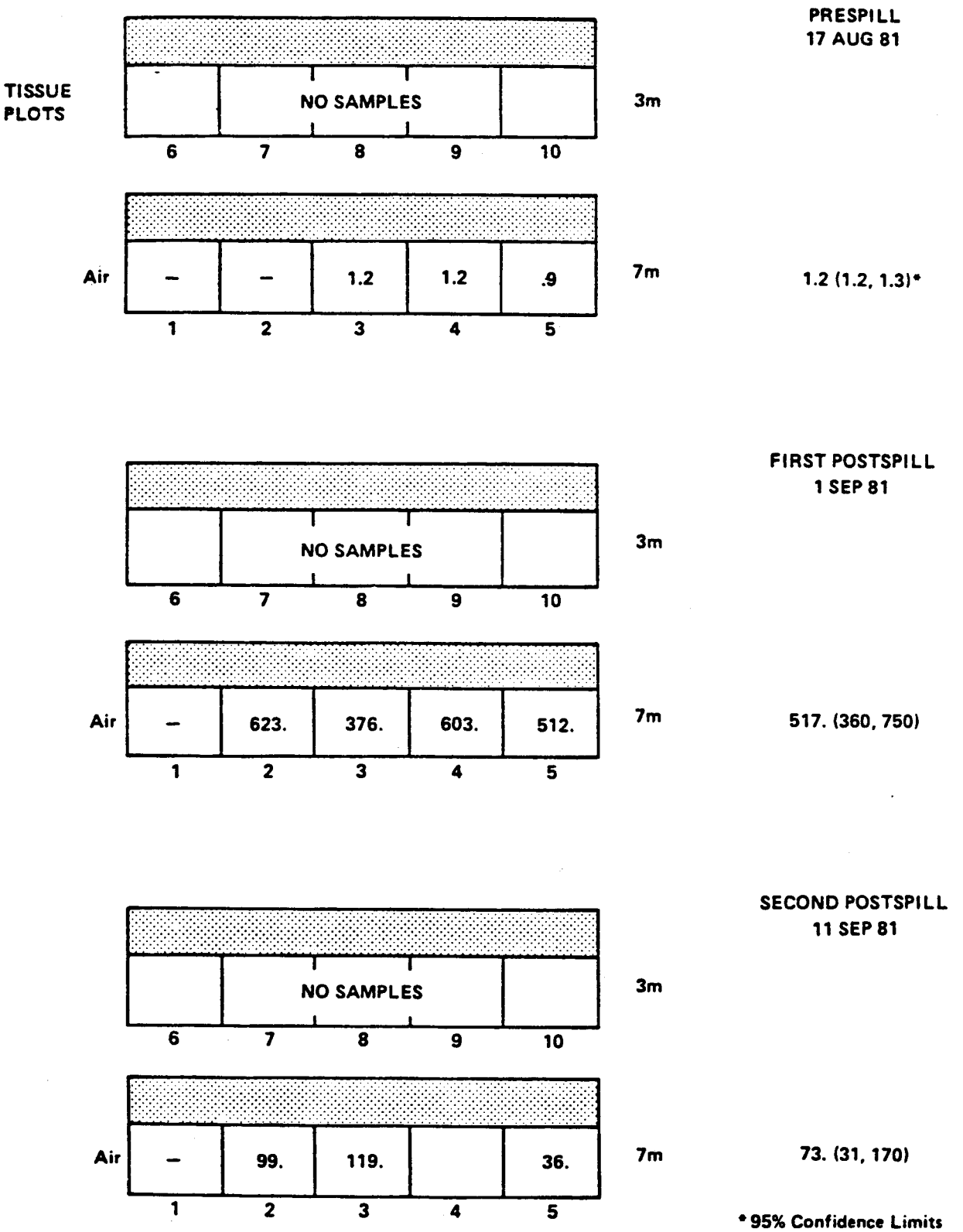

Figure 2.25. Concentrations of oil in Serripes, Bay 7 by UV/F (µg/g).

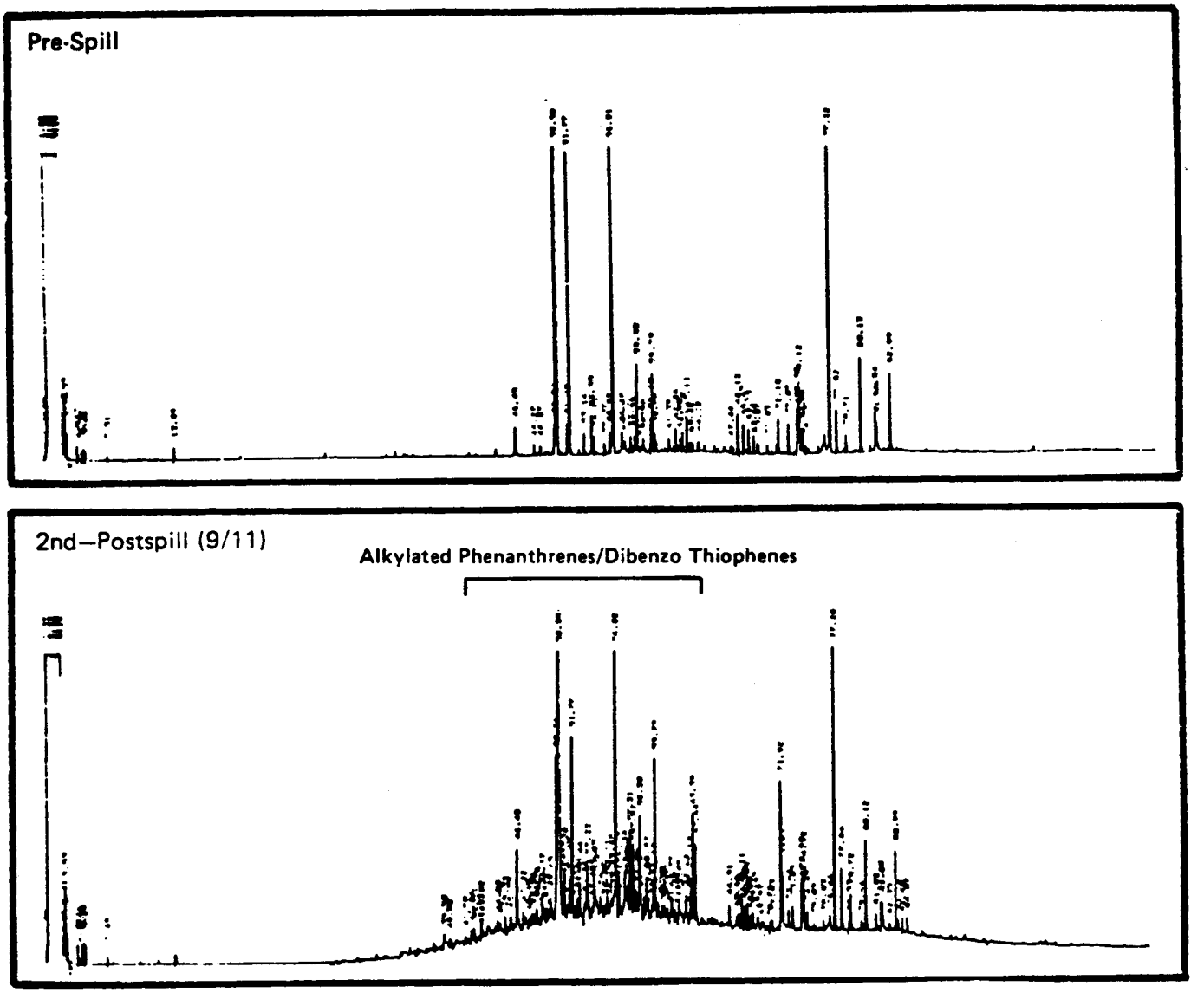

Figure 2.26. Serripes-Bay 7 (aromatics).

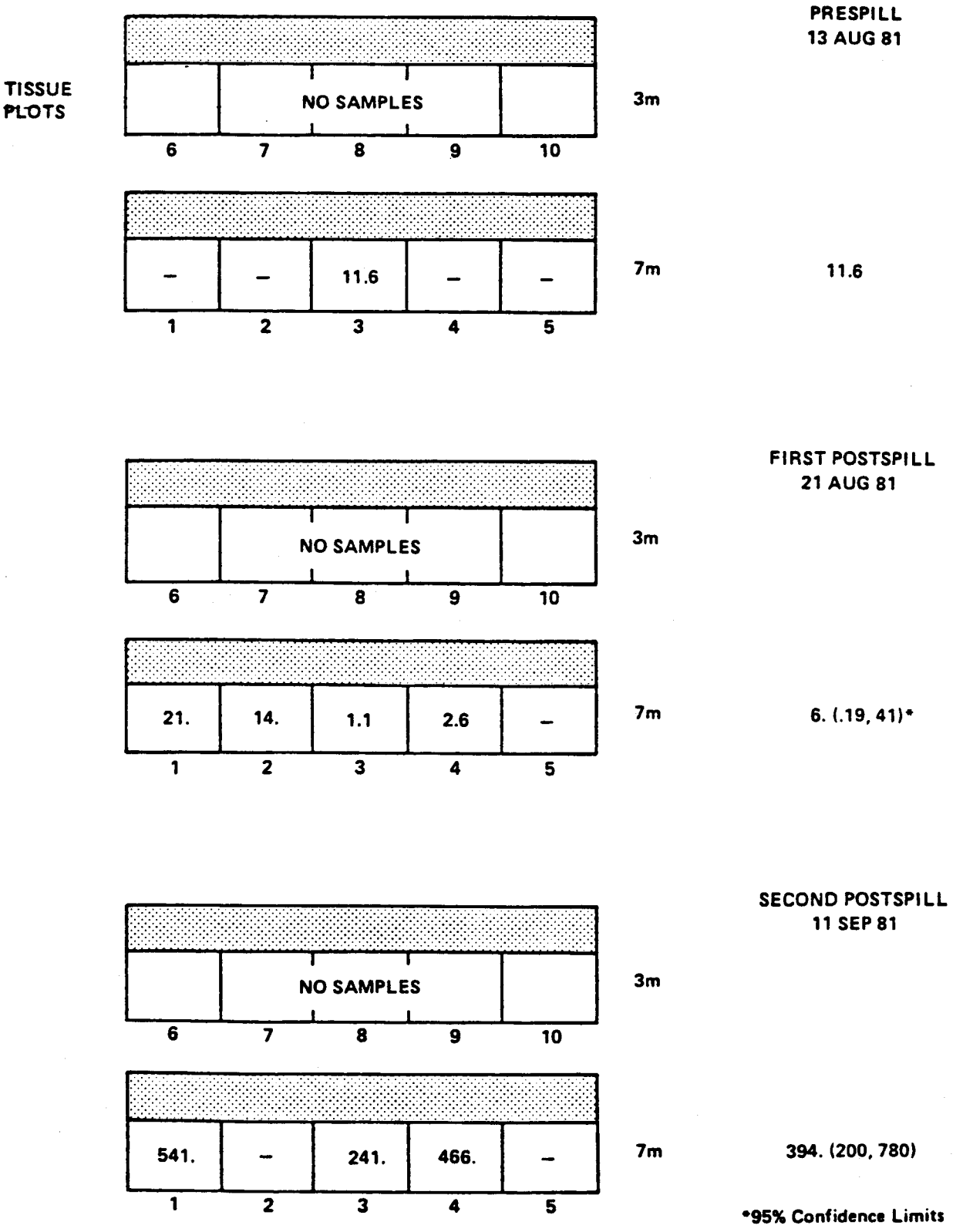

Figure 2.27. Concentrations of oil in Serripes, Bay 11 by UV/F (µg/g).

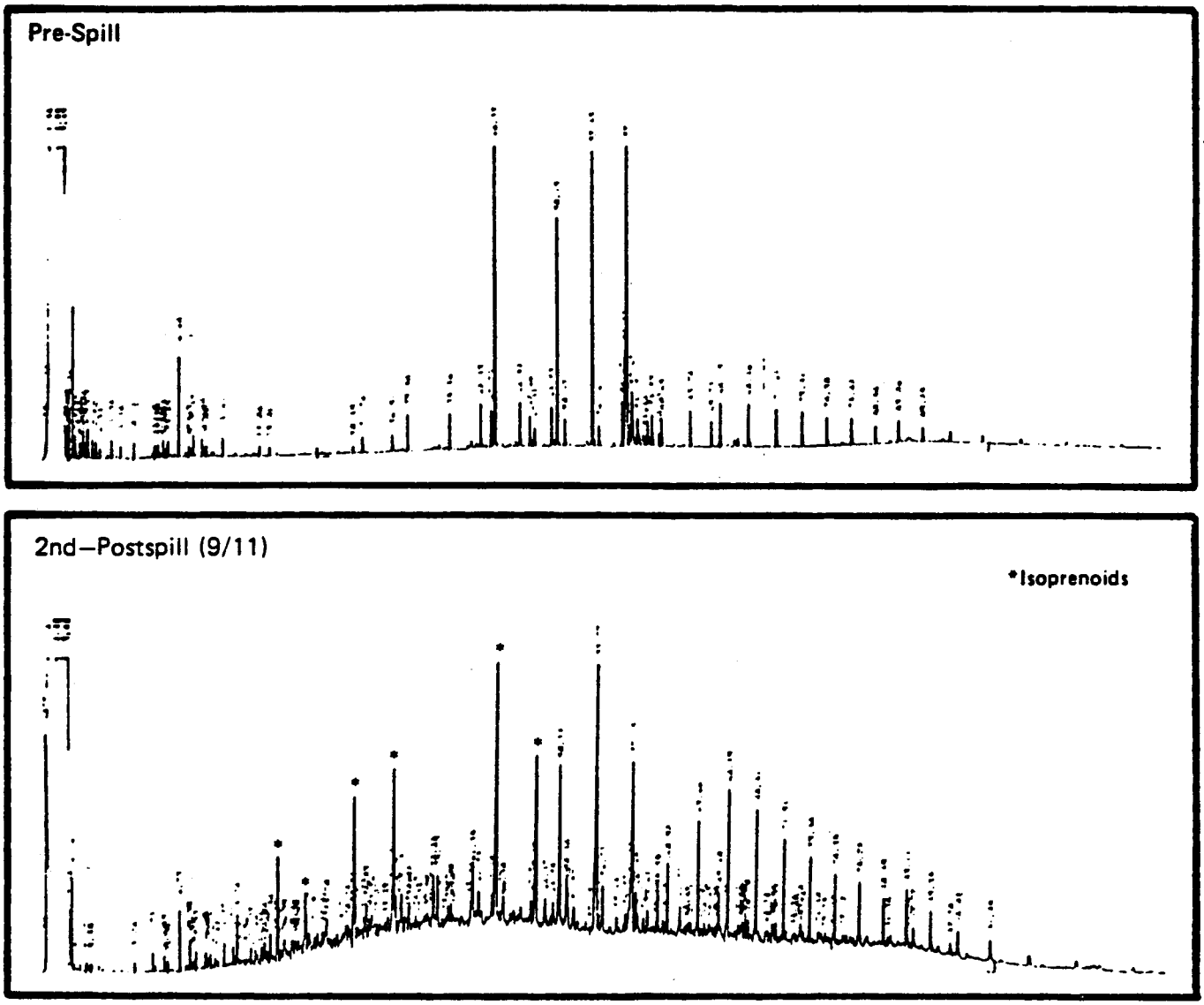

Figure 2.28. Serripes-Bay 11 (saturates).

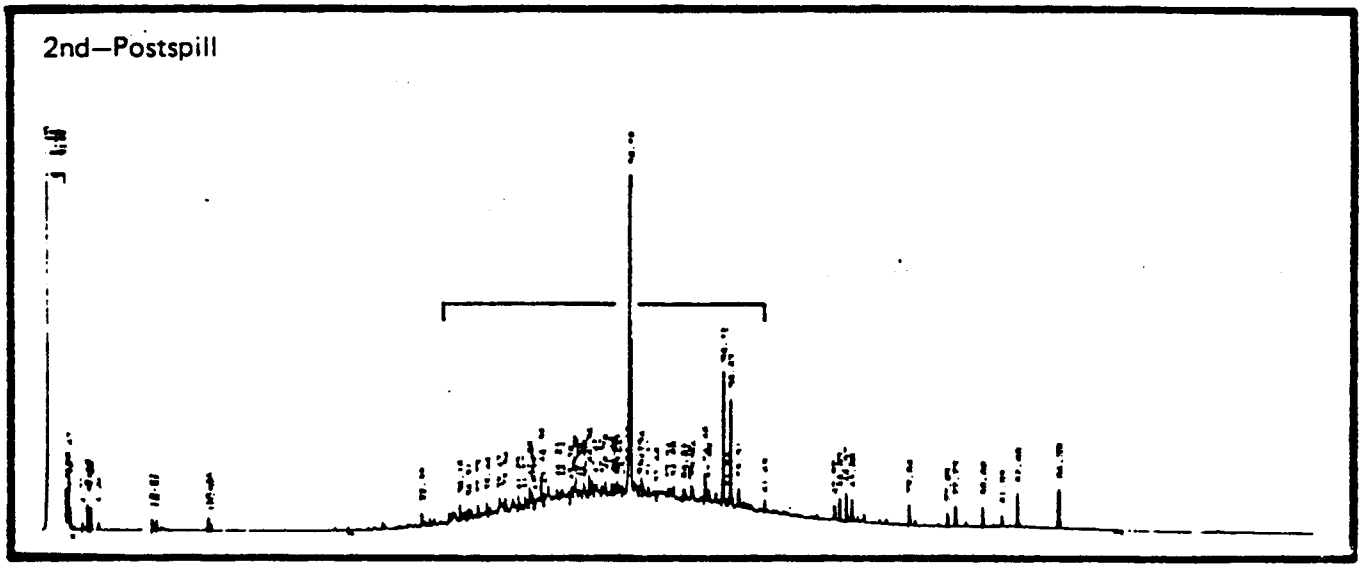

Figure 2.29. Serripes-Bay 11 (aromatics).

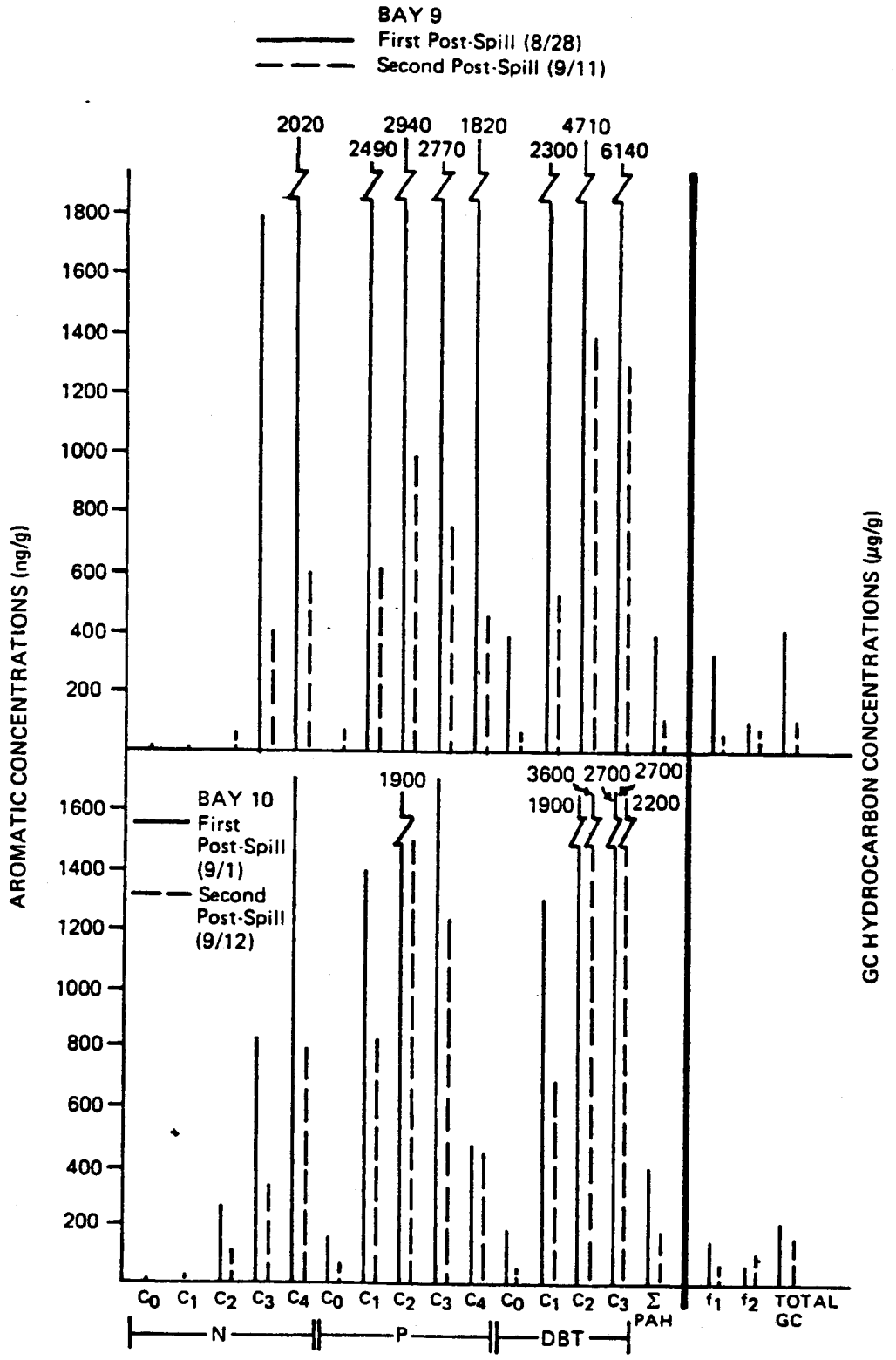

Figure 2.30. Astarte aromatic profiles (Bays 9 and 10).

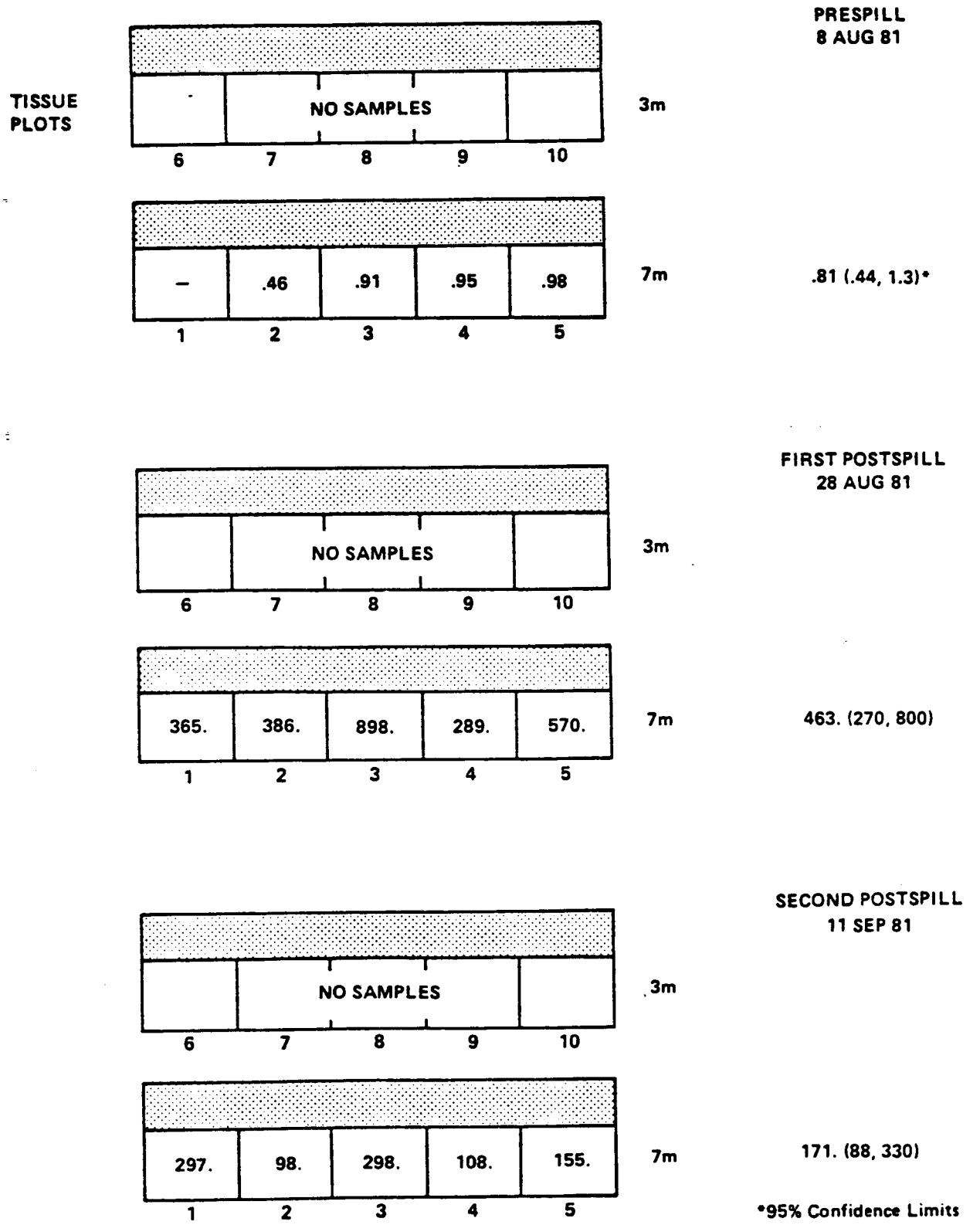

Figure 2.31. Concentrations of oil in Astarte borealis, Bay 9 by UV/F (µg/g).

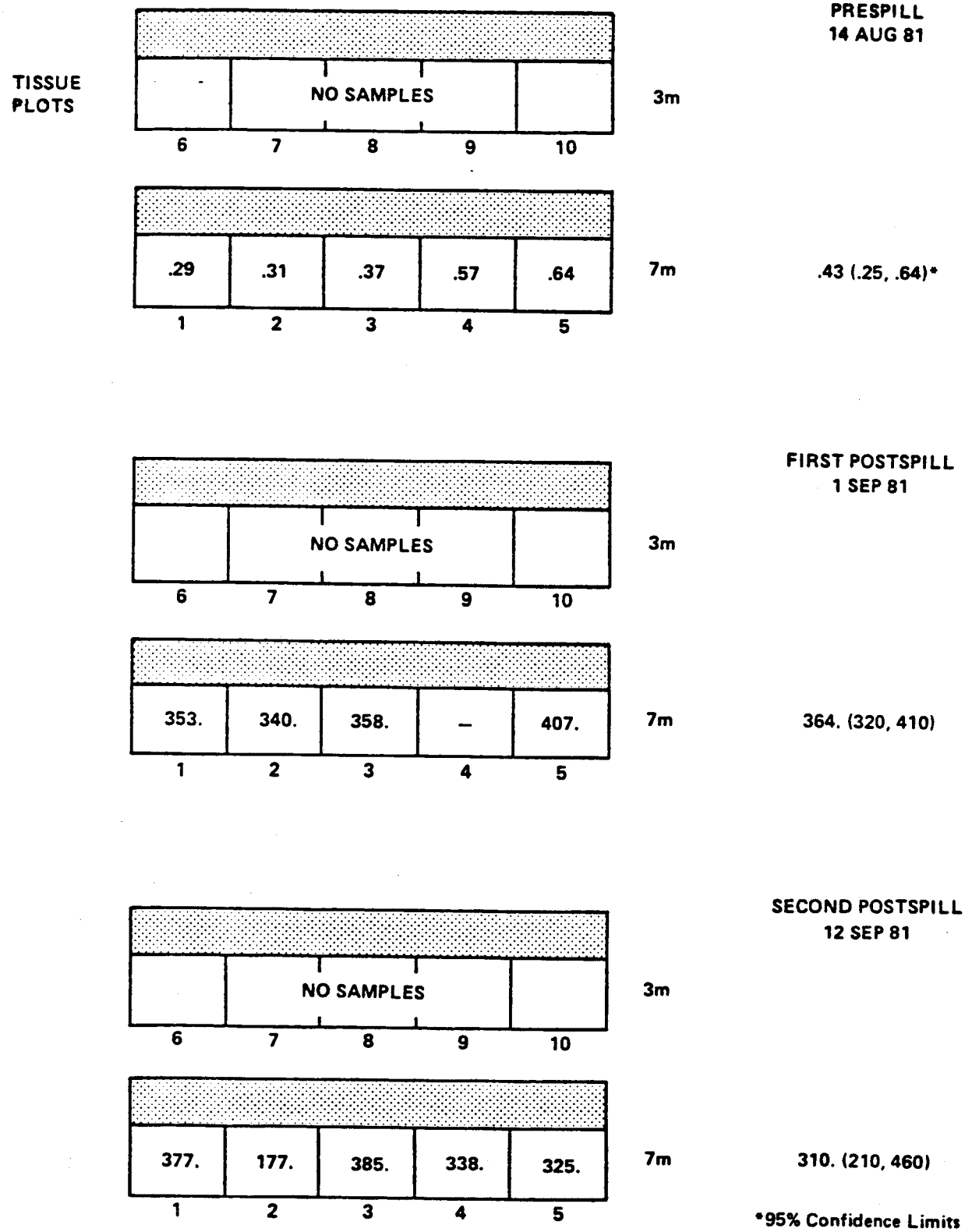

Figure 2.32. Concentrations of oil in Astarte borealis, Bay 10 by UV/F (µg/g).

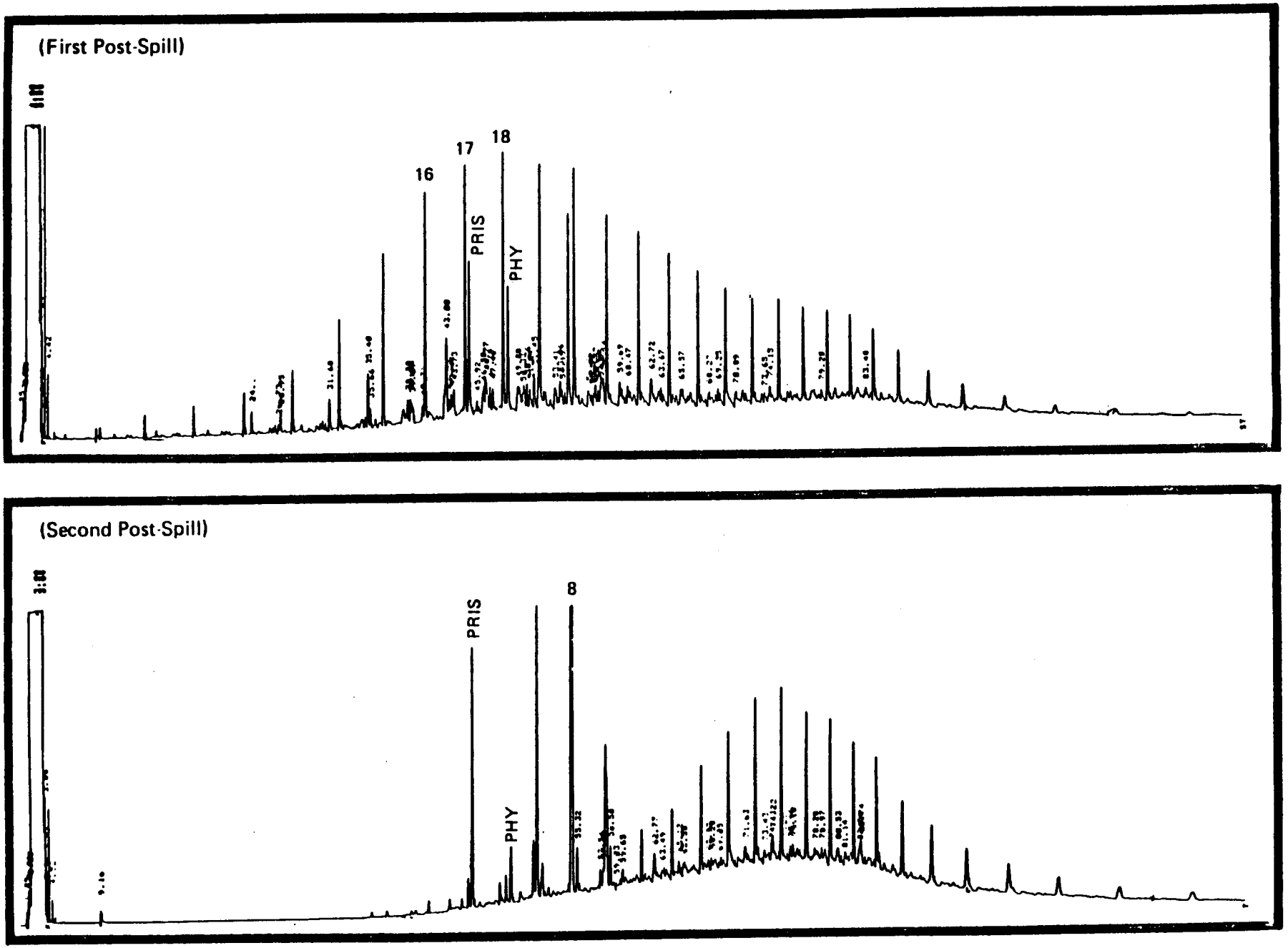

Figure 2.33. Saturated hydrocarbon GC[2] profiles of Astarte sample from Bay 9.

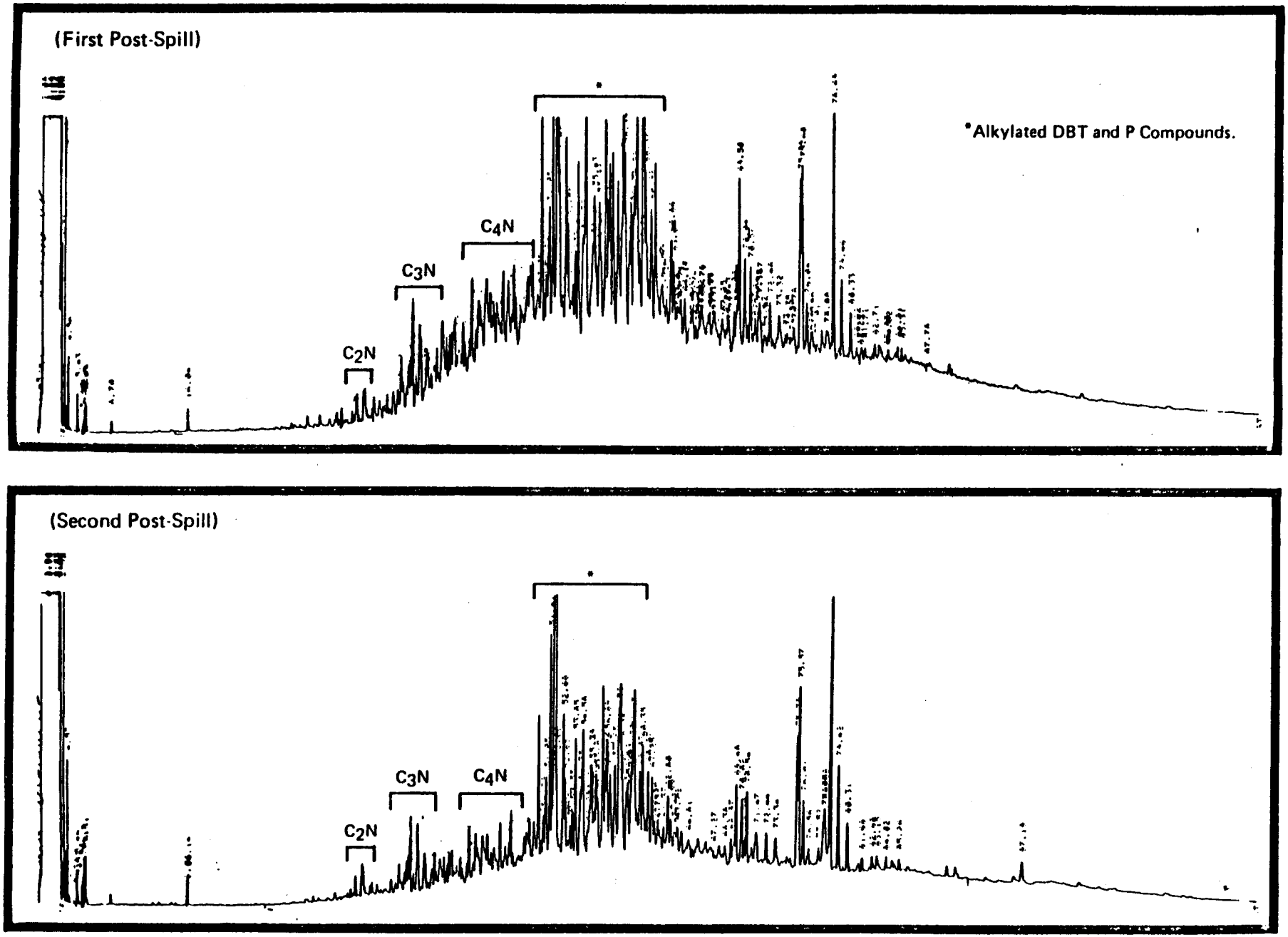

Figure 2.34. Aromatic hydrocarbon GC[2] profiles of Astarte sample composite from Bay 9.

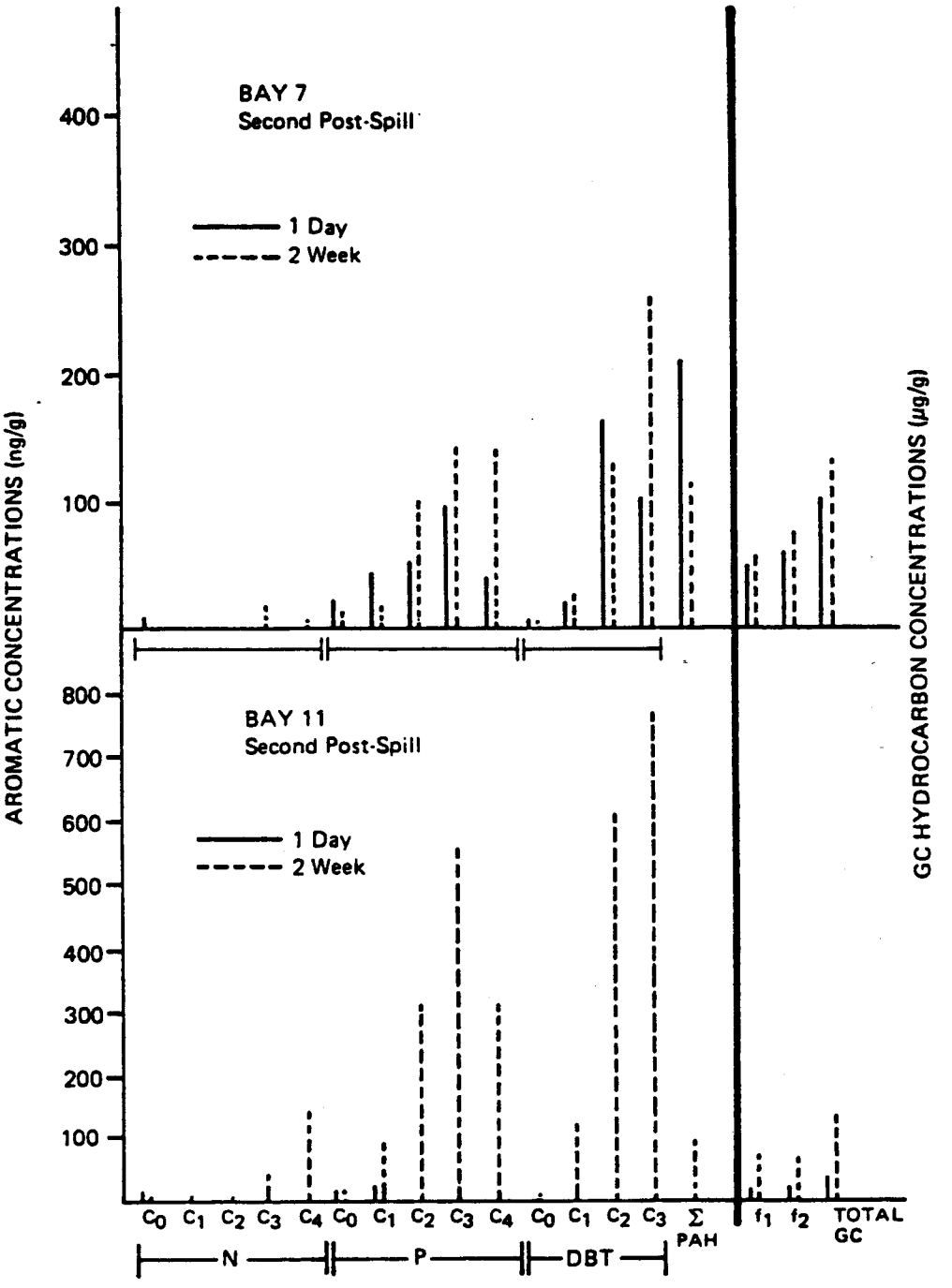

Figure 2.35. Astarte **aromatic profiles (Bays 7 and 11).**

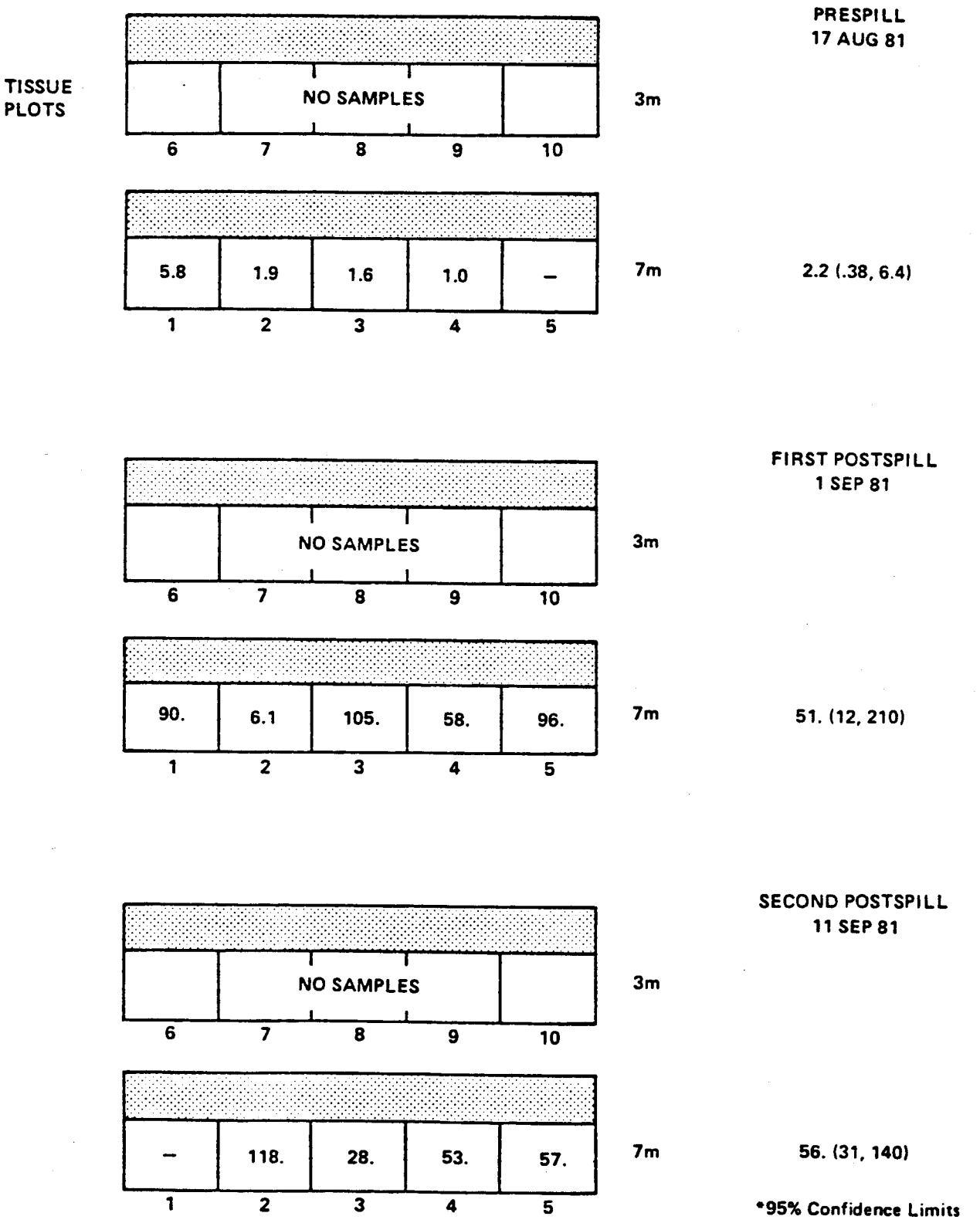

Figure 2.36. Concentrations of oil in Astarte borealis, Bay 7 by UV/F (µg/g).

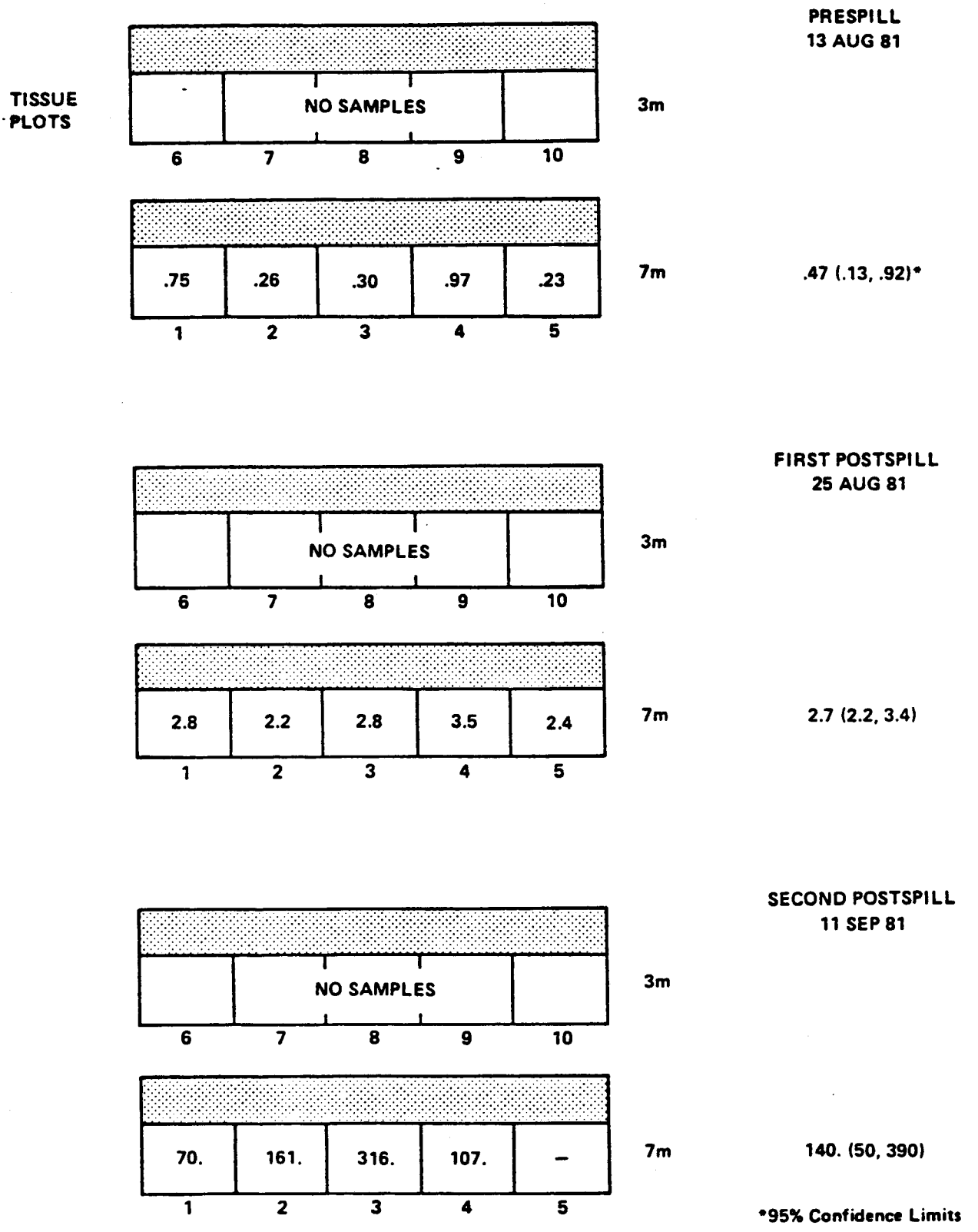

Figure 2.37. Concentrations of oil in Astarte borealis, Bay 11 by UV/F (µg/g).

Astarte, Bay 9, 1-day post-spill, 7 meter

Astarte, Bay 9, 2-week post-spill, 7 meter

Serripes, Bay 10, 1-day post-spill, 3 meter

Serripes, Bay 10, 2-week post-spill, 7 meter

Extracts were available in sufficient quantities for PANH analyses of these samples.

The results shown in the following GC/MS/DS data packets illustrate that PANH compounds were only detected at low levels (<10 ng/g) in the 1-day post-spill Astarte sample. In this sample, dimethyl and trimethyl phenanthridines or acridines were detected. The other samples did not contain detectable PANH compounds. PANH compounds would be present at levels two orders of magnitude lower than the aromatics. The Astarte aromatic values (Figure 2.30) were the highest of any of the animals (1000-2000 ng/g). Therefore, it is entirely consistent to find the PANH values of <10 ng/g. The detection limit for the PANH compounds was <5 ng/g.

2.2.4.1 PANH Compounds in Oil. The accompanying figures are the reconstructed mass spectra of the polycyclic aromatic nitrogen heterocyclic (PANH) compound fraction of the Lagomedia crude oil used in the BIOS Program. C_3-C_6-quinolines, C_2-C_5 acridines, or phenanthridines, benzacridine, and C_1-C_2 benzacridines were identified at concentrations about two orders of magnitude lower than the aromatics (See Appendix I).

2.2.4.2 Astarte borealis: Bay 9: 1 Day. Only trace concentrations (<10 ng/g, parts per billion) of dimethyl- and trimethyl-acridines or phenanthridines were detected in Astarte borealis collected from Bay 9 one day after the spill (See Appendix II).

2.2.4.3 Astarte borealis: Bay 9: 2 Weeks. No PANH at concentrations above the detection limit of 5 ng/g were detected in this sample (See Appendix III).

2.2.4.4 Serripes groenlandicus: Bay 10: 1 Day. No PANH at concentrations above the detection limit of 5 ng/g were detected in this sample (See Appendix IV).

2.2.4.5 Serripes groenlandicus: Bay 10: 2 Weeks. No PANH at concentrations above the detection limit of 5 ng/g were detected in this sample (See Appendix V).

2.3 Discussion

The analytical results presented here and in Boehm (1982) considerably increase our knowledge of the differential fate and behavior of chemically dispersed and surface oil. Furthermore, the transport of oil to the benthos, its route of transport to benthic organisms (oil acquisition), and the species-specific chemical nature of biotal oil depuration are revealed in the wealth of data obtained in this study. We will discuss some of the most important observations and trends here as they pertain to the behavior of oil in the experiments, and to specific important transport paths and biotal impacts.

The quantities of oil driven into the water column as a result of chemical dispersion are far greater than those that result from transport of untreated surface oil into the water column. Concentrations of chemically dispersed oil in the water column ranged from 1 to greater than 50 ppm (~100 ppm) during the dispersed oil discharge and for as long as twelve hours after discharge ceased at some points in Bay 9. Differential movement of oil released at different points along the diffuser resulted in direct northward movement of oil at greater depths of release (10 m) and initial southerly movement of oil at shallower depths followed by subsequent reversal of direction and "reinvasion" of Bays 9 and 10 four hours after formal oil/dispersant discharge ceased. The dispersed oil plume formed a very stable layer of oil in the water column for perhaps 6-13 hours after dispersal. Dispersed oil droplets carried by strong shore currents were advected for considerable distances without a significant change in the composition of the oil. Whether this occurred due to the stability of the small (~10 μm) oil droplets, thus retarding fractionation (i.e., dissolution or evaporation), or whether particulate and dissolved parcels of oil traveled coherently due to strong advection (0.5 knot currents), is difficult to ascertain. Results of large volume water samplings which were taken outside of these concentrated plumes and after the passage of the highest concentrations indicated that a physical-chemical fractionation of hydrocarbon compounds did occur. It is, however, quite significant that fresh oil with its full suite of low molecular weight saturated and aromatic components persisted as a coherent plume for considerable periods of time (6-13 hours), apparently cut off from evaporative loss from either the dissolved state or by advection to the surface. Indeed, confirmation of this coherent oil layer was made by fluorescence profiling and by discrete sampling, sometimes indicating a tenfold

increase in water-borne oil concentrations within a water layer sandwiched by lower concentrations of more highly weathered oil. The persistence of low molecular weight saturates (C_6-C_{10} alkanes) and alkylated benzenes and naphthalenes in the plume in similar proportion to the total petroleum in the neat oil was unexpected. Surely the subsurface release of dispersed oil accounted for this. A surface release followed by application of chemical dispersants would have allowed some loss of light aromatics to occur by evaporation.

The very striking similarity between the BIOS dispersed oil plume behavior and that observed in the Ixtoc I spill (Boehm, Barak, Fiest and Elskus 1982) is of no small importance. A subsurface release of oil that creates small oil droplets either through shear (Ixtoc) or through stabilization through chemical dispersion (BIOS) with resulting droplets advected by strong currents, results in subsurface coherent plumes of unweathered fresh oil with a full contingent of toxic aromatics. The similarities between the two events are also striking given the 25°C water column temperature differential between Gulf of Mexico and Arctic waters. Of course these initial high levels of oil (roughly 10 ppm in the Ixtoc I and 10 ppm and greater in the BIOS scenarios) will eventually be reduced through dilution and diffusion even if the coherent subsurface plume persists as it did for 20 km or so in the Ixtoc I spill.

During and after the dispersed oil experiment, there was little evidence for either the large-scale beaching of dispersed oil or the surfacing, in the water column, of dispersed oil. However, both phenomena did occur to minor extents and resulted in some important information. Oil that was found adhering to the Bay 9 beach was present at low levels (5-10 ppm). The oil had weathered significantly, due mainly to losses of low molecular weight components. Both the concentration of oil on the beach and its composition were nearly identical to those found in the offshore benthic sediments implying a detectable, but low sorptive affinity of dispersed oil. Oil which did appear to have coalesced at the sea surface was highly weathered through loss of low boiling saturates and aromatics. The state of weathering of this surface oil sampled several hours after initial dispersed oil discharge was equivalent to that of nine-day-old beached surface oil (Bay 11). Thus it appears that the coalesced oil formed after solubles were stripped from the oil in the water column with the coalesced oil forming from a weathered residue.

Oil did impact the sediments of Bays 9 and 10 immediately after the dispersed oil spill where initially a significant amount of the sedimented oil (~20%) resided in the surface floc. Sedimentation rates were estimated to be in the 2-10 mg/m^2/day range. Subsequently, the floc was tranported elsewhere, probably offshore, because floc from all bays sampled in the second post-spill period (September 11) was free of any detectable oil. Levels of oil in the sediments, however, remained elevated (1-5 ppm) in Bays 9 and 10 and although this dosing is considerably less than a "massive" dosing, it will continue to affect benthic biota for an unknown period of time. The overall sediment impact due to passage of dispersed oil through Bays 9 and 10 was minimal, with less than 1 % of the discharged oil probably residing in the sediment at any time.

Results from the initial sampling of sediments indicated that 80 % of the oil detected in the top 0-3 cm was not associated with the floc. This is in contrast to results from other spills (e.g., Boehm, Barak, Fiest and Elskus 1982; Boehm, Wait, Fiest and Pilson 1982) and to experimental tank studies (Gearing et al., 1980) in which most of the initially sediment-associated oil was in the floc layer. What appears to be occurring in the BIOS dispersed oil spill is a low level, direct and rapid penetration of dispersed oil into the bulk surface sediment, presumably a process mediated by the decrease of the oil's interfacial tension due to chemical dispersion allowing for penetration of the solid interface perhaps into interstitial waters. Indeed chemical results from polychaete analyses in Bays 9 and 10 (Norstrom and Engelhardt, 1982) revealed an initial uptake of an alkylated benzene and napthalene (i.e., water-soluble fraction) enriched petroleum hydrocarbon assemblage in Bays 9 and 10 only, perhaps associated with interstitial water penetration of fractions of the oil.

The Bay 7 "control" did receive 50-100 ppb of dispersed oil in the first few days after the discharge. This quantity of oil was measured directly (Green et al., 1982) and was monitored indirectly through hydrocarbon body burdens in filter-feeding bivalves (i.e., Mya, Serripes). Direct sediment analyses and indirect evidence from deposit-feeding animals (Macoma, Strongylocentrotus) indicate, however, that oil impact to Bay 7 sediments was quite minimal with only patchy low level inputs noted. The Bay 7 analytical results point to an important conclusion regarding application of UV/F and GC^2 techniques to the BIOS study. While background (by UV/F) levels of "oil equivalents" in the sediments was ~0.5 ppm, many samples did exhibit post-spill oil levels of 1.0-1.5 ppm. In this concentration, range levels were too low to unambiguously yield an oil/no oil

decision based on GC^2. Oil levels of ~1.0 ppm would contain individual component concentrations (i.e., n-alkanes) of ~.01 ppm (or 10 ng/g). Due to significant biogenic background in the GC^2 traces, this level of individual components was often too low to see in the GC^2 traces. Thus UV/F becomes a key to assessing oil concentrations in sediments. However, in several cases in Bay 7 sediments, low UV/F levels (~0.3 ppm), generally associated with background levels, were shown by GC^2 to contain small amounts of oil. The weathering of oil while in transit to Bay 7 with resulting loss of water-soluble aromatics and a concomitant decrease in UV/F response caused whatever oil was seen in Bay 7 sediments to be relatively enriched in saturates (not detectable by UV/F). Thus the two techniques of UV/F and GC^2 proved to be an extremely powerful complementary set.

Water-borne oil in Bay 11 was initially confined to the surface (0-2 meters) layer during which time large-scale transport of oil to the benthos via sorption and sinking did not occur. Through large volume water samples, low levels (ppb) of oil were detected in mid-depth and bottom waters largely in a particulate form, prior to any possible cross-contamination from the dispersed oil spill occurring a week later. That oil did impact the sediment in Bay 11 prior to the dispersed oil spill is evident from uptake patterns of all of the benthic animals, especially those of the deposit-feeders Macoma and Nuculana and of the filter-feeder Serripes which all revealed uptake of oil, albeit at lower levels relative to those which were acquired in the dispersed oil scenario, prior to any possible cross-contamination from Bays 9 and 10. We do know that the dispersed oil's influence was far-ranging including a transient water column impact at Bay 7 causing elevated levels of oil in all benthic biota, especially the filter-feeders Mya and Serripes. Thus it may be logical to "subtract" the observed Bay 7 animal levels from the Bay 11 values to derive a "pure" Bay 11 result for the second post-spill sampling. Using this logic, it can be concluded that although low levels of oil are acquired in Bay 11 by the filter-feeders, the major Bay 11 impact is on the deposit-feeders which are more closely linked to the sediments and which acquire weathered oil from off of the beach face.

The most significant findings of the study concern the relationship between water-borne levels of oil, sediment concentrations and levels in benthic biota. Initial uptake of oil by Mya and Serripes is from the water column wherein oil is acquired through pumping of contaminated seawater through gills. Most of this oil initially resides in the animal's gut as confirmed through Serripes dissections. Chemically, even the initial

oil residues in the gut and muscle tissue are different. The more water-soluble aromatics (naphthalene, alkylated benzenes) are transported to the muscle tissues (including gills) more rapidly, with the phenanthrenes and dibenzothiophenes preferentially located in the gut. During the first two weeks after the spill, however, it is these higher molecular weight aromatics which persist, the water-soluble aromatics being depurated more readily.

Initial levels of oil in filter-feeders from Bay 7 are equal or greater than those from Bays 9 and 10, where water column levels of oil were 20 to 200 times as great. Sediments are ruled out as an oil-biotal intermediary due to the near absence of oil in Bay 7 sediments. Thus one must postulate that while Mya and Serripes from Bays 9 and 10 either cease pumping due to water column levels or die after initial accumulation of oil, animals in low-to-moderately contaminated waters continue to pump and acquire oil as long as it is present in the water. At water column concentrations of 50 µg/l (50 ppb), a clam (1 g dry weight) pumping at a rate of 1 liter per hour would pass 1.2 mg of oil through its body in 24 hours, more than enough to acquire a 100-500 ppm concentration. As levels of oil in Bays 9 and 10 were much higher, 1-50 ppm initially and 100-200 ppb for at least a day to a day and a half after cessation of the oil spillage, opportunities for greater bioaccumulation in Bays 9 and 10 were available but were probably not achieved due to either saturation in the gut, inability to transport oil across the membranes fast enough to acquire more oil, or a wholesale cessation of pumping. The latter explanation is the most likely.

Mya truncata and Serripes groenlandicus are filter-feeders and accumulate oil primarily from the water column. They depurate 60-75 percent of the accumulated oil within two weeks, even though the sediments in which they reside remain contaminated with oil. On the other hand, Macoma calcarea and Nuculana minuta are deposit-feeders, and accumulate petroleum hydrocarbons primarily from the sediments. In controlled laboratory experiments, Roesijadi et al. (1978) showed that the deposit-feeder, Macoma inquinata, accumulated higher concentrations of aromatic hydrocarbons from Prudhoe Bay crude oil-contaminated sediments than did the filter-feeder, Protothaca staminea. In the BIOS study, the deposit-feeders continued to accumulate hydrocarbons during the two weeks after the spill (Bays 9 and 11) or became heavily contaminated immediately after the spill and retained the hydrocarbons for at least two weeks (Bay 7 and 10). The GC^2

profiles of tissue extracts of the deposit-feeders show evidence of uptake of oil from sediment, rather than from the water column, after an initial rapid uptake of perhaps 30-50 ppm oil from the water column.

As discussed previously, the two oil spill experiments conducted introduced oil into the nearshore system in two distinct manners. The Bay 11 surface oil (untreated) spill resulted in detectable water-borne oil concentrations only in the top meter or so of the water column (Green et al., 1982). That low levels of water-soluble oil may have penetrated to the benthos during the first day or so following the spill can not be confirmed from direct chemical evidence of water samples, but may have occurred, causing the low intitial increases in petroleum hydrocarbon levels and levels of water soluble aromatics in some of the filter-feeders (Mya, Serripes, Astarte). That oil did impact the benthos of Bay 11 as soon as one day after the spill is indicated by the uptake of oil by Macoma, Pectinaria and Strongylocentrotus in the immediate post-spill period. Subsequent benthic impact of oil in Bay 11 is clearly indicated in increased sediment concentrations (~5 ppm) as well as by the increased uptake of oil by the deposit and detrital feeders. The oil reaching the benthos during the 1 day to 2 week post-spill period was weathered due to evaporation/dissolution as evidenced by the loss of alkylated benzene and naphthalene compounds relative to the spilled oil.

The uptake and depuration curves during the first several days are difficult to reconstruct due to differences in sampling times. For example, it is not clear whether higher levels of oil in Serripes in Bay 10 versus Bay 9 were due to a combination of animal behavior and water column concentration or due to the additional day during which they acquired oil. Alternatively, filter-feeders may very well have "shut down" their pumping systems in Bay 9 (or were narcotized or killed outright) due to high water column oil concentrations, while those animals in Bay 10 may have continued to pump and acquire more oil. Indeed this seems to have been the case in Bay 7. Low levels of oil (50-100 ppb) were detected in Bay 7 two days after the spill (Green et al., 1982), as were these same levels in Bays 9, 10, and at other Ragged Channel locations. Bay 7 Serripes were especially efficient at concentrating oil from these lower water column levels, with oil residing primarily in the gut initially. Serripes and Mya from Bay 7 probably did not detect those lower levels of oil and may have continued their normal pumping of water throughout the first several days after the spill.

As alike as Mya and Serripes behave vis-a-vis routes of oil uptake, they differ in the compositional nature of the oil which they retain. During the two week post-spill period of depuration, an in vivo biodegradation, presumably by a microbial population within the animal's guts, occurred to a significant extent. At this point, the similarity between Mya and Serripes erodes, because although on a gross level both species depurated oil, on a detailed chemical basis Serripes preferentially retained a high molecular weight saturated hydrocarbon assemblage as well as the higher alkylated naphthalene, phenanthrene and dibenzothiophene compounds. Mya, on the other hand, depurated all hydrocarbon components, although the water-soluble alkyl benzenes and naphthalenes were depurated somewhat faster.

Thus, as the exposure levels in the water column decreased, levels of total hydrocarbons in Mya and Serripes decreased. This, plus the fact that whole, undegraded oil resided in Bay 11, 9, and 10 sediments without a concomitant increase in concentrations of oil in the filter-feeders provides evidence of decoupling of sedimentary sources of hydrocarbons from these animals. This decoupling is accented by the fact that while oil residues in sediments were not degraded, residues in the animals were microbially degraded.

Macoma, Nuculana, Strongylocentrotus, and Pectinaria clearly are influenced by sediment oil levels more than those in the water column. Though there is some indication that low levels of soluble aromatics in the water were reflected in early oil compositions in the deposit-feeders, steady uptake of sediment-bound oil by this group dominates. Thus, the lack of detectable sediment-bound oil in Bay 7 is reflected in much lower petroleum body burdens in deposit-feeders from this bay. Additionally, over two weeks we see much less of an indication of microbial degradation in the Bay 9, 10 and 11 deposit-feeding animals due to the acquisition of undegraded oil from the sediments appearing as a constant compositional overprint. Furthermore, those aromatic hydrocarbon components longest-lived in the sediments (i.e., alkylated dibenzothiophene and phenanthrene compounds) steadily increase in the deposit-feeders.

Thus, the various filter-feeders and deposit/detrital feeders reflect the fate of oil in the system quite well. The fact that the polychaete acquires whole oil, dominated somewhat by a water-soluble grouping of alkylated benzenes and naphthalenes, may reflect the association of oil with interstitial waters in the upper sediment column.

A similar differential behavior of filter-feeding versus detrital feeding bivalves was reported recently in an actual spill (Boehm et al. 1982b). In this study, the authors found that the benthic-dwelling Macoma balthica was slower to initially acquire oil than was the filter-feeder Mytilus edulis which resided in the phytal zone. After beaching and erosional transport, and/or direct sedimentation of oil, the petroleum body burden increased in Macoma and only slowly decreased as the sediment levels dropped. Mytilus, on the other hand, exposed to a massive initial amount of water-borne oil, depurated rapidly and almost completely over one year's time.

During the first two to three weeks after the spills, there was a notable lack of significant biodegradation of oil in the water column and in the sediments. There is no chemical evidence for the existence of biodegradation as a removal mechanism with the short-term post-spill period (3 weeks) either in the water column or in the sediment. One would have predicted higher rates of biodegradation in surface sediments, especially in the surface floc, but none was observed through degradation of the "easily" degraded n-alkanes. However, degradation of n-alkanes in the oil resulting in the classic loss of n-alkane relative to isoprenoid and other highly branched alkanes is observed within Mya and Serripes and to lesser extents in other benthic species. Rapid degradation of alkanes only occurs in vivo. Whether or not this unique finding can be ascribed to microbiotal populations within the organism itself, a likely mechanism, must be confirmed independently. We suspect that given an unspecified amount of time, microbial populations will begin to utilize the hydrocarbons as an energy source (i.e., biodegradation will become more significant).

The use of a variety of biological monitors or sentinel organisms in the BIOS study has served to delineate oil transport paths and changing environmental compartment levels with time during the immediate post-spill (0-3 weeks) period. Furthermore, this study has shown that although similarly behaving animals (e.g., Mya/Serripes; Macoma/Strongylocentrotus) may on a gross level appear to act in concert, the details of in vivo modifications and retentions of individual petroleum components are quite different and may be intimately associated with long-term biological effects on the individual benthic species.

3. HISTOPATHOLOGY

3.1 Materials and Methods

3.1.1. Collections. The first series of specimens of Mya truncata were collected by divers between August 7 and August 17, 1981. A second group of specimens was collected between August 21 and September 3, 1981, following the application of dispersed oil to Bay 11 on August 19, and of dispersed oil to Bay 9 (and subsequently to Bay 10) on August 27. Because of the unlikely possibility that any major pathological conditions caused by the oil or dispersed oil would be apparent within the approximately two-week period following the spill, a third series of samples was not collected until a year later, on August 27 and 28, 1982.

Specimens of Macoma calcarea were collected prior to the spill only from Bay 9. Collections were made in Bay 7, the control bay, on September 2 and 3, 1981, a few days after oil and dispersant were added to Bay 9, and almost two weeks after oil was applied to Bay 11.

The dates and sites of collection and the number of specimens of each species collected for histopathology investigations are shown in Tables 3.1 and 3.2.

3.1.2. Processing. Specimens were fixed at the Baffin Island location by the collectors. Fixation for the 1981 collections was in Carson's modified Millonig's phosphate-buffered formalin. This fixative was used rather than the originally proposed Helly's fixative because of its ease of handling by the divers under field conditions. Neutral buffered 10 percent formalin was used for the 1982 collections for the same reason.

For fixation, larger specimens such as Mya truncata were to have one valve removed before being placed in the fixative. Smaller specimens such as Macoma calcarea were to be treated similarly if possible, or at least to have the shell cracked slightly to permit entry of the fixative. In fact, some specimens were placed intact in the fixative. The specimens were placed in fixative in small plastic tissue bags, in which were also placed coded identification tags. The bags were then sealed by having the tags rolled down and secured with attached plastic strips. The bags were packed in shipping containers and shipped to the laboratory in Duxbury, Massachusetts for histopathological analysis.

Table 3.1. Dates of collection and collection sites for specimens of Mya truncata for BIOS histopathology investigation

	Date Collected	Bay Number	No. of Specimens
Immediate Pre-Spill	8/7-8/9/1981	9	94
	8/12/81	11	63
	8/14-8/15/81	10	84
	8/17/81	7	40
Immediate Post-Spill	8/21/81	11	59
	8/28-8/29/81	9	80
	8/29-8/30/81	10	102
	8/31/81	7	47
1 year Post-Spill	8/27/82	11	77
	8/27-8/28/82	10	75
	8/28/82	9	75
	8/28/82	7	75

Table 3.2. Dates of collection and collection sites for specimens of Macoma calcarea for BIOS histopathology investigation

	Date Collected	Bay Number	No. of Specimens
Immediate Pre-Spill	8/9/81	9	83
Immediate Post-Spill	9/2-9/3/81	7	72
1 Year Post-Spill	8/27/82	10	83
	8/27/82	11	120
	8/28/82	7	86
	8/28/82	9	75

Fixed specimens from the 1981 collections were received at Battelle New England Marine Research Laboratory on November 6, 1981. Specimens from the 1982 collections were received on September 22, 1982.

Upon receipt at BNEMRL, the samples were removed from the shipping containers and logged in according to the coded label by station number, species, and date collected. The specimens were then washed in running tapwater for several hours and transferred to 70% ethyl alcohol until histological processing.

For processing, the specimens were trimmed to provide cross-sectional pieces of tissue which were dehydrated and embedded in Paraplast Plus.

The embedded tissues were sectioned at 5 to 6 μm and stained with hematoxylin and eosin using standard procedures. The stained sections were examined for any pathological conditions.

3.2 Results

Results of histopathological observations of tissues of Baffin Island molluscs are summarized in Tables 3.3 through 3.7. Tables 3.3, 3.4, and 3.5 show the results of observations of Mya truncata from the pre-spill, immediate post-spill, and one year post-spill collections, respectively. Tables 3.6 and 3.7 summarize the results of the pre-spill and one year post-spill observations of Macoma calcarea.

Despite indications of poor fixation, a number of pathological conditions were noted primarily in tissues sampled after the spill. The most serious of these included hematopoietic neoplasms, or blood tumors, in both species of clams studied.

Details of the pathology of each of the two species studied are provided below.

3.2.1 Mya truncata. The most common pathological problems observed were hemocytic infiltration, or inflammation, and the occurrence of an unidentified trematode parasite (Table 3.3, 3.4, and 3.5). Immediately following the spill, the incidence of necrotic tissue, particularly in the gills and digestive tract, increased in Bays 7, 9, and 10 (Table 3.4), but a year later this incidence had decreased considerably (Table 3.5). Necrotic lesions in the digestive tract were accompanied by an increase in the number of mucus-producing cells in the gastrointestinal tissues, and in Bay 10 by unidentified basophilic inclusions in the digestive gland tubules. Bays 9 and 10 produced a few one-year post-spill clams with granulocytomas throughout the tissues (Figure 3.1).

Table 3.3. Summary of histopathological observations of tissues of the truncate soft-shelled clam Mya truncata from the Baffin Island oil spill area prior to the application of oil and dispersant

			Condition								
Bay No.	Station	Numbers of Specimens	Hemocytosis	Necrosis	Abscesses	Digestive Tubule Vacuolization	Metaplasia	Hyperplasia	Neoplasia	Parasites	Other
7	1	9	2					1		6	
	2	8	1					1		4	
	3	8	1							4	
	4	6									
	5	9								1	
9	1	21	1							2	
	2	6									
	3	12								5	
	4	10						1			
	5	9									
	6	9			1					3	
	7	9								4	
	8	9								6	
	9	9								7	
10	1	10								1	
	2	10								2	
	3	9	1							3	
	4	8								1	
	5	6	1							1	
	6	8	1							3	
	7	9	1							4	
	8	9					1			3	1-mass of hypertrophic hemocytes in stomach
	9	7								2	
	10	8								4	
11	1	9	1			1					
	2	9									
	3	10	1							5	
	4	9	1		1					3	
	5	11	3								

Table 3.4. Summary of histopathological observations of tissues of the truncate soft-shelled clam Mya truncata from the Baffin Island oil spill area immediately following the application of oil and dispersant

			Condition								
Bay No.	Station	Numbers of Specimens	Hemocytosis	Necrosis	Abscesses	Digestive Tubule Vacuolization	Metaplasia	Hyperplasia	Neoplasia	Parasites	Other
7	1	10		1						3	2-mucus cells in gastrointestinal epithelium
	2	8									
	3	10									
	4	10							1		
	5	9									
9	3	11								5	
	4	11	3							4	
	5	10	1							2	
	6	8								4	1-fibrous connective tissue
	7	11								3	
	8	10		2	2					2	
	9	9		1						3	
	10	10		1						6	
10	1	11		5						4	
	2	10	1							4	
	3	11		4						2	3-mucus cells in gastrointestinal epithelium
	4	10		3						1	
	5	9	2	1						2	
	6	10	1							5	
	7	9	1		1					4	
	8	11					1			5	1-basophilic inclusions in digestive mass of hypertrophic hemocyte tubules
	9	11	1							7	1-basophilic inclusions in digestive tubles
	10	10								2	2-basophilic inclusion in digestive tubules
11	1	12								5	
	2	11	1							5	
	3	13								6	
	4	13								5	
	5	10	1							1	

Table 3.5. Summary of histopathological observations of tissues of the truncate soft-shelled clam Mya truncata from the Baffin Island oil spill area one year following the application of oil and dispersant

			Condition								
Bay No.	Station	Numbers of Specimens	Hemocytosis	Necrosis	Abscesses	Digestive Tubule Vacuolization	Metaplasia	Hyperplasia	Neoplasia	Parasites	Other
7	1	15	1	1						8	
	2	15	3							3	
	3	15	4							5	
	4	15	2							5	
	5	15	6	1	1					1	
9	1	15								6	1-granulocytomas
	2	15	2	1			1			7	
	3	15	3	1						6	1-granulocytomas
	4	15	2							6	1-fibrous connective tissue
	5	15	2							5	
10	1	15	1							7	1-granulocytomas
	2	15	2							4	
	3	15								4	1-granulocytomas
	4	15	2	1						5	
	5	15								3	1-inclusions in digestive tubule epithelium
11	1	15								9	
	2	15								8	
	3	15	1	3						7	
	4	15	1						1	7	1-cysts on gill from gregarine-like organism
	5	17							2	10	

Table 3.6. Summary of histopathological observations of tissues of the chalky macoma Macoma calcarea from the Baffin Island oil spill area prior to and immediately following the application of oil and dispersant

			Condition								
Bay No.	Station	Numbers of Specimens	Hemocytosis	Necrosis	Abscesses	Digestive Tubule Vacuolization	Metaplasia	Hyperplasia	Neoplasia	Parasites	Other
9	1	11									
	2	9									
	3	20									1-unidentified inclusions in testis
	4	28	1	1	2					1	
	5	15									
7	1	15		1	1						1-granulocytomas
	2	16		1						2	
	3	23		3		1				2	1-small cyst in digestive tubule
	4	7		1							
	5	11		3							

Table 3.7. Summary of histopathological observations of tissues of the chalky macoma Macoma calcarea from the Baffin Island oil spill area one year following the application of oil and dispersant

			Condition								
Bay No.	Station	Numbers of Specimens	Hemocytosis	Necrosis	Abscesses	Digestive Tubule Vacuolization	Metaplasia	Hyperplasia	Neoplasia	Parasites	Other
7	1	16									1-unidentified inclusions in digestive gland
	2	15								1	
	3	20								1	
	4	18								1	
	5	17		1	1					3	1-encysted inclusion
9	1	13									
	2	15		2						1	
	3	15								1	
	4	16		2							
	5	16		3				1			
10	1	18			1	1				2	
	2	20	1	1		3				1	
	3	16	2	2	1	1					
	4	14									
	5	15		1	1	3				1	
11	1	25	1	3	1	13				5	1-encysted inclusion
	2	31		1	1	22			1	7	
	3	26	3		1	17	1			7	
	4	13	1			8				4	
	5	25	1		1	3				1	1-unidentified inclusions in gonad

Figure 3.1. Granulocytoma in testis of truncate soft-shelled clam, Mya truncata, from Bay 9 one year following oil spill.

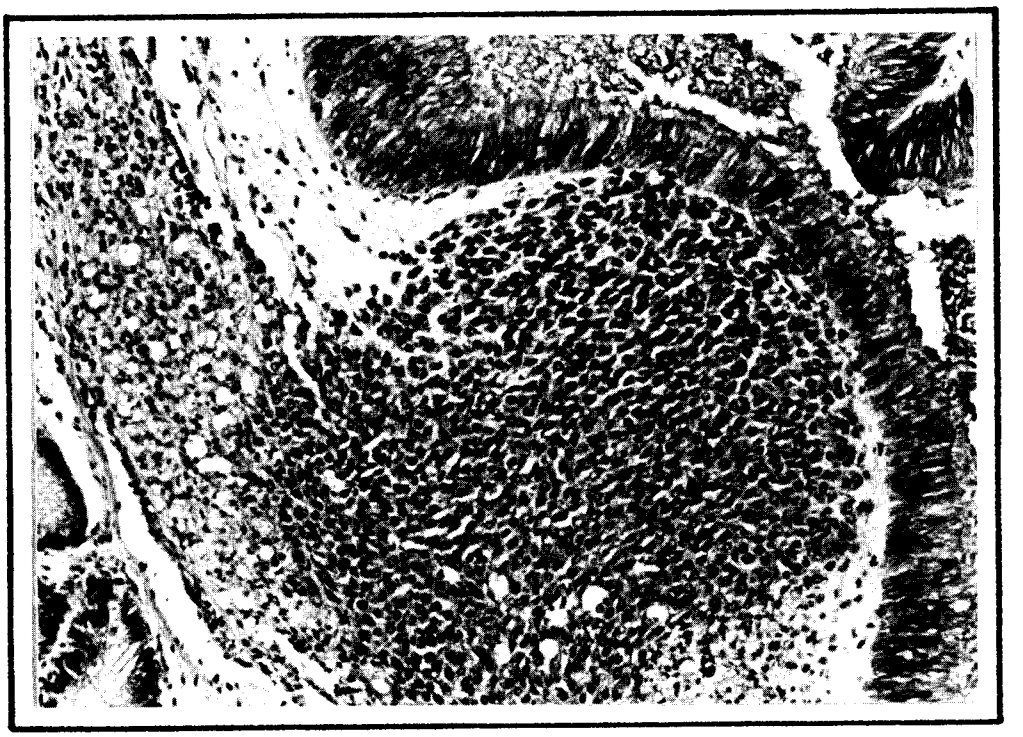

Figure 3.2. Neoplastic hemocytes in tissues of the truncate soft-shelled clam, Mya truncata, collected from Bay 7 immediately following the oil spill.

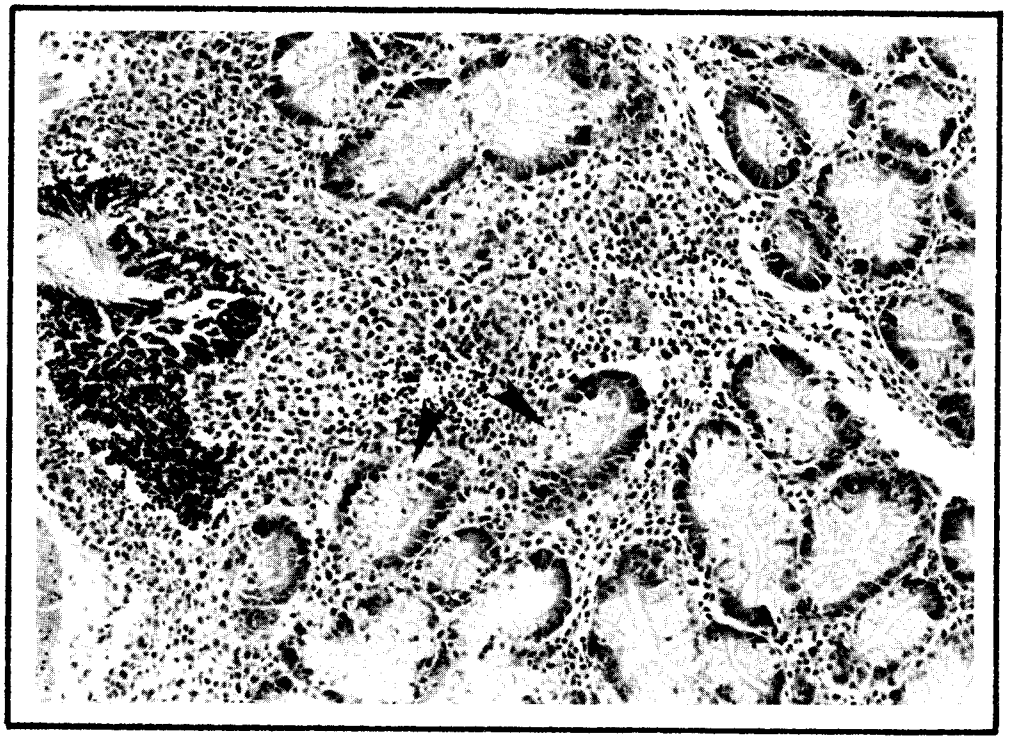

Figure 3.3. Hematopoietic neoplasm in digestive tubule area of truncate soft-shelled clam, Mya truncata, collected from Bay 11 one year after oil spill. Note invasion of digestive tubules by neoplastic cells (arrows).

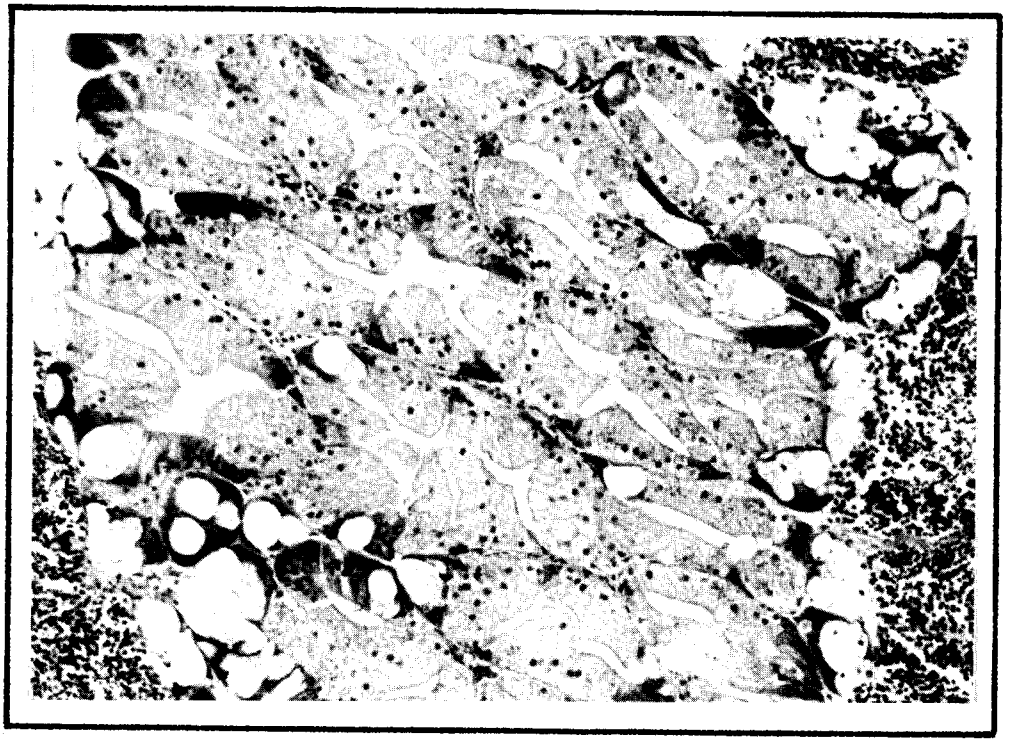

Figure 3.4. Normal digestive tubules of the chalky Macoma, Macoma calcarea, from Bay 11 one year following the oil spill.

Figure 3.5. Excessively vacuolated digestive tubules of the chalky Macoma, Macoma calcarea, from Bay 11 one year following the oil spill.

by the oil has not been established. Of the five observed incidences of neoplasms, four occurred in Bay 11 a year after the application of the oil.

The presence of granulocytomas in several specimens of Mya truncata from Bays 9 and 10 after a year also is of interest. Lowe and Moore (1979) suggest a relationship between this non-neoplastic inflammatory cellular condition, which they describe in the marine mussel Mytilus edulis, and water quality. They point out that mussels from areas of chronic domestic and industrial pollution have a high incidence of granulocytomas, whereas mussels exposed to low-level pollution exhibit a low to zero incidence of the condition.

The parasite burden in Bay 11 also appears to be higher than in the other bays. Both species, but especially Mya truncata, were quite heavily parasitized before and after the oil spill. This degree of parasitism might have an effect on the ability of the clams to withstand toxic effects of the oil. Conversely, the effects of the oil could lead to an increased parasite burden.

A small amount of vacuolization of digestive tubule epithelium is not uncommon and may be normal. The degree to which the tubules of M. calcarea from Bay 11 a year after the oil spills were vacuolated seems excessive when compared to the condition of the tubules from M. calcarea specimens at other times and at other sites. It is undoubtedly related to diet or feeding, but whether there is an effect of the oil is not fully understood at this time. Similar conditions of the digestive tubule epithelium were reported in bivalve molluscs contaminated by the Amoco Cadiz oil spill (Wolfe et al., 1981; Neff and Haensly, 1982).

None of the pathological effects noted can be attributed directly to the oil, although there are indications of some relationship between the experimental oil spill and the noted effects. More needs to be known, not only about the relationship of oil and dispersed oil to the observed lesions, but about how the various toxicants affect a mollusc's ability to mobilize its own natural defense mechanisms.

4. BIOCHEMICAL EFFECTS OF OIL

The objective of the biochemistry program was to compare the state of health of infaunal bivalve molluscs from bays at the BIOS experimental site receiving dispersed oil, undispersed oil, and no oil. A suite of diagnostic biochemical tests of proven utility was used to diagnose sublethal pollutant stress in four populations of molluscs from the oil spill site.

4.1 Materials and Methods

There were four experimental bays used in these experiments, located on the northwest coast of Baffin Island, Northwest Territories, Canada. Bay 7 was considered a reference bay (though it received oil), Bays 9 and 10 received dispersed oil, and Bay 11 received oil alone. A Lagomedio crude oil and the dispersant, Corexit 9527, were used in these field experiments.

Mollusc specimens were collected by divers, using an air-lift system, at ten stations located along two transects paralleling the shore at the 3-meter and 7-meter isobaths in each bay. Stations 1-5 were along the 7-meter transect and Stations 6-10 were along the 3-meter transect. Specimens were collected several days before the spill, 1-4 days after the spill, and approximately 2 weeks after the spill. Some samples were kept over night or longer before freezing.

Mollusc specimens for biochemistry were frozen and returned to the U.S. on dry ice. A complete set of the truncate soft-shell clam Mya truncata was available for analysis. Only small numbers of Macoma calcarea, Astarte borealis, and Serripes groenlandicus were available from a few bays at each sampling time. Therefore, we examined only Mya, but analyzed more replicate samples of this species from each collection than originally proposed. A total of 228 specimens of Mya truncata were analyzed for carbohydrates and lipids and 230 specimens were analyzed for tissue free amino acids.

In the laboratory, individual clams were thawed, shucked, and weighed. Tissue glucose, glycogen, and other glucose-containing carbohydrates (mainly trehalose, a glucose disaccharide) were analyzed with the Beckman automatic glucose analyzer after

selective hydrolysis according to the method of Carr and Neff (1983). The tissue was homogenized. An aliquot of the homogenate was centrifuged and glucose concentration in the supernatant was measured. Another aliquot of the homogenate was incubated overnight in acid buffer with amyloglucosidase which selectively and quantitatively hydrolyzes glycogen to glucose. The homogenate was centrifuged and the glucose concentration in the supernatant was measured. For the other carbohydrates, an aliquot of the tissue homogenate was incubated in concentrated HCL for three hours at 100°C. The mixture then was neutralized with 12N NaOH and centrifuged. Glucose concentration in the supernatant was measured. Glycogen concentration was calculated as glucose concentration in the amyloglucosidase digest minus glucose concentration in the original supernatant. The concentration of other glucose-containing carbohydrates was calculated as the glucose concentration in the acid digest minus the glucose concentration in the amyloglucosidase digest.

Total lipids were determined according to the methods of Holland and Gabbott (1971). An aliquot of the tissue homogenate was extracted with chloroform-methanol, centrifuged, and the supernatant dried and taken up in chloroform. Total lipids were measured spectrophotometrically following treatment with H_2SO_4 at 200°C.

Whole soft tissues of clams were extracted and analyzed for tissue free amino acids by methods similar to those described by Roesijadi and Anderson (1979). The tissues were homogenized in 7 percent trichloroacetic acid. The homogenate was centrifuged and the supernatant was washed three times with diethyl ether to remove trichloroacetic acid. The supernatant then was lyophylized and dissolved in 0.1N HCl. Samples were analyzed with a Waters Associates gradient high-performance liquid chromatograph equipped for post-column derivatization with O-phthalaldehyde and fluorescence detection.

Data were analyzed for statistically significant differences between control and treatment means by the Mann-Whitney one-tailed U-test, Student's t-test and Kruskal-Wallis one-way analysis of variance. The Spearman rank correlation test was used to detect association between pairs of biochemical parameters among animals from different sampling times and treatment groups.

4.2 Results

Based on analyses of petroleum hydrocarbons in tissues of five species of molluscs, performed as part of this program (see Section 2), all four bays received some oil during or after the simulated oil spill. Mya truncata from Bay 10 became the most heavily contaminated with petroleum hydrocarbons, followed in order by clams from Bays 9, 7, and 11 (Table 4.1). Mya from the two dispersed oil bays (Nos. 9 and 10) accumulated the most oil immediately after the spill. The mean concentration of petroleum hydrocarbons in clams from Bay 11 (oil alone) increased between one-day and 2 weeks post-spill. Clams from the reference bay (Bay 7) were contaminated with a mean of 114 ppm (range 60-194 ppm in clams from the 5 stations on the 7-meter transect) one day after the spill, indicating that some oil reached this bay. Before the spill, clams from all four bays contained similar low levels of petroleum hydrocarbons.

There was a great deal of variation among replicates, experimental bays, and sampling times in the concentration of carbohydrates and lipids in the tissues of Mya truncata (Table 4.1). Mean concentrations of free glucose were higher in clams from all four bays two weeks after the simulated oil spills (second post-spill sample) than in samples collected at the two earlier sampling times. There was a drop in the concentration of free glucose in clam tissues between the pre-spill and first post-spill samples in Bay 10 (dispersed oil) and 11 (oil alone). Glucose concentrations in tissues of clams from the four bays were nearly the same at the time of the second post-spill sampling. In clams collected before the spills, clams from Bays 9 and 10 had significantly lower tissue glucose concentrations than clams from Bay 11. Immediately after the spill, clams from the three experimental bays (9, 10, and 11) had significantly lower tissue mean glucose concentrations than clams from the reference bay (7). Clams from the more heavily oiled of the two bays receiving dispersed oil (Bay 10) had a significantly lower tissue glucose concentration than clams from the less heavily oiled, dispersed oil bay (Bay 9).

There was a tendency for tissue glycogen concentration in clams to increase between the first, second, and third collections, particularly in clams from the reference bay. In clams from Bays 10 and 11, mean tissue glycogen concentrations dropped between the first and second post-spill samples. The mean concentration of tissue glycogen in

Table 4.1. Carbohydrates and lipids in tissues of the truncated soft-shell clam Mya truncata collected from the BIOS site before and after the simulated oil spill. All values are in mg/g wet tissue. Mean concentrations of petroleum hydrocarbons in tissues of the clams also are given.

Station/Collection	Petroleum (ppm)	(mg/g wet wt. ± SE)			
		Glucose	Glycogen	Other Carbohydrates	Total Lipids
7 (Reference)					
Pre-Spill	0.34	0.642 ± 0.037	11.68 ± 0.77	3.11 ± 1.20	158.08 ± 17.76
1st Post-Spill	114	1.272 ± 0.127	13.85 ± 0.96	0.26 ± 0.19	141.07 ± 15.29
2nd Post-Spill	47	1.608 ± 0.125	16.84 ± 1.30	0.74 ± 0.41	163.14 ± 22.02
9 (Dispersed Oil)					
Pre-Spill	0.38	0.742 ± 0.044^{C}	10.32 ± 0.64^{B}	1.12 ± 0.58^{C}	148.39 ± 17.18
1st Post-Spill	168	0.722 ± 0.032^{ABC}	11.31 ± 1.02^{C}	2.11 ± 0.60	183.52 ± 10.21^{BC}
2nd Post-Spill	124	1.517 ± 0.098	12.88 ± 1.40^{A}	1.66 ± 0.52	166.01 ± 13.16
10 (Dispersed Oil)					
Pre-Spill	0.68	0.744 ± 0.058^{C}	14.58 ± 1.02	0.13 ± 0.07^{C}	170.31 ± 11.98
1st Post-Spill	322	0.428 ± 0.048^{A}	17.39 ± 1.75	0.63 ± 0.25	133.40 ± 8.59
2nd 14 d Post-Spill	144	1.515 ± 0.140	14.50 ± 1.01	0.95 ± 0.29	215.50 ± 12.87
11 (Oil Alone)					
Pre-Spill	0.43	1.482 ± 0.155^{A}	12.29 ± 0.99	1.67 ± 0.53	169.65 ± 12.47
1st Post-Spill	2.0	0.514 ± 0.075^{A}	15.03 ± 0.60	0.27 ± 0.26	118.52 ± 12.10
2nd Post-Spill	93	1.459 ± 0.071	13.86 ± 1.02	1.34 ± 0.39	166.34 ± 18.42

A, Significantly different from Reference (Sta. 7), Student's T-test, or Kruskal-Wallis one-way ANOVA
B, Significantly different from Disp. Oil (Sta. 10), Student's T-test, or Kruskal-Wallis one-way ANOVA
C, Significantly different from Oil Alone (Sta. 11), Student's T-test, or Kruskal-Wallis one-way ANOVA

clams from Bay 9 in the second post-spill sample was the only value which was significantly different from the corresponding value in clams from the reference bay. Concentrations of total other carbohydrates, which consist of trehalose and other non-glycogen oligosaccharides and polysaccharides which yield glucose upon hydrolysis, were highly variable and no obvious trends among samples from different bays or sampling times were apparent.

Concentrations of total lipids in clams from Bays 7, 10 and 11 dropped between the pre-spill and first post-spill samples and then returned to pre-spill or higher values by the time of the second post-spill sampling. In clams from Bay 9, total lipid concentration increased between pre-spill and first post-spill and then dropped to the pre-spill range by the time of the second post-spill sampling.

The degree of contamination of Mya truncata with petroleum hydrocarbons varied greatly within each bay depending on the station at which clams were collected (see Section 2.). Data were available by station for petroleum hydrocarbon burden and tissue glucose and glycogen concentration in Mya truncata from the second post-spill collection (Table 4.2). Mean body burdens of petroleum hydrocarbons in clams from 30 stations in 4 bays ranged from 35 to 238 μg/g (ppm). However, there was no relationship between body burden of petroleum hydrocarbons and concentrations of glucose and glycogen in the tissues of clams. In Bays 9 and 10, clams were collected at both the 3-meter and 7-meter isobaths. There were no statistically significant differences between clams from the two depths in concentration in the tissues of petroleum, glucose, or glycogen.

Fourteen different free amino acids were identified and quantified in the adductor muscles of Mya truncata from the four bays. The mean concentration of total free amino acids ranged from 12.45 to 23.25 μM/mg wet weight in clams from different bays at different sampling times (Tables 4.3, 4.4, and 4.5). In clams from the two bays receiving dispersed oil (Bays 9 and 10), the mean concentration of tissue total free amino acids dropped between the pre-spill and first post-spill samples and then rose again in the second post-spill samples. The opposite trend was observed in clams from the bay receiving oil alone (Bay 11), while tissue total free amino acid concentrations in clams from the reference bay (Bay 7) remained relatively constant (range 15.37-17.65 μM/mg).

Table 4.2. Concentrations of petroleum hydrocarbons, glucose and glycogen in tissues of truncate soft-shell clams Mya truncata collected at Stations 1-5 along the 7-meter isobath in four bays and stations 6-10 along the 3-meter isobath in two bays. Samples were taken during the second postspill sampling period. Oil concentrations are in µg/g (ppm) and glucose and glycogen values are in mg/g wet weight, with a sample size of four.

		Station									
		1	2	3	4	5	6	7	8	9	10
Bay 7	Oil	79	35	37	49	44	-	-	-	-	-
	Glucose	1.25	1.46	1.90	2.17	1.17	-	-	-	-	-
	Glycogen	16.82	18.65	20.08	17.03	11.58					
Bay 9	Oil	115	104	116	90	152	128	153	147	119	129
	Glucose	2.08	1.15	1.11	1.62	1.86	1.32	1.50	1.19	2.04	1.29
	Glycogen	15.83	12.11	11.84	14.21	7.46	20.69	9.21	11.78	9.76	15.96
Bay 10	Oil	173	238	167	125	111	104	193	131	139	107
	Glucose	2.31	1.22	1.37	1.58	1.27	0.96	0.98	1.40	2.58	1.47
	Glycogen	17.79	16.13	13.70	16.18	21.09	12.32	10.13	5.62	14.56	17.25
Bay 11	Oil	130	87	81	81	96	-	-	-	-	-
	Glucose	1.46	1.15	1.63	1.28	1.78	-	-	-	-	-
	Glycogen	13.84	12.30	15.57	12.12	15.47	-	-	-	-	-

Table 4.3. Mean concentrations of free amino acids in adductor muscles of truncate soft-shell clams Mya truncata collected from the four BIOS experimental bays before the simulated oil spills. Values are in µM/mg dry wt. and are the mean and standard error from 9 to 13 replicate animals. The number of clams analyzed is given in parentheses.

Amino Acid	Bay 9	Bay 10	Bay 11	Bay 7
Taurine	1.114 ± 0.175(9)[A]	1.020 ± 0.085(13)	0.726 ± 0.069(10)	1.020 ± 0.173(10)
Aspartate	1.023 ± 0.152[ABC]	0.438 ± 0.070	0.480 ± 0.080	0.480 ± 0.080
Threonine	0.208 ± 0.025[ABC]	0.112 ± 0.009	0.127 ± 0.019	0.123 ± 0.011
Serine	0.369 ± 0.040	0.277 ± 0.025[A]	0.216 ± 0.028[A]	0.402 ± 0.061
Glutamate	-	0.392 ± 0.031[A]	0.425 ± 0.084	0.517 ± 0.053
Glycine	10.259 ± 1.250[ABC]	7.551 ± 0.558	7.098 ± 0.943	7.252 ± 0.634
Alanine	2.675 ± 0.535	2.117 ± 0.223	1.728 ± 0.313[A]	2.811 ± 0.374
Valine	-	-	-	-
Methionine	-	-	-	-
Isoleucine	-	-	-	-
Phenylalanine	0.172 ± 0.056	0.145 ± 0.020	0.120 ± 0.021	0.125 ± 0.012
Histidine	0.917 ± 0.145[ABC]	0.457 ± 0.059	0.446 ± 0.061	0.415 ± 0.089
Lysine	0.194 ± 0.037[AB]	0.112 ± 0.012	0.140 ± 0.022	0.125 ± 0.015
Arginine	-	-	-	-
NH_3	1.963 ± 0.874	1.825 ± 0.173	2.006 ± 0.236	2.102 ± 0.177
Mean Total Free Amino Acids	**18.894**	**14.446**	**13.510**	**15.372**

A. Significantly different from Control (Bay 7) by Student's T-test or Mann-Whitney one-tailed U-test at $\alpha \leq 0.05$.

B. Significantly different from Bay 10 by Student's t-test or Mann-Whitney one-tailed u-test at $\alpha \leq 0.05$.

C. Significantly different from Bay 11 by Student's T-test or Mann-Whitney one-tailed U-test at $\alpha \leq 0.05$.

Table 4.4. Mean concentrations of free amino acids in adductor muscles of truncate soft-shell clams Mya truncata collected from the four BIOS experimental bays one to three days after the simulated oil spills. Values are in μM/mg dry wt. and are the mean and standard error from 7 to 20 replicate animals. The number of clams analyzed is given in parentheses.

Amino Acid	Bay 9	Bay 10	Bay 11	Bay 7
Taurine	0.999 ± 0.110(20)	0.908 ± 0.050(18)	2.007 ± 0.001(10)	1.173 ± 0.095(7)
Aspartate	0.368 ± 0.051ABC	0.112 ± 0.025AC	0.716 ± 0.061A	0.595 ± 0.051
Threonine	0.119 ± 0.012	0.151 ± 0.012	0.124 ± 0.011	0.156 ± 0.030
Serine	0.253 ± 0.031	0.208 ± 0.015C	0.281 ± 0.021	0.267 ± 0.040
Glutamate	0.382 ± 0.038	0.315 ± 0.020	0.438 ± 0.020	0.443 ± 0.090
Glycine	7.311 ± 2.911	6.539 ± 0.305	7.640 ± 0.562	8.647 ± 0.848
Alanine	2.399 ± 0.317	1.768 ± 0.180	2.145 ± 0.288	2.643 ± 0.512
Valine	-	-	-	-
Methionine	-	-	-	-
Isoleucine	-	-	-	-
Phenylalanine	0.125 ± 0.032B	0.044 ± 0.006AC	0.129 ± 0.013	0.103 ± 0.009
Histidine	0.342 ± 0.071	0.311 ± 0.019	0.470 ± 0.037	0.391 ± 0.051
Lysine	0.104 ± 0.011AC	0.118 ± 0.006C	0.163 ± 0.013	0.176 ± 0.025
Arginine	-	-	-	-
NH_3	2.340 ± 0.206B	1.979 ± 0.071A	2.002 ± 0.196	2.549 ± 0.249
Mean Total Free Amino Acids	**14.742**	**12.453**	**16.115**	**17.651**

A. Significantly different from Control (Bay 7) by Student's T-test or Mann-Whitney one-tailed U-test at $\alpha \leq 0.05$.

B. Significantly different from Bay 10 by Student's T-test or Mann-Whitney one-tailed U-test at $\alpha \leq 0.05$.

C. Significantly different from Bay 11 by Student's T-test or Mann-Whitney one-tailed U-test at $\alpha \leq 0.05$.

Table 4.5. **Mean concentrations of free amino acids in adductor muscles of truncate soft-shell clams Mya truncata collected from the four BIOS experimental bays 14 days after the simulated oil spills. Values are in μM/mg dry wt. and are the mean and standard error from 10 to 20 replicate animals. The number of clams analyzed is given in parentheses.**

Amino Acid	Bay 9	Bay 10	Bay 11	Bay 7
Taurine	1.021 ± 0.011(20)^{B}	3.924 ± 0.550(16)^{AC}	0.771 ± 0.053(10)	0.944 ± 0.049(10)
Aspartate	0.091 ± 0.012^{C}	0.106 ± 0.029^{C}	0.171 ± 0.013^{A}	0.101 ± 0.010
Threonine	0.249 ± 0.035^{B}	0.060 ± 0.018^{AC}	0.157 ± 0.018	0.266 ± 0.109
Serine	0.284 ± 0.034^{B}	0.115 ± 0.026	0.212 ± 0.109	0.213 ± 0.011
Glutamate	0.454 ± 0.052^{B}	0.293 ± 0.028^{AC}	0.403 ± 0.032	0.425 ± 0.028
Glycine	9.132 ± 1.070^{B}	12.912 ± 1.910^{AC}	6.946 ± 0.450	8.769 ± 0.350
Alanine	2.130 ± 0.254^{ABC}	0.886 ± 0.120^{AC}	1.538 ± 0.177^{A}	2.866 ± 0.263
Valine	0.121 ± 0.010	0.068 ± 0.024^{AC}	0.125 ± 0.018	0.097 ± 0.008
Methionine	0.048 ± 0.005^{B}	0.761 ± 0.014^{AC}	0.045 ± 0.010	0.033 ± 0.004
Isoleucine	0.065 ± 0.013	0.052 ± 0.019	0.086 ± 0.015	0.010 ± 0.006
Phenylalanine	0.072 ± 0.020	0.053 ± 0.011	0.064 ± 0.017	0.070 ± 0.019
Histidine	0.365 ± 0.024^{BC}	0.163 ± 0.016^{AC}	0.282 ± 0.015^{A}	0.401 ± 0.015
Lysine	0.182 ± 0.022^{B}	0.087 ± 0.026^{AC}	0.157 ± 0.022	0.140 ± 0.010
Arginine	0.396 ± 0.049^{B}	2.616 ± 0.540^{AC}	0.310 ± 0.026	0.382 ± 0.023
NH_3	1.707 ± 0.169^{B}	1.154 ± 0.099^{C}	1.738 ± 0.141^{A}	1.374 ± 0.091
Mean Total Free Amino Acids	**16.317**	**23.250**	**13.005**	**16.141**

A. Significantly different from Control (Bay 7) by Student's T-test or Mann-Whitney one-tailed U-test at $\alpha \leq 0.05$.

B. Significantly different from Bay 10 by Student's T-test or Mann-Whitney one-tailed U-test at $\alpha \leq 0.05$.

C. Significantly different from Bay 11 by Student's T-test or Mann-Whitney one-tailed U-test at $\alpha \leq 0.05$.

In clams collected immediately before the BIOS oil spills, concentrations of several tissue free amino acids were significantly different in clams from the four bays (Table 4.3). The mean concentration of 6 free amino acids was significantly different in clams from the reference bay (Bay 7) and Bay 9, while concentrations of only two amino acids in clams from Bays 10 and 11 were significantly different from those of clams from the reference bay. Immediately after the spills, concentrations of 1-3 amino acids were significantly different in clams from the reference bay and from the three bays receiving dispersed or undispersed crude oil (Table 4.4). Concentrations of total and most individual tissue free amino acids were lower in clams from the most heavily contaminated bay (Bay 10) than in clams from the other two bays receiving oil and the reference bay. In clams collected during the second post-spill sampling approximately 2 weeks after the spills, there were many statistically significant differences in concentrations of individual tissue free amino acids among clams from the four bays (Table 4.5). Values for clams from Bay 10 (the most heavily contaminated bay) varied most from the corresponding values for clams from the other three bays.

Two parameters which have been recommended as indices of sublethal stress in marine invertebrates are the molar ratio of taurine to glycine and the sum of the concentrations of threonine plus serine. Stressed animals should have a higher taurine/glycine ratio and lower threonine plus serine concentration than unstressed animals. The only oil-exposed group of clams with taurine/glycine ratio and threonine plus serine concentration significantly different from that of clams from the reference bay was that from the most heavily contaminated bay (Bay 10) collected during the second post-spill sampling (Table 4.6). Taurine/glycine ratio was elevated and threonine plus serine concentration was depressed relative to reference animals.

Spearman rank correlation tests were performed on all biochemical parameters measured for clams from the three sampling times and four experimental bays. Parameters which showed a high ($\alpha<0.05$) degree of interassociation, positive or negative, are tabulated according to sampling time and inter-bay association in Table 4.7. Clams from the second post-spill sampling had the largest number of associated pairs of biochemical parameters (Table 4.8). One-hundred and five associated pairs were shared by all four bays, indicating that in these samples, clams from the four bays were very uniform in relative (though not necessarily absolute) values for the biochemical

Table 4.6. Molar ratio of taurine to glycine and the sum of the concentrations of threonine plus serine in the free amino acid pool of adductor muscles of truncate soft-shell clams Mya truncata from the four BIOS experimental bays. Concentrations of threonine plus serine are in μM/mg dry weight and are the mean and standard error of 7 to 20 replicate animals per treatment. The number of clams analyzed is given in parentheses.

Parameter	Pre-Spill	1st Post-Spill	2nd Post-Spill	Pre-Spill	1st Post-Spill	2nd Post-Spill
	Bay 9			Bay 10		
Taurine/Glycine	0.108 ± 0.007^{AB} (9)	0.134 ± 0.006^{C} (19)	0.109 ± 0.006^{B} (20)	0.137 ± 0.007 (13)	0.141 ± 0.007^{C} (18)	0.297 ± 0.036^{AC} (16)
Threonine + Serine	0.577 ± 0.065^{BC} (9)	0.365 ± 0.040 (20)	0.533 ± 0.067^{B} (20)	0.389 ± 0.033^{A} (13)	0.359 ± 0.024 (18)	0.191 ± 0.047^{AC} (13)
	Bay 11			Bay 7		
Taurine/Glycine	0.109 ± 0.007^{AB} (10)	0.263 ± 0.109 (10)	0.112 ± 0.006 (10)	0.141 ± 0.012 (10)	0.141 ± 0.012 (7)	0.109 ± 0.006 (10)
Threonine + Serine	0.343 ± 0.045^{A} (10)	0.424 ± 0.035 (10)	0.384 ± 0.038 (10)	0.525 ± 0.070 (10)	0.367 ± 0.056 (7)	0.479 ± 0.104 (10)

A. Significantly different from Control (Bay 7) by Student's T-test or Mann-Whitney one-tailed U-test at $\alpha \leq 0.05$.

B. Significantly different from Bay 10 by Student's T-test or Mann-Whitney one-tailed U-test at $\alpha \leq 0.05$.

C. Significantly different from Bay 11 by Student's T-test or Mann-Whitney one-tailed U-test at $\alpha \leq 0.05$.

Table 4.7. A summary of associated pairs of biochemical parameters in Mya truncata determined by the Spearman Rank Correlation Test. Data are tabulated by pairs shared among bays and by sampling times.

	Taurine	Aspartate	Threonine	Serine	Glutamate	Glycine	Alanine	Valine	Methionine	Isoleucine	Phenylalonine	Histidine
Taurine												
Aspartate	3A											
Threonine	2B,3A	3A										
Serine	1E,3A	3A	1B,3A									
Glutamate	3A	3A	3A	3A								
Glycine	1E,3A	1A,3A	1A,3A	1A,3A								
Alanine	1E,3A	3A	1A,3A	1A,2B,3A	1C,3A	1E,3A						
Valine	3A	3A	3A	3A	3A	3A	3A					
Methionine	3A	3A	3A	3A	3A	3A	3A	3A				
Isoleucine	3A	3A	3A	3A	3A	3A	3A	3A				
Phenylalanine	3A	3A	3A	1C,3A	3A	3A	3A	3A	3A	3A		
Histidine	3A	3A	3A	3A	3A	3A	3A	3A	3A	3A	3A	
Lysine	3A	3A	1E,3A	2B,3A	3A	3A	1E,3A	3A	3A	3A	3A	1B,3A
Arginine	3A	3A		3A	3A	3A	3A	3A	3A	3A	3A	3A
NH_3	3A	3A		1A,3A	1C,3A	1E,3A	3A	3A	3A	3A	3A	3A
Total AA			1C	1A			1C				1C	1B
Taurine/Glycine												
Threonine + Serine	1E		1A,2B	1A			1E					1B
Glycogen												
Glucose												
Other Carbons												
Lipids												

	Lysine	Arginine	NH_3	Total AA	Taurine/Glycine	Threonine + Serine	Glycogen	Glucose	Other Carbons	Lipids
Taurine										
Aspartate										
Threonine										
Serine										
Glutamate										
Glycine										
Alanine										
Valine										
Methionine										
Isoleucine										
Phenylalanine										
Histidine										
Lysine										
Arginine	3A									
NH_3	3A	3A								
Total AA	1E									
Taurine/Glycine										
Threonine + Serine	1B			1C						
Glycogen										
Glucose										
Other Carbons										
Lipids							3D			

Sampling Periods: 1, pre-spill; 2, first post-spill; 3, second post-spill.
Bay Associations: A, Bays, 7,9,10,11; B, Bays 7,9,10; C, Bays 7,9,11; D, Bays 7,10,11; E, Bays 9,10,11

Table 4.8. The number of associated pairs of biochemical parameters in the truncate clam Mya truncata collected from the BIOS experimental bays at three sampling times. Bay combinations denote paired associations which are shared.

Bay Combinations	Pre-Spill	First Post-Spill	Second Post-Spill
7,9,10,11	9		105
7,9,10	5	5	
7,9,11	7		
7,10,11			1
9,10,11	10		
7,9	9	9	
7,10		3	
7,11			
9,10	16	6	
9,11	11		
10,11	1		
7	1	5	
9	26	36	
10	1	4	
11	1		
Total Associated Pairs	**97**	**68**	**106**

parameters measured. Clams from the first post-spill sampling had the lowest number of associated pairs and the greatest inter-bay diversity. Clams from the pre-spill sample were intermediate. At all three sampling times, there was little association among values for carbohydrate, lipid and free amino acid parameters. In clams from the first post-spill sampling, there were no associated pairs shared by Bay 11 (receiving oil alone) and the other three bays.

4.3 Discussion

There was a high degree of variability in the values for different biochemical parameters in replicate clams from the same sample, among samples from different bays, and in samples collected at different times. This variability makes it difficult to identify biochemical responses of clams to the oil spills. There are several possible explanations for the observed variability.

Bivalve molluscs, like many other marine invertebrates, typically show a wider range of normal (unstressed) values for many biochemical parameters than do fish and other "higher" animals (Newell, 1976; Gabbott, 1976; Carr and Neff, 1981, 1982). In species such as the mussel Mytilus edulis for which an extensive body of basic biochemical and physiological information is available (Bayne, 1976), some of this variability can be accounted for or controlled. There are practically no data available on the normal biochemistry, physiology, and seasonal cycles of Mya truncata.

Perhaps more important, and a major problem in a remote field experiment of this sort, are the methods used to sample and handle animals in the field. Mya from the second post-spill sampling were much more uniform in all biochemical parameters measured than were clams from the first two collections. It is quite possible that this was due in part to differences in handling of the animals by the field collecting teams. A substantial time delay between collecting the clams and freezing them can result in large and unpredictable changes in several of the biochemical parameters studied, particularly concentrations of tissue glucose and free amino acids. Ideally, samples should be frozen in liquid nitrogen or dry ice immediately upon collection. This was not feasible in the BIOS study. Although samples apparently were frozen within a few hours of collection in most cases, notes in the collecting log book indicate that some samples were held

overnight or even for several days in a refrigerator before freezing. The most variable set of samples was that from the first post-spill collection. Examination of the field log book indicated that these samples were collected over a 10-day period (from Bay 9 on 8/28, 29 and 31/81; from Bay 10 on 8/29-30/81; from Bay 11 on 8/21/81; and from Bay 7 on 8/31/81). The simulated spill of oil alone in Bay 11 was on 8/19/81 and the simulated spill of dispersed oil in Bay 9 was on 8/27/81. Thus, clams from the bay receiving oil alone (Bay 11) were sampled two days after the spill, while those from bays receiving dispersed oil were sampled up to four days after the spill. Thus, it is difficult to compare acute responses of clams to the different treatments. Collection of the pre-spill and second post-spill samples also took place over several days, but the interpretive problem in these cases is less severe. It also should be pointed out that samples for hydrocarbon analysis were not always taken at the same time as samples for biochemical analysis at a given bay and station.

Despite these problems, some conclusions can be drawn from the results of these biochemical studies on Mya truncata. Based on results of the biochemical analyses, truncate soft-shell clams were not severely stressed by either dispersed or undispersed oil at the contaminant levels attained in the BIOS experiment. Although all treatment groups were exposed to and subsequently accumulated some petroleum, and therefore there was no true control or reference group of animals, clams from Bay 7 were the least heavily contaminated. Therefore, they can be used, in lieu of a true reference. Clams from Bay 11 (undispersed crude oil) differed the most from clams from Bay 7, particularly in the second post-spill sample. Clams from Bay 10 (dispersed crude oil) became more heavily contaminated with petroleum hydrocarbons than clams from the other dispersed oil bay (Bay 9) and showed greater differences than the latter in several biochemical parameters, as compared to clams from Bay 7. These differences were most marked in the first post-spill survey. Thus, we can conclude that chemically dispersed oil may cause more severe acute effects than undispersed oil in benthic infaunal molluscs, but longer-term impacts of undispersed crude oil may be more severe than those of chemically dispersed oil. This is undoubtedly related to the observations documented in the Section 2 of this report that petroleum contamination of filter-feeding molluscs was greatest in the bays receiving dispersed oil and reached a peak in the first post-spill samples, decreasing in the second post-spill samples. On the other hand, contamination of clams in the bay receiving oil

alone was more gradual and reached a peak in the second post-spill sample. Undispersed crude oil may be more persistent than chemically dispersed oil in bottom sediments and so lead to more serious long-term effects. We have obtained similar results in recent mesocosm experiments with chemically dispersed oil (Neff, 1982). Benthic animals in tanks receiving chemically dispersed crude oil experienced higher short-term mortality and sublethal effects than animals receiving oil alone. However, after a month, sublethal physiological and biochemical responses were more marked in animals from the undispersed oil treatment groups than the dispersed oil treatment groups.

In this investigation, several biochemical parameters were evaluated as indices of pollutant stress in truncate soft-shell clams exposed to dispersed and non-dispersed crude oil in the BIOS experiment. The parameters used were chosen based on their proven utility for this purpose, and because they could be measured in frozen samples, an important consideration considering the remoteness of the sampling site and lack of facilities to make measurements on-site on fresh tissues. Values for some of the biochemical parameters were significantly different in the four populations of Mya samples. Tissue free amino acid concentrations and ratios showed the most changes. Tissue free amino acids also were the most useful index of pollutant stress in oysters Crassostrea gigas from bays contaminated with crude oil from the Amoco Cadiz crude oil spill (Neff and Haensly, 1982). It is possible that other parameters would have exhibited more significant differences than they did if there had been better control of the sampling and sample handling in the field.

4.3.1. Weight-Length Relationships of Bivalves. Cross and Thompson (1982) and Cross et al. (1983) have performed analyses of dry weight-shell length relationships of four species of bivalve molluscs from the four bays. Samples of up to 50 individuals each of Mya truncata, Macoma calcarea, Astarte borealis and Serripes groenlandicus were collected along the middle transect at the 7-meter depth in each bay on five sampling occasions (pre-spill, September, 1980 and August, 1981; post-spill, September, 1981, August 1982, September, 1982).

The investigators found evidence that weight-length relationships in Serripes groenlandicus and Macoma calcarea were affected by the experimental oil spills. The other species were unaffected. Larger specimens of S. groenlandicus from Bay 7 showed a progressive decrease in dry weight of soft tissues adjusted to a standard shell length from

the second pre-spill sample (immediate pre-spill sample in this investigation) to the third post-spill sample (September, 1982). No progressive changes in adjusted dry weights or weight-length regressions were observed in S. groenlandicus from the other bays. A decrease in weight per unit shell length or adjusted to a standard shell length indicates a decrease in the condition or nutritional status of the mollusc. Although Bay 7 was considered a reference bay, it did receive 50-100 ppb of dispersed oil in the first few days after the discharge (Green et al., 1982). S. groenlandicus from the 7-meter depth in Bay 7 accumulated hydrocarbons to higher levels immediately after the spill than did the same species from the 7-meter depth in the other bays (See Section 2 of this report). S. groenlandicus from Bays 9 and 10, which received much higher levels of dispersed oil, probably were narcotized and/or stopped filtering, and therefore became less contaminated than animals from Bay 7. S. groenlandicus differed from the other filter-feeding mollusc studied, Mya truncata, in that it preferentially retained in its tissues a high molecular weight saturated hydrocarbon assemblage as well as the toxic highly alkylated naphthalenes, phenanthrenes, and dibenzothiophenes. These observations may partially explain the apparent impact of oil on S. groenlandicus from Bay 7.

Whereas S. groenlandicus is a filter-feeder and accumulates petroleum hydrocarbons primarily from the water, Macoma calcarea is a deposit-feeder and accumulates petroleum hydrocarbons primarily from contaminated sediments. Thus, as reported in the bioaccumulation section of this report, M. calcarea from Bay 7 did not accumulate significant body burdens of hydrocarbons because very little of the water-borne hydrocarbons entering the bay were deposited in the sediments. In the other three bays, substantial amounts of oil were deposited in bottom sediments and M. calcarea became the most heavily contaminated. Hydrocarbon body burdens in the deposit-feeders increased between the first and second post-spill samplings. Cross and Thompson (1982) and Cross et al. (1983) reported that M. calcarea from Bay 7 underwent a seasonal cycle of increasing length-adjusted tissue dry weight between August and September in both 1981 and 1982. This probably represented a natural cycle of fattening and gonadal maturation in the animals. However, M. calcarea from the other bays did not show evidence of this cycle, and in clams from Bay 9, there actually was a decrease in length-adjusted tissue dry weight between August, 1981 (pre-spill) and September, 1981 (second post-spill sampling). These results suggest that petroleum contamination of sediments

interfered with feeding, gonadal development, and bioenergetics of M. calcarea. Similar responses have been reported in bivalve molluscs impacted by the Chedabucto Bay, Nova Scotia oil spill (Gilfillan and Vandermeulin, 1978) and the Amoco Cadiz oil spill in Brittany, France (Neff and Haensly, 1982). Interestingly, M. calcarea from Bay 9 did not have an elevated incidence of histopathological lesions compared to clams from other bays. M. calcarea from Bay 11 (receiving undispersed crude oil) did have an increased incidence of parasitism and hemolytic infiltration, and one specimen had a blood neoplasm. One year after the spill, these clams had a high incidence of vacuolization of the digestive tubule epithelium, a pathological condition also reported in bivalve molluscs transplanted to a site heavily contaminated by the Amoco Cadiz oil spill (Wolfe et al., 1981).

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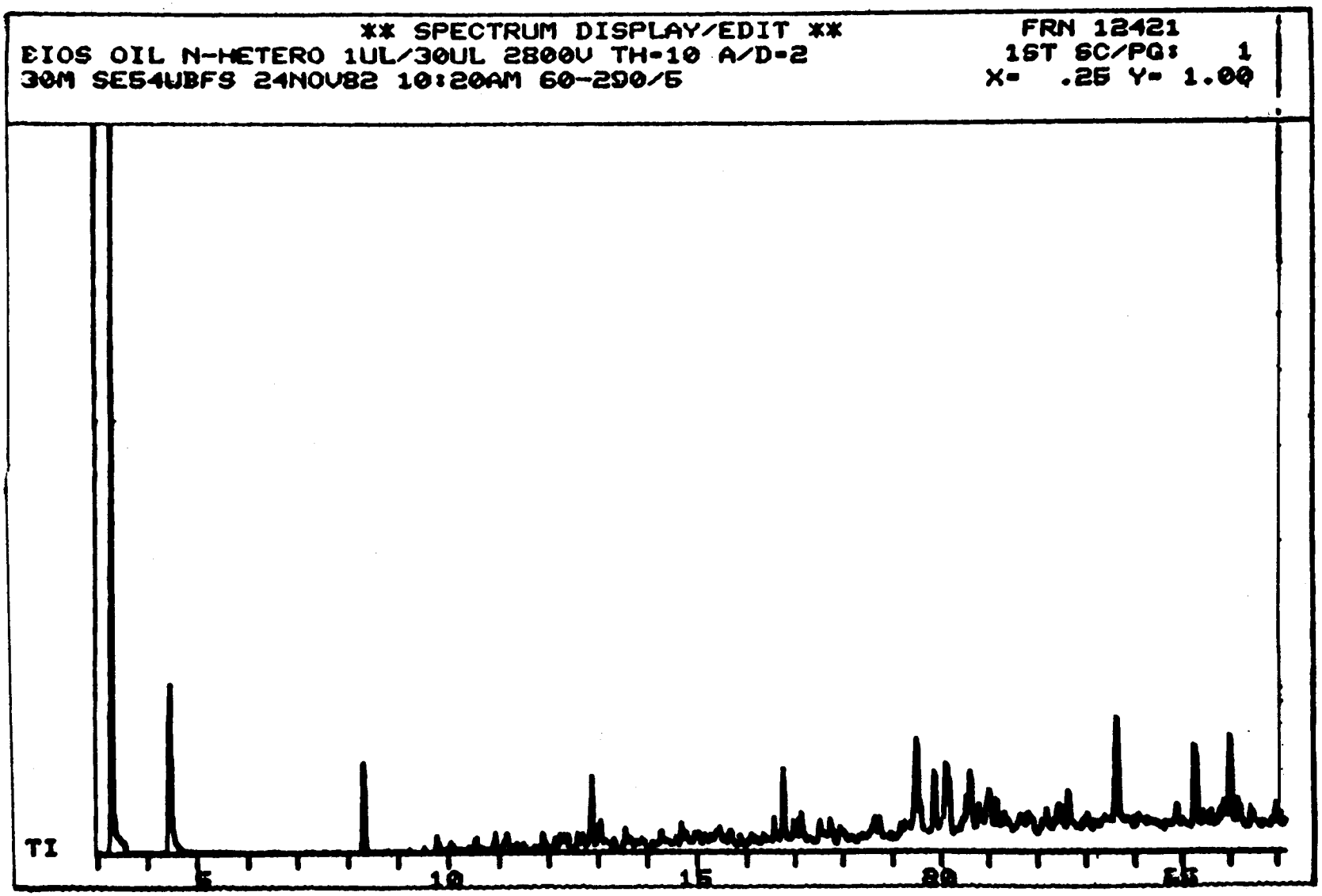
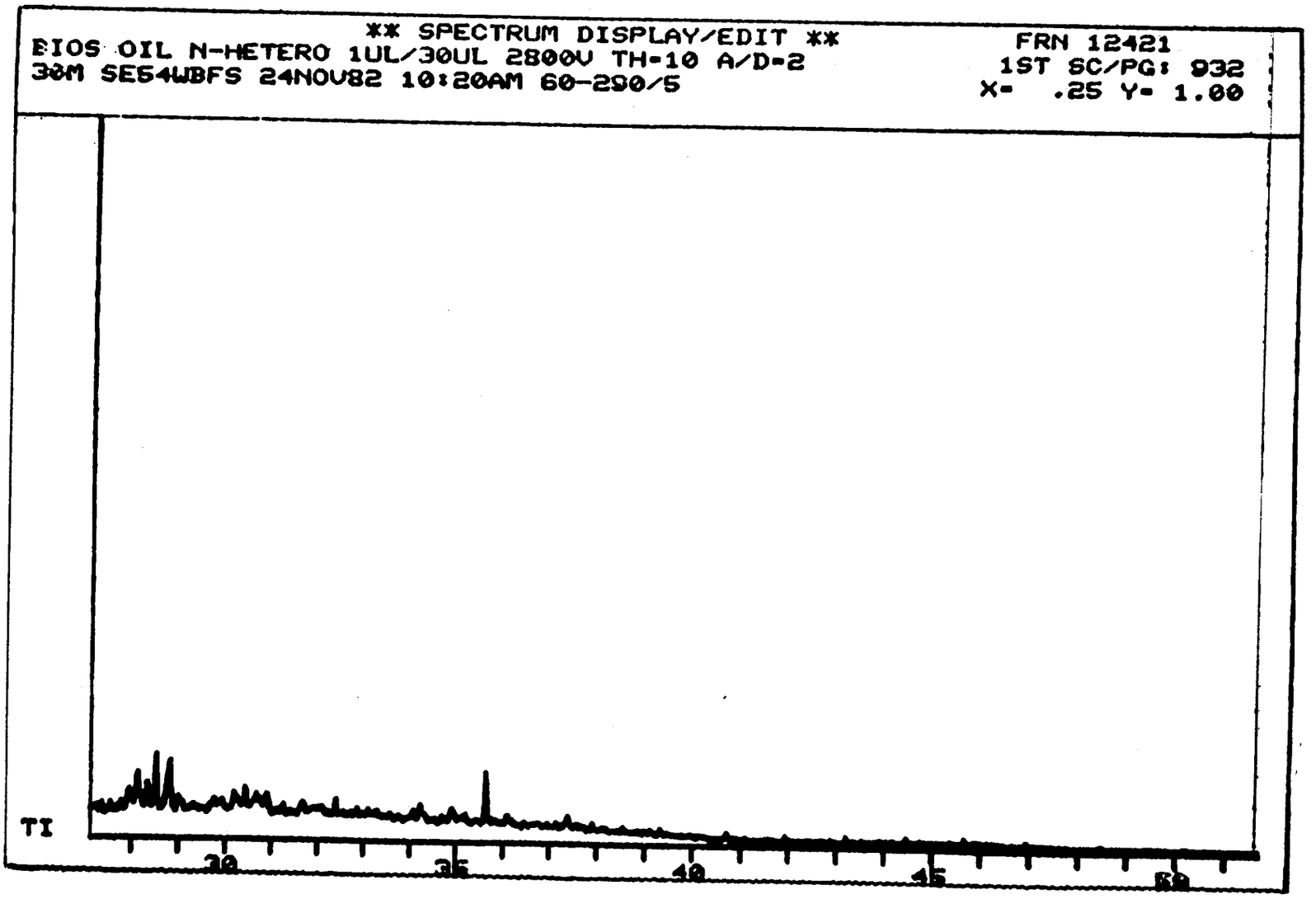
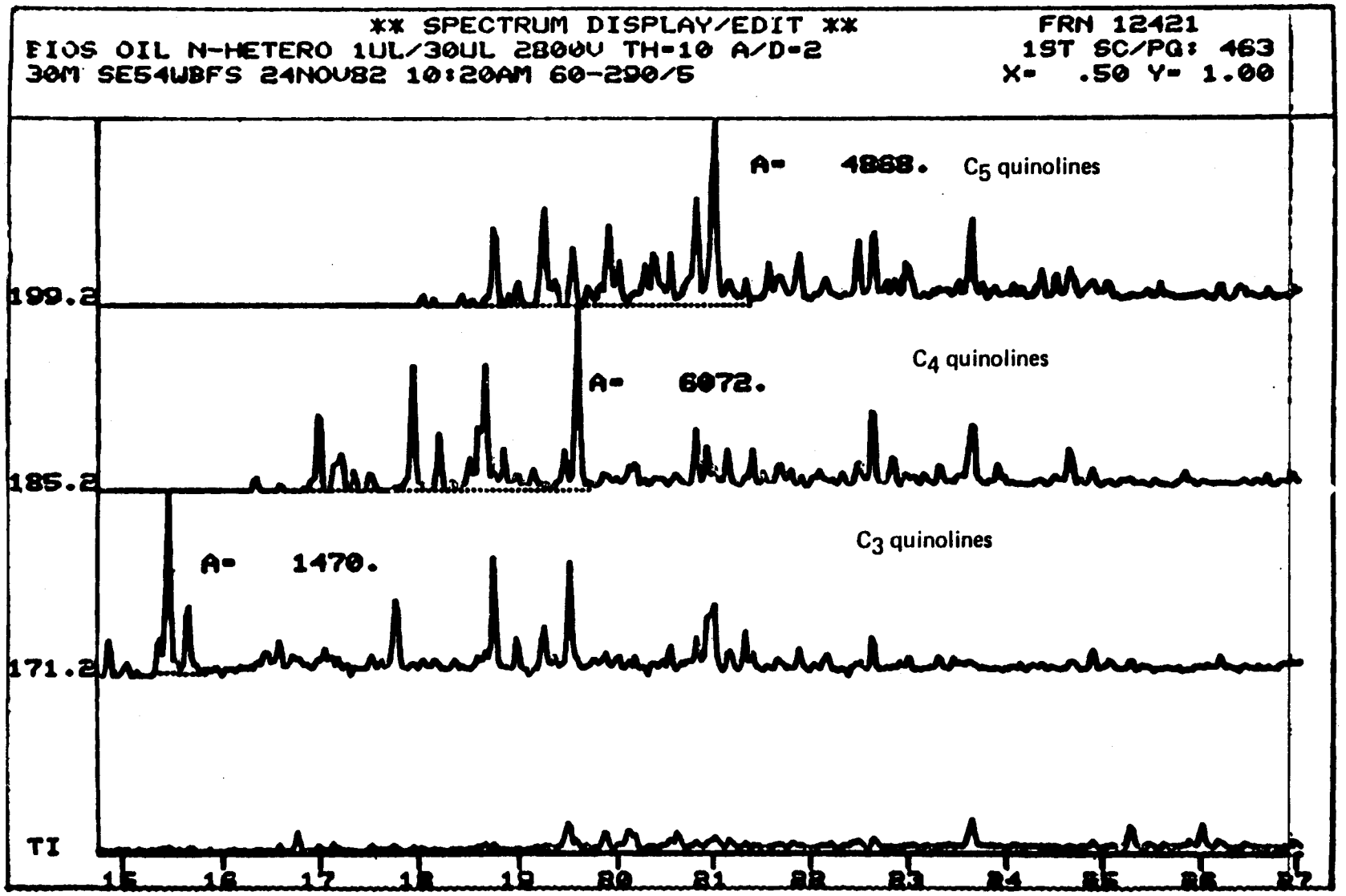
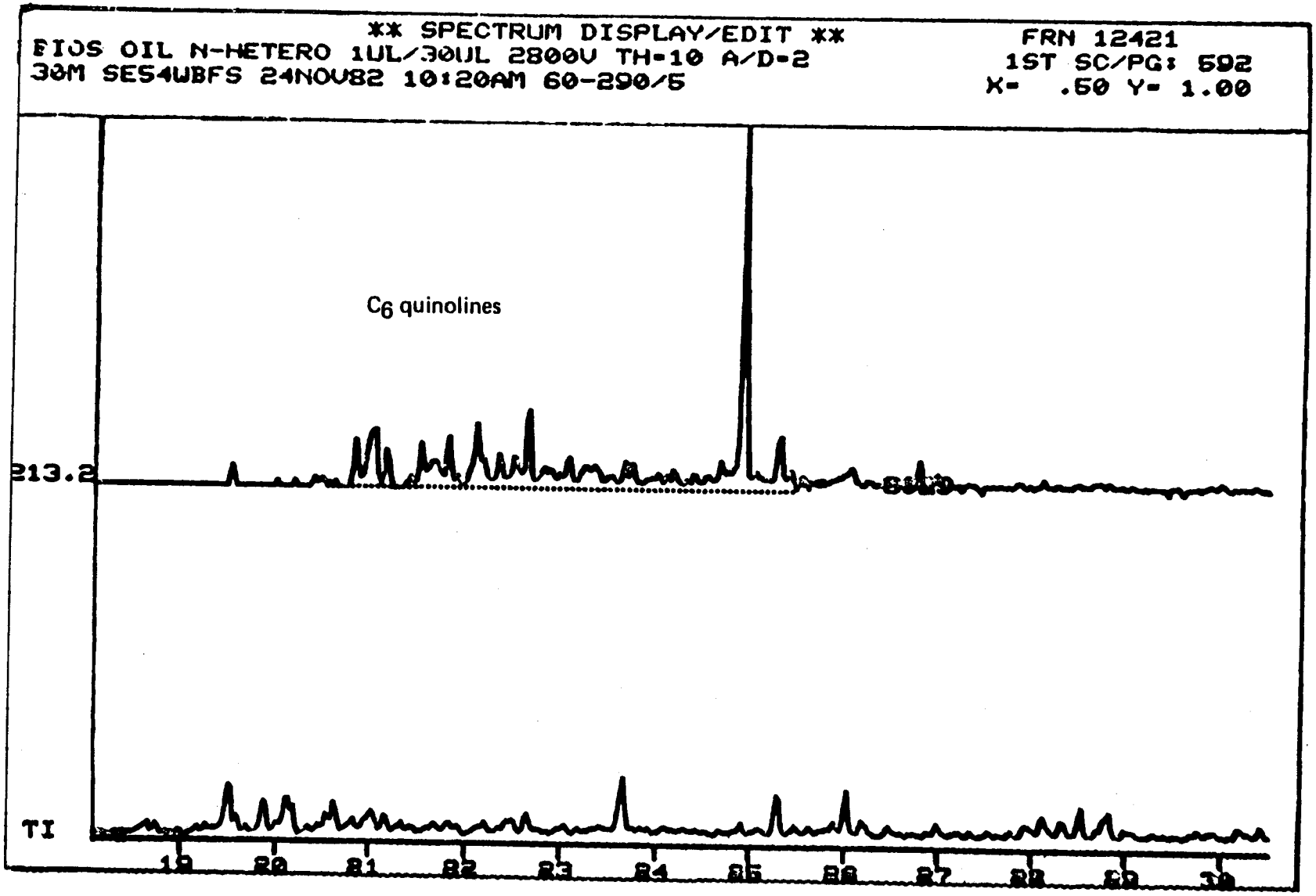
APPENDIX I:

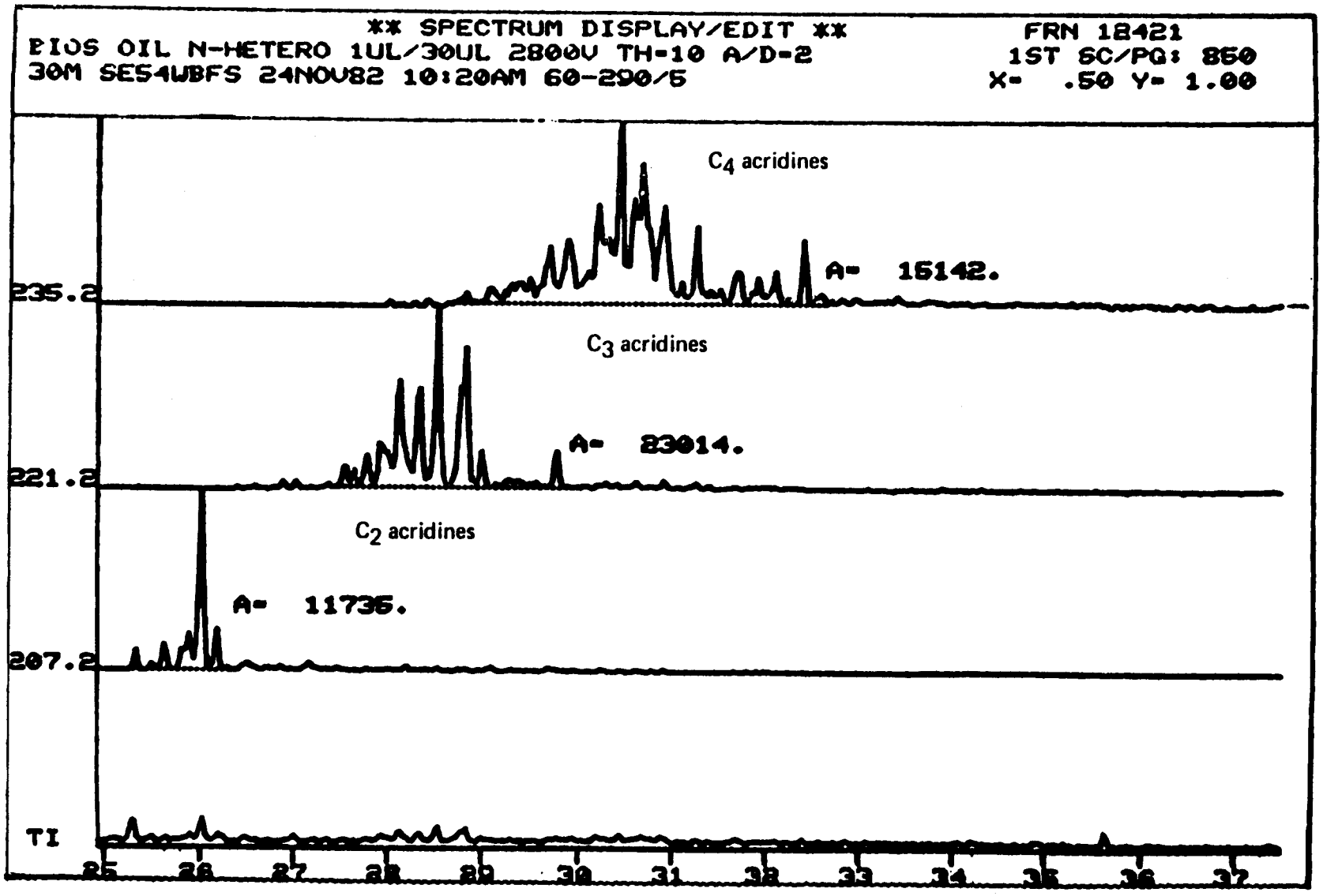
PANH COMPOUNDS IN OIL

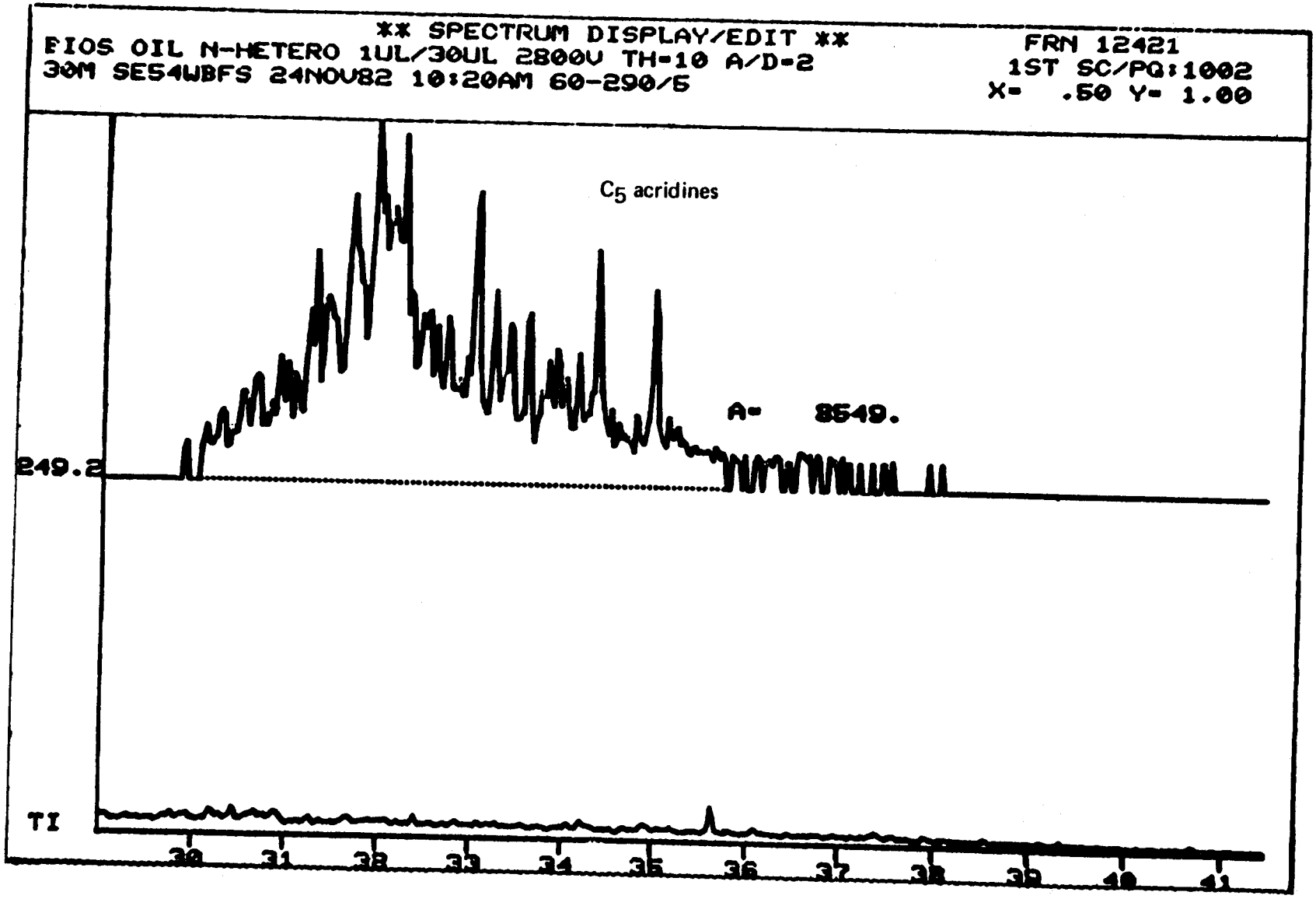

** SPECTRUM DISPLAY/EDIT **
FRN 12421
EIOS OIL N-HETERO 1UL/30UL 2800V TH-10 A/D-2
1ST SC/PQ: 1
30M SE54UBFS 24NOV82 10:20AM 60-290/5
X= .25 Y= 1.00
TI
5
10
15
20
25

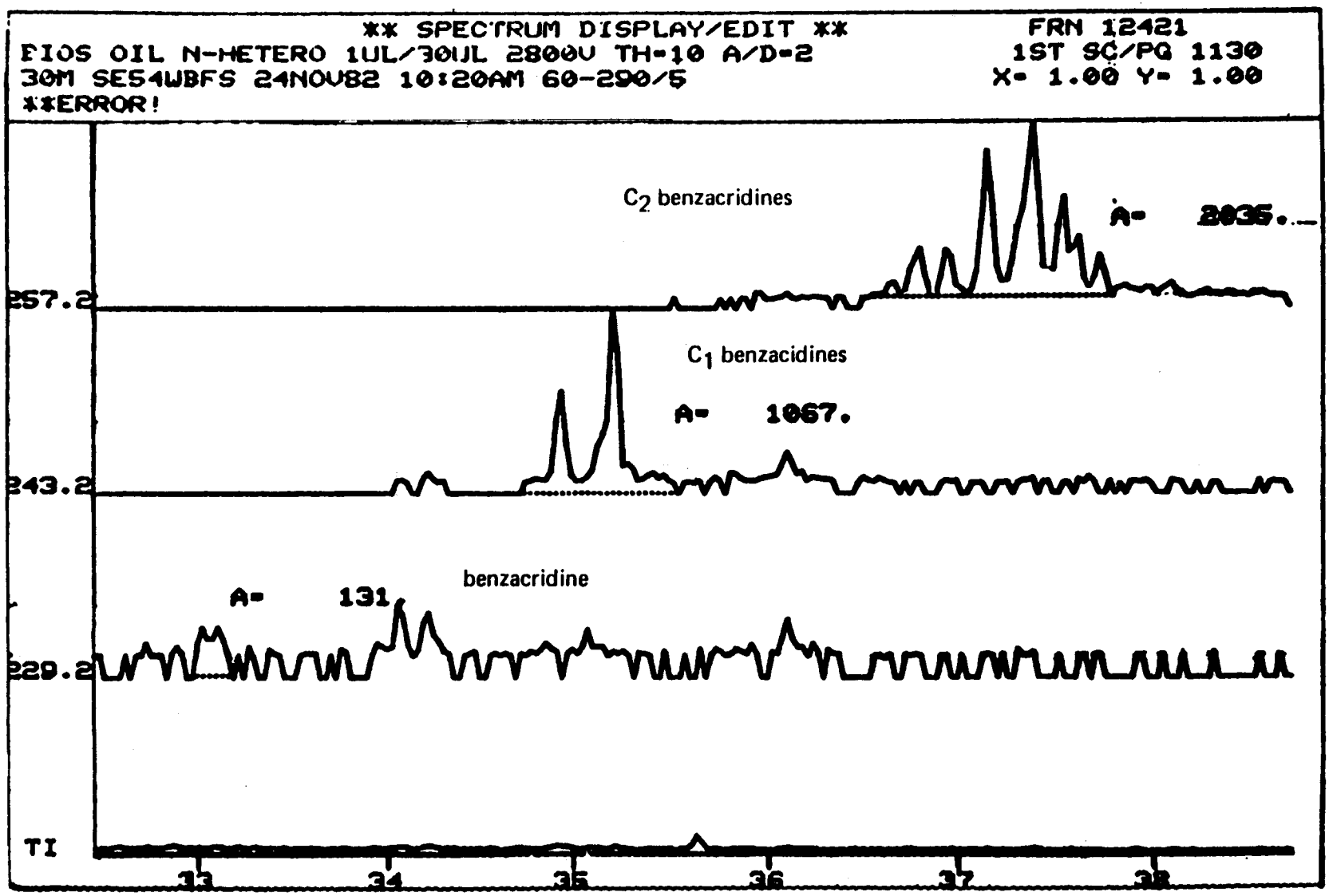

** SPECTRUM DISPLAY/EDIT **
EIOS OIL N-HETERO 1UL/30UL 2800V TH-10 A/D-2
30M SE54WBFS 24NOV82 10:20AM 60-290/5
FRN 12421
1ST SC/PG: 932
X= .25 Y= 1.00
TI
30
35
40
45
50


** SPECTRUM DISPLAY/EDIT **
FRN 12421
FIOS OIL N-HETERO 1UL/30UL 2800V TH=10 A/D=2
1ST SC/PG: 463
30M SE54WBFS 24NOV82 10:20AM 60-290/5
X= .50 Y= 1.00
A= 4888.
C5 quinolines
199.2
C4 quinolines
A= 6072.
185.2
C3 quinolines
A= 1470.
171.2
TI
15
16
17
18
19
20
21
22
23
24
25
26
27


** SPECTRUM DISPLAY/EDIT **
FRN 12421
FIOS OIL N-HETERO 1UL/30UL 2800V TH=10 A/D=2
1ST SC/PG: 592
30M SE54WBFS 24NOV82 10:20AM 60-290/5
X= .50 Y= 1.00
C6 quinolines
213.2
TI
10
20
30


** SPECTRUM DISPLAY/EDIT **
FRN 18421
BIOS OIL N-HETERO 1UL/30UL 2800V TH=10 A/D=2
1ST SC/PG: 850
30M SE54WBFS 24NOV82 10:20AM 60-290/5
X= .50 Y= 1.00
C4 acridines
A= 15142.
235.2
C3 acridines
A= 23014.
221.2
C2 acridines
A= 11735.
207.2
TI
25
26
27
28
29
30
31
32
33
34
35
36
37


** SPECTRUM DISPLAY/EDIT **
FRN 12421
FIOS OIL N-HETERO 1UL/30UL 2800V TH=10 A/D=2
1ST SC/PQ:1002
30M SE54WBFS 24NOV82 10:20AM 60-290/5
X= .50 Y= 1.00
C5 acridines
A= 8549.
249.2
TI
30
31
32
33
34
35
36
37
38
39
40
41


** SPECTRUM DISPLAY/EDIT **
FRN 12421
FIOS OIL N-HETERO 1UL/30UL 2800V TH=10 A/D=2
1ST SC/PQ 1130
30M SES4WBFS 24NOV82 10:20AM 60-290/5
X= 1.00 Y= 1.00
**ERROR!
C2 benzacridines
A= 2035.
257.2
C1 benzacidines
A= 1067.
243.2
benzacridine
A= 131.
229.2
TI
33
34
35
36
37
38

FILE NUMBER 12421

ENTRY	TIME	MASS	AREA	%
1	15.5	171.2	1470.	1.86
2	19.6	185.2	6072.	7.70
3	21.0	199.2	4868.	6.17
4	24.9	213.2	8029.	10.18
5	26.0	207.2	11735.	14.88
6	28.5	221.2	23014.	29.18
7	30.5	235.2	15142.	19.20
8	31.9	249.2	8549.	10.84

CAL % ON ENTRY?

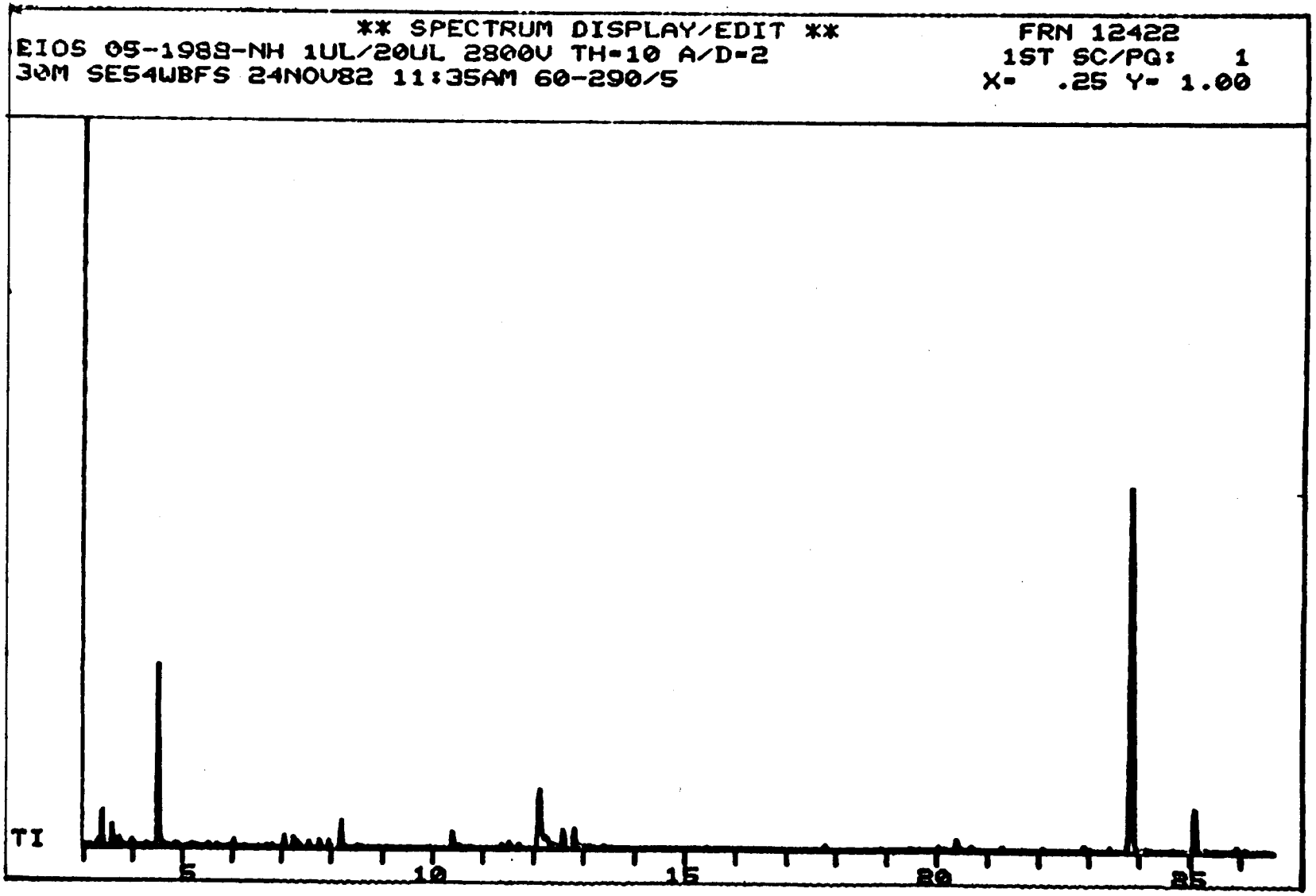
FILE NUMBER 12431

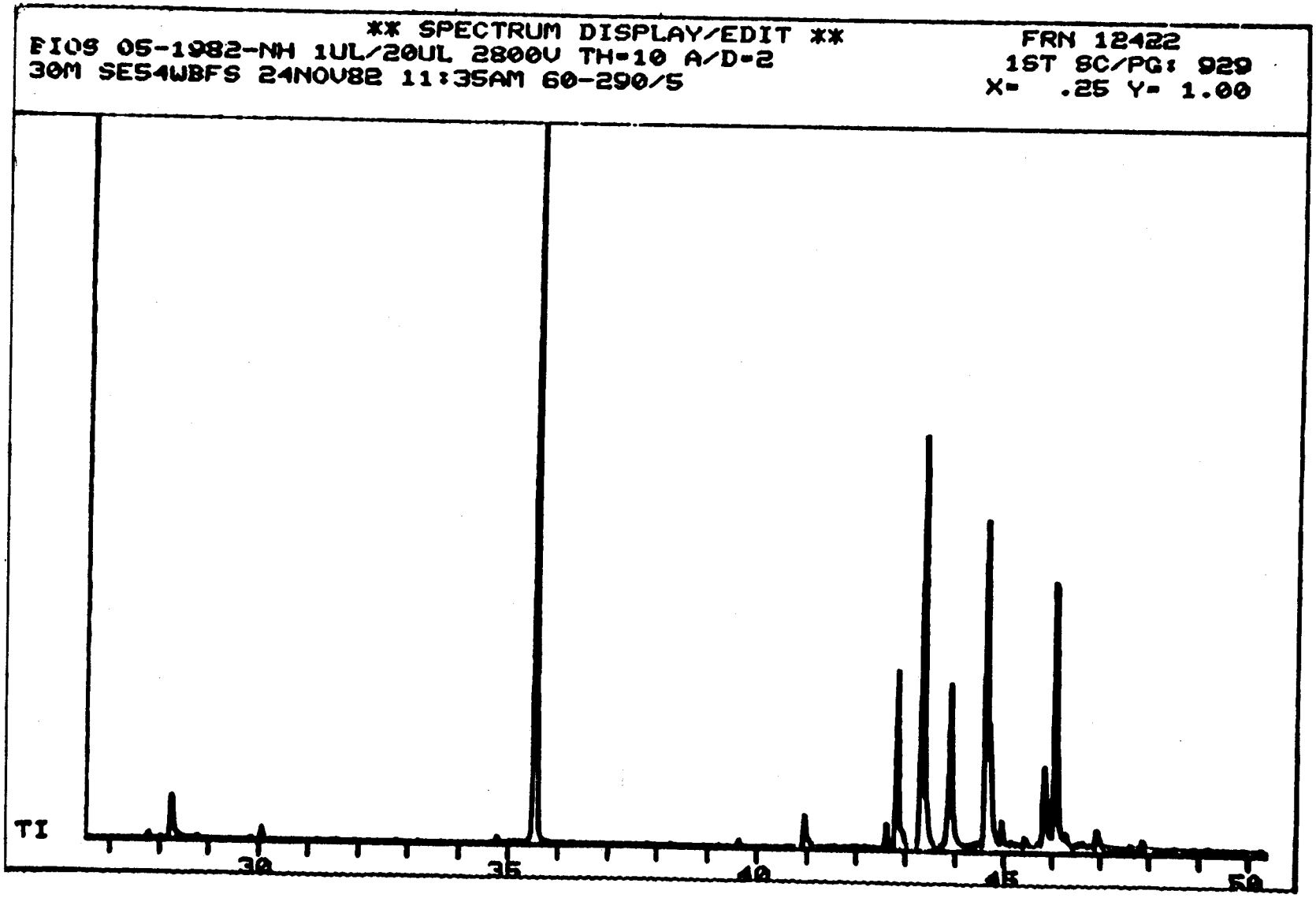
ENTRY	TIME	MASS	AREA	%
1	33.0	229.2	131.	4.04
2	35.2	243.2	1067.	33.01
3	37.4	257.2	2035.	62.95

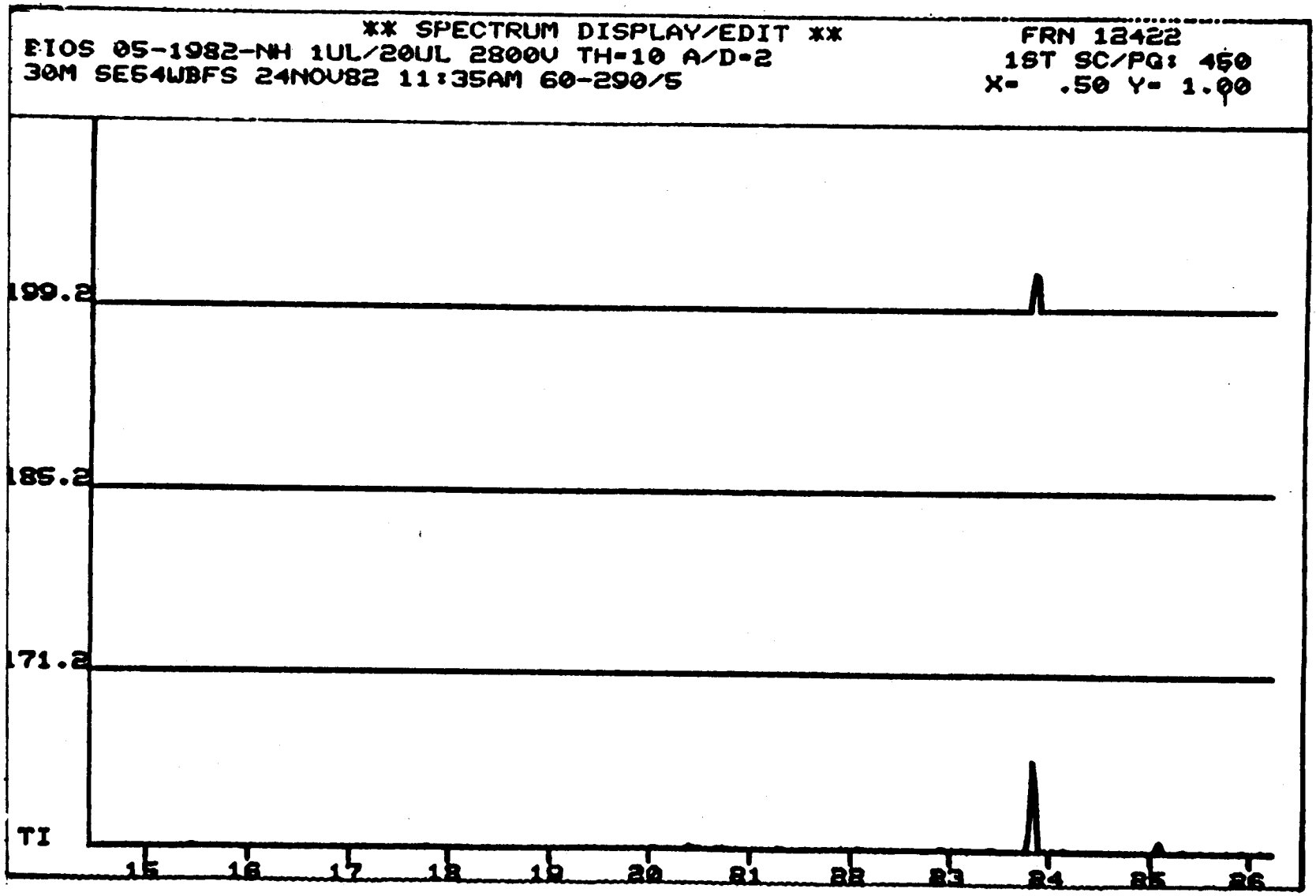
CAL % ON ENTRY?

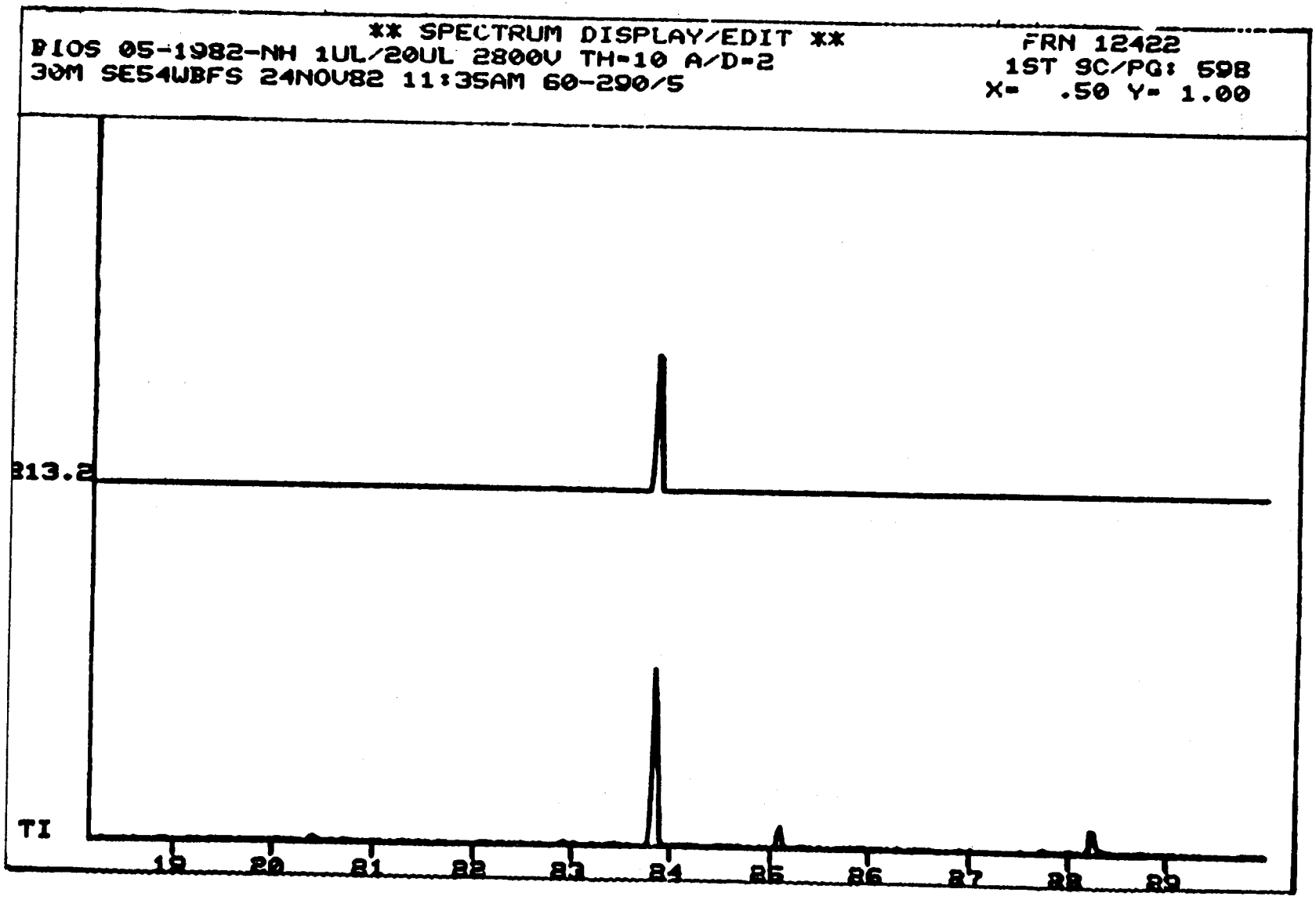
APPENDIX II:

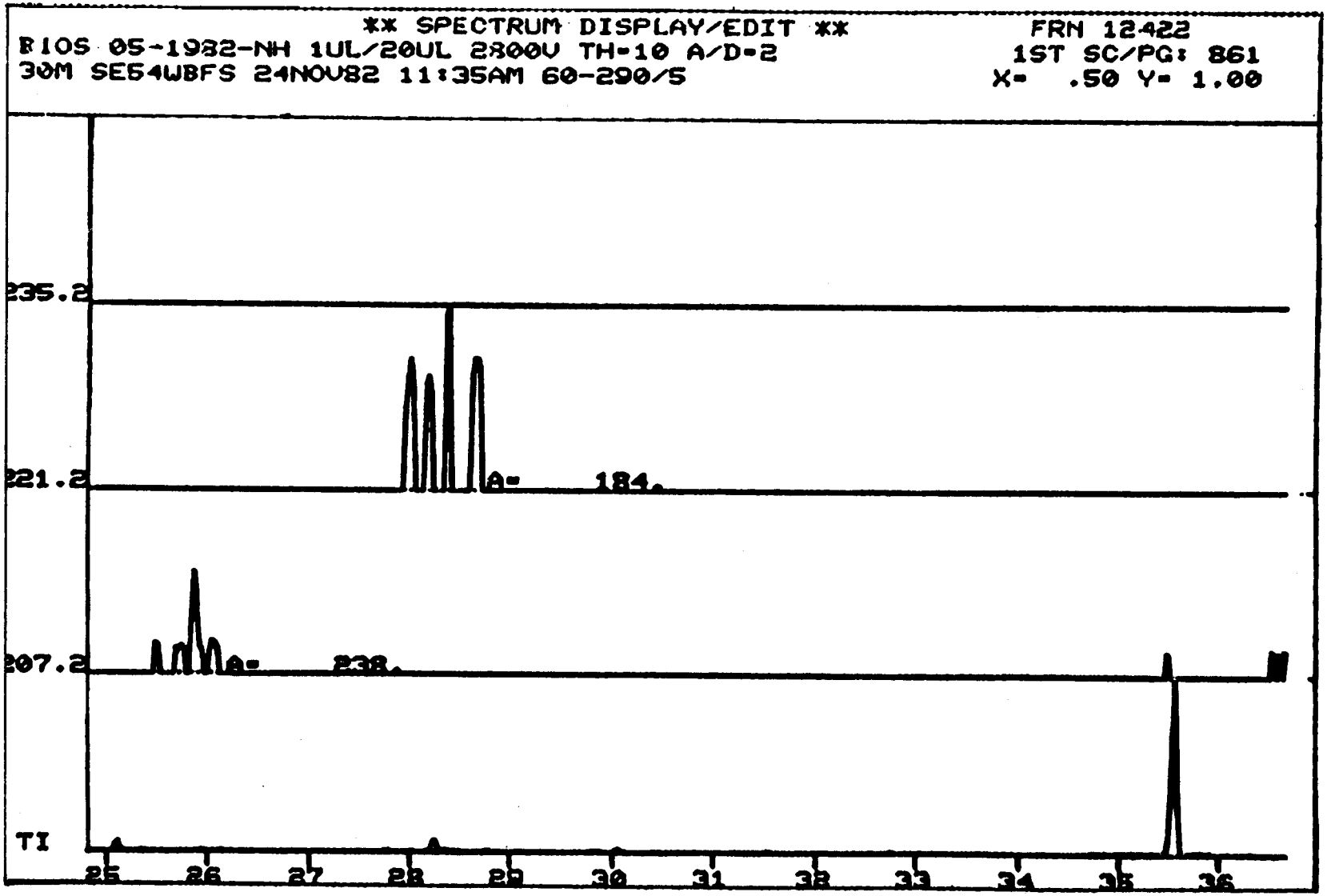
ASTARTE BOREALIS: BAY 9: 1 DAY

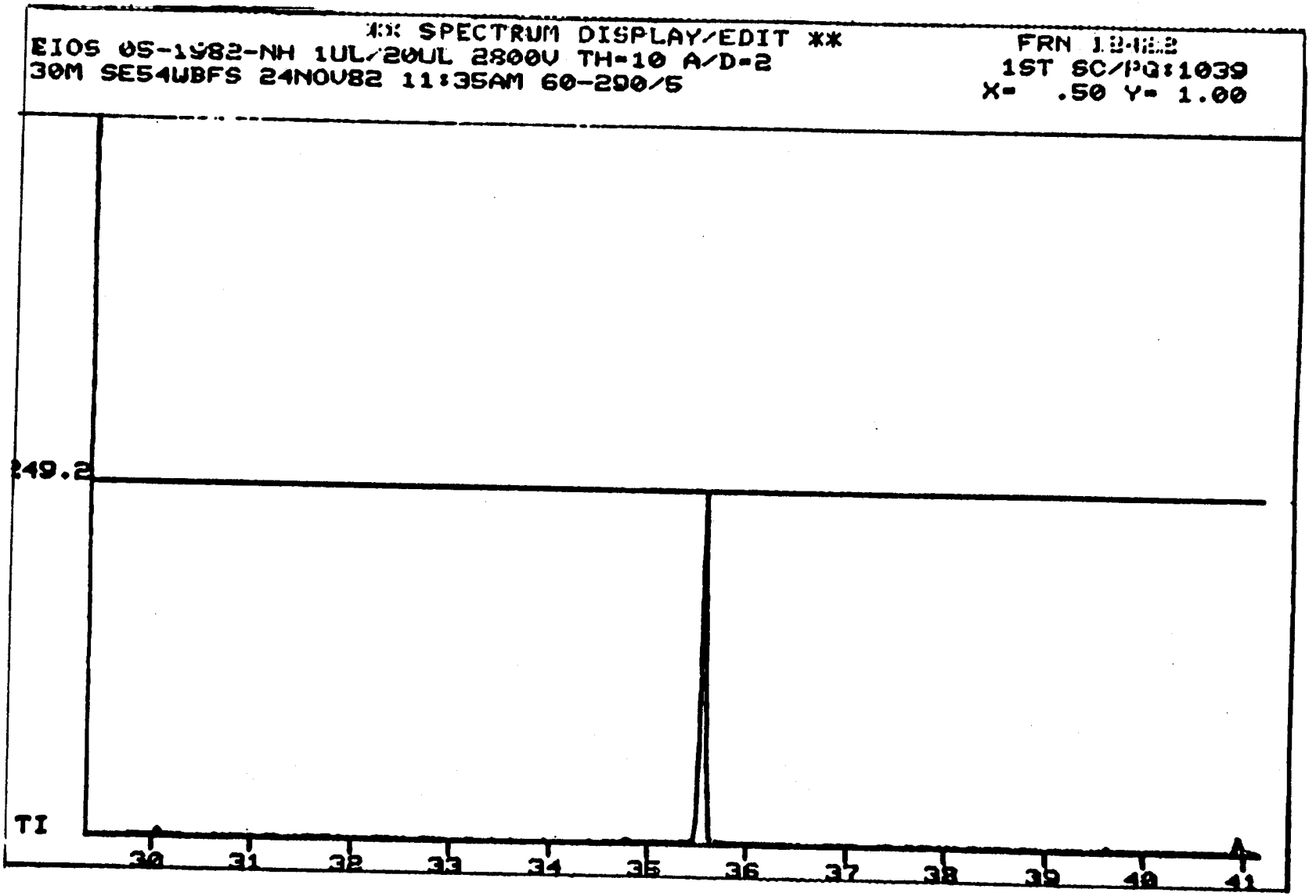

** SPECTRUM DISPLAY/EDIT **
FRN 12422
EIOS 05-1989-NH 1UL/20UL 2800V TH=10 A/D=2
1ST SC/PQ: 1
30M SE54WBFS 24NOV82 11:35AM 60-290/5
X= .25 Y= 1.00
TI
5
10
15
20
25

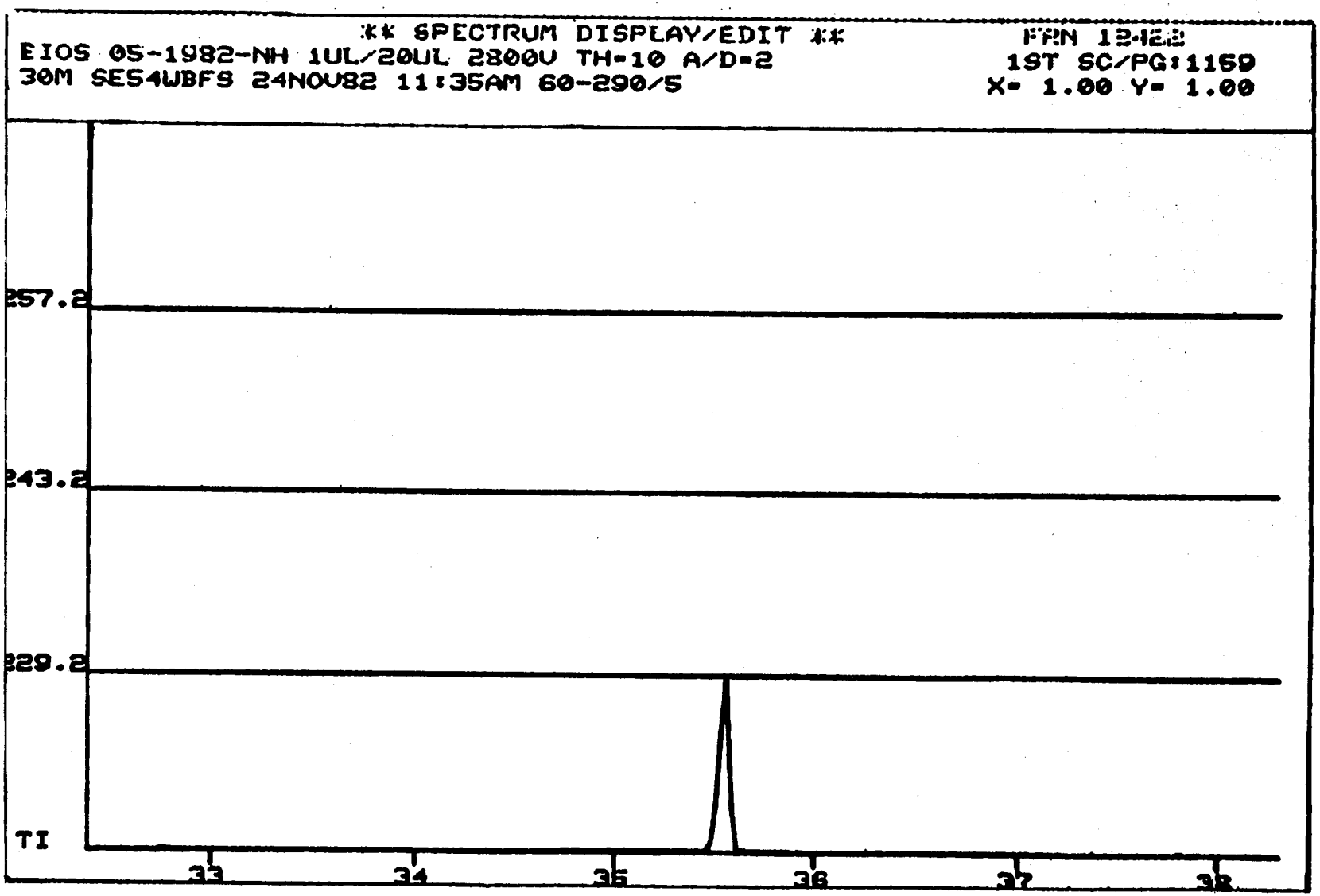

** SPECTRUM DISPLAY/EDIT **
FIOS 05-1982-NH 1UL/20UL 2800V TH=10 A/D=2
30M SE54WBFS 24NOV82 11:35AM 60-290/5
FRN 12422
1ST SC/PG: 929
X= .25 Y= 1.00
TI
30
35
40
45
50


** SPECTRUM DISPLAY/EDIT **
FRN 12422
BIOS 05-1982-NH 1UL/20UL 2800V TH=10 A/D=2
1ST SC/PQ: 450
30M SE54WBFS 24NOV82 11:35AM 60-290/5
X= .50 Y= 1.00
199.2
185.2
171.2
TI
15
16
17
18
19
20
R1
R2
R3
R4
R5
R6


** SPECTRUM DISPLAY/EDIT **
BIOS 05-1982-NH 1UL/20UL 2800V TH=10 A/D=2
30M SE54WBFS 24NOV82 11:35AM 60-290/5
FRN 12422
1ST SC/PQ: 598
X= .50 Y= 1.00
313.2
TI
19
20
21
22
23
24
25
26
27
28
29


** SPECTRUM DISPLAY/EDIT **
FRN 12422
BIOS 05-1932-NH 1UL/20UL 2800V TH=10 A/D=2
1ST SC/PG: 861
30M SE54WBFS 24NOV82 11:35AM 60-290/5
X= .50 Y= 1.00
235.2
221.2
A= 184.
207.2
A= 238.
TI
25
26
27
28
29
30
31
32
33
34
35
36


** SPECTRUM DISPLAY/EDIT **
EIOS 05-1982-NH 1UL/20UL 2800V TH=10 A/D=2
30M SE54WBFS 24NOV82 11:35AM 60-290/5
1ST SC/PG:1039
X= .50 Y= 1.00
249.2
TI
30
31
32
33
34
35
36
37
38
39
40
41


** SPECTRUM DISPLAY/EDIT **
FRN 12:12:2
EIOS 05-1982-NH 1UL/20UL 2800V TH=10 A/D=2
1ST SC/PG:1159
30M SE54WBFS 24NOV82 11:35AM 60-290/5
X= 1.00 Y= 1.00
257.2
243.2
229.2
TI
33
34
35
36
37
38

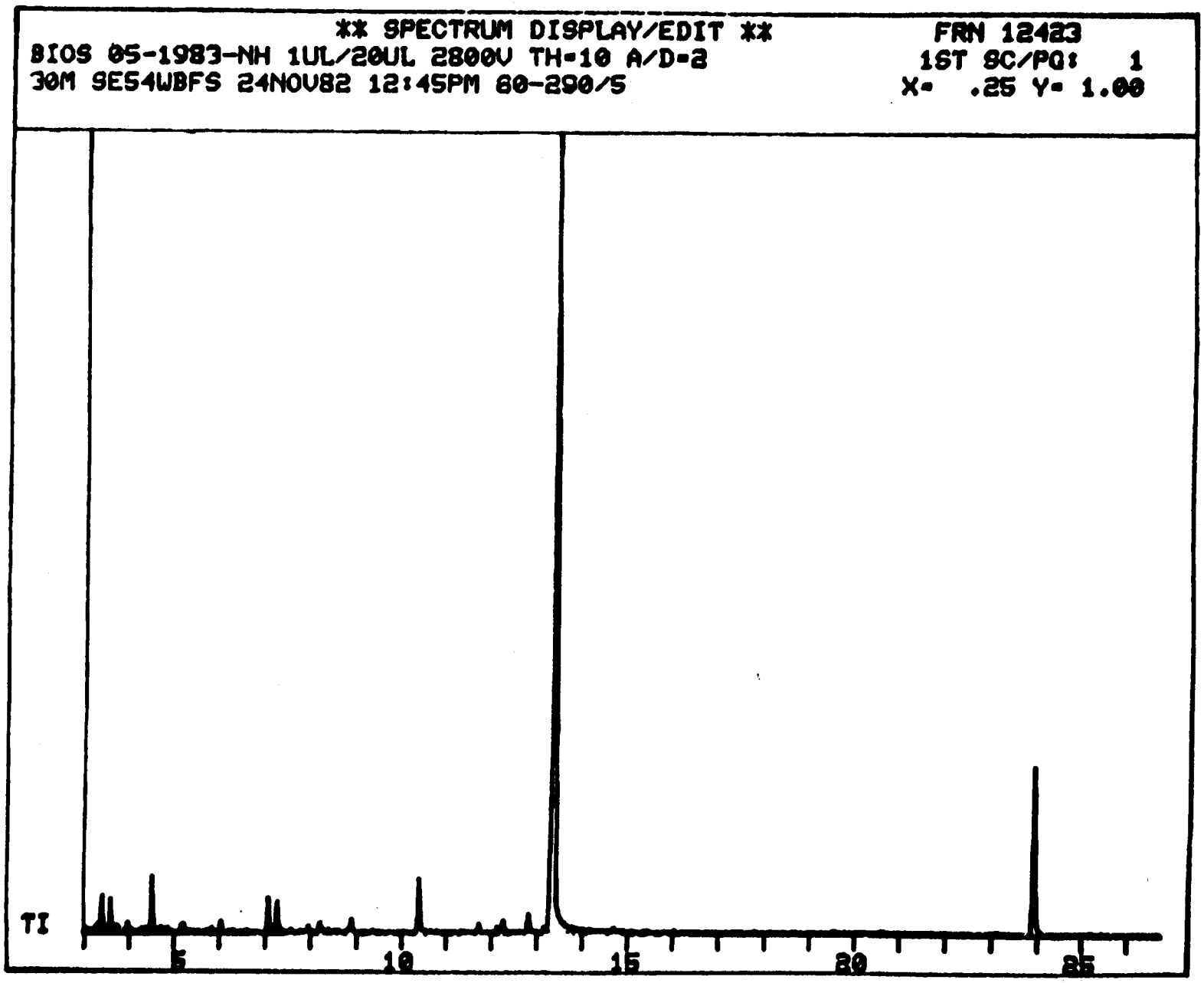
FILE NUMBER 12423

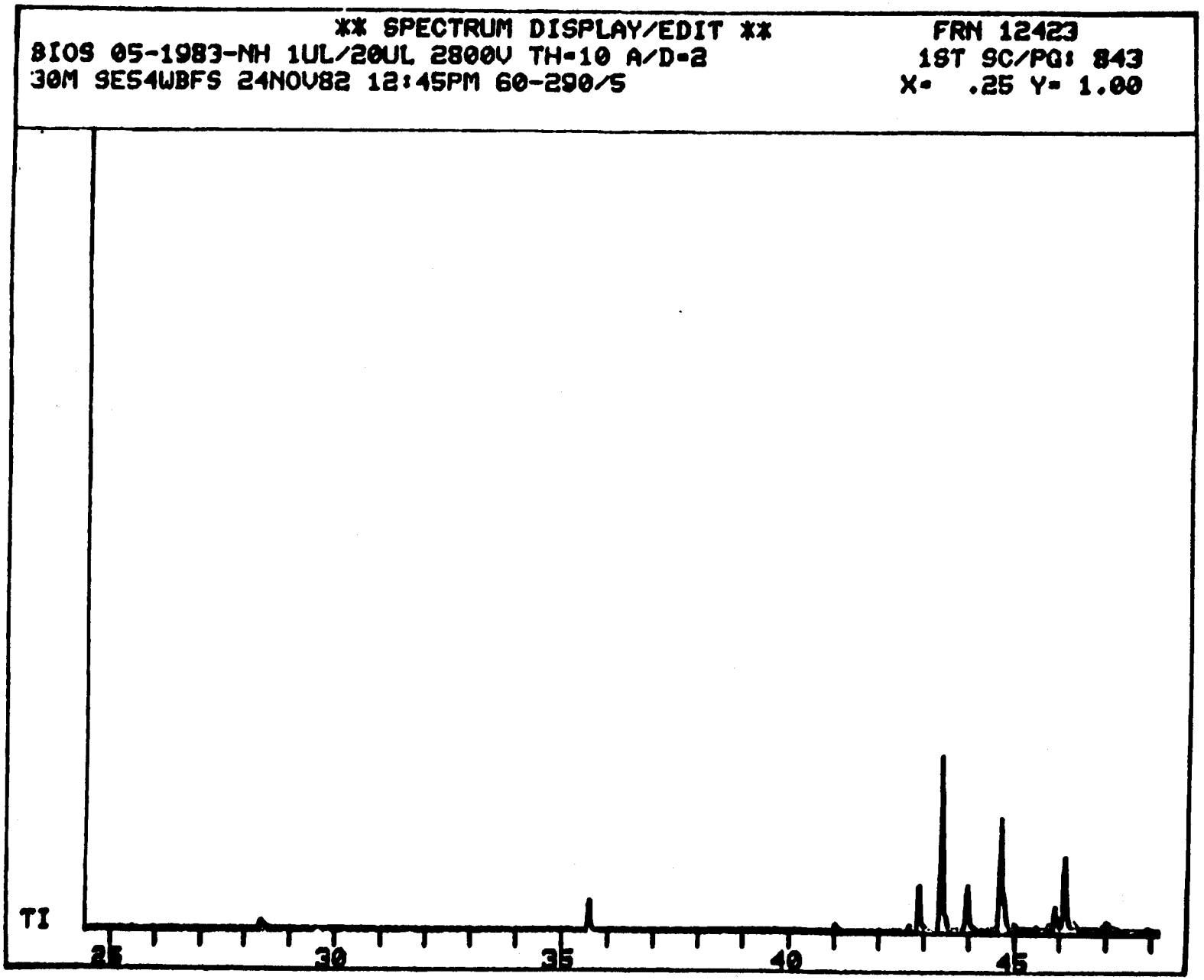
ENTRY	TIME	MASS	AREA	%
1	25.9	207.2	238.	56.40
2	28.4	221.2	184.	43.60

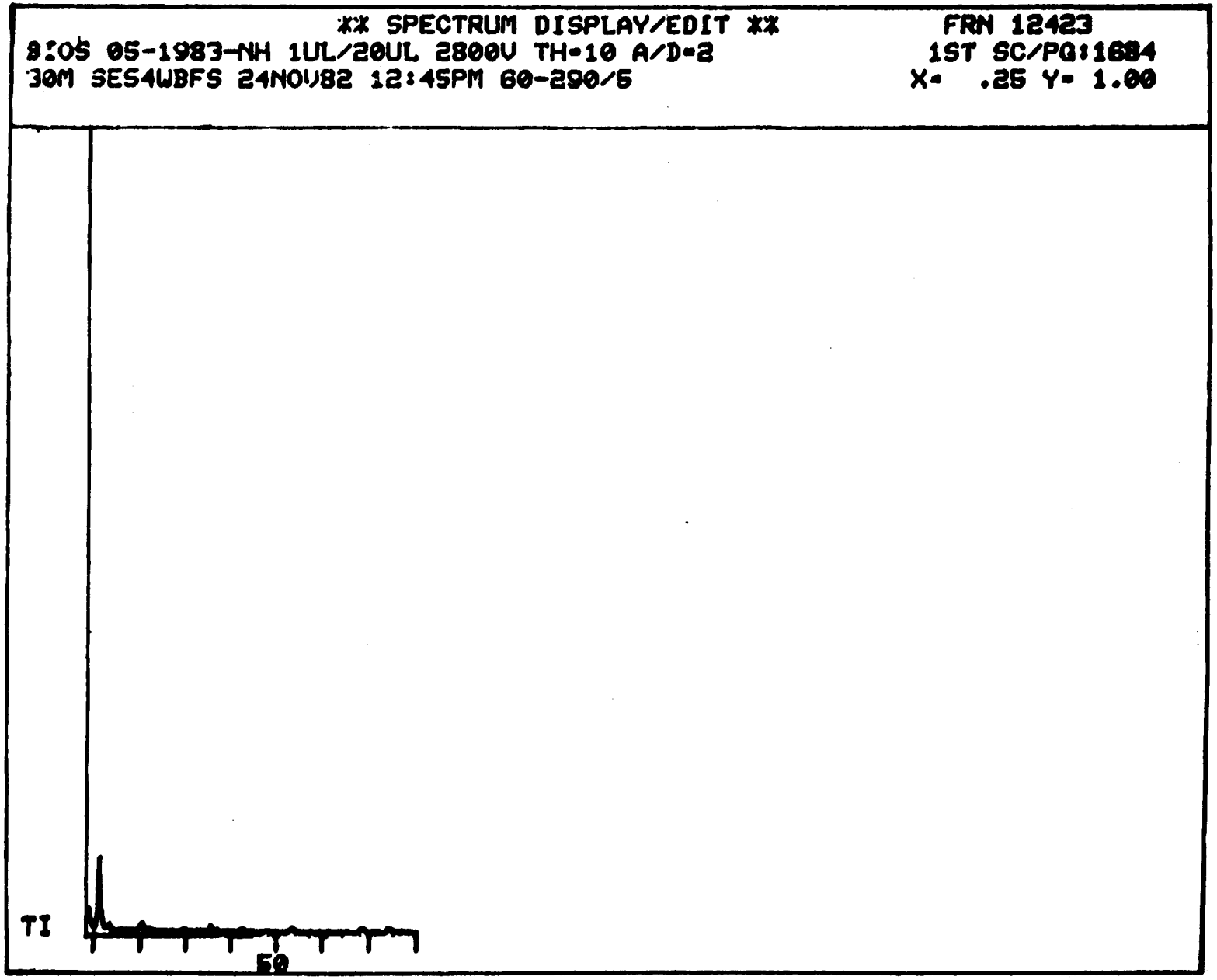
CAL % ON ENTRY?

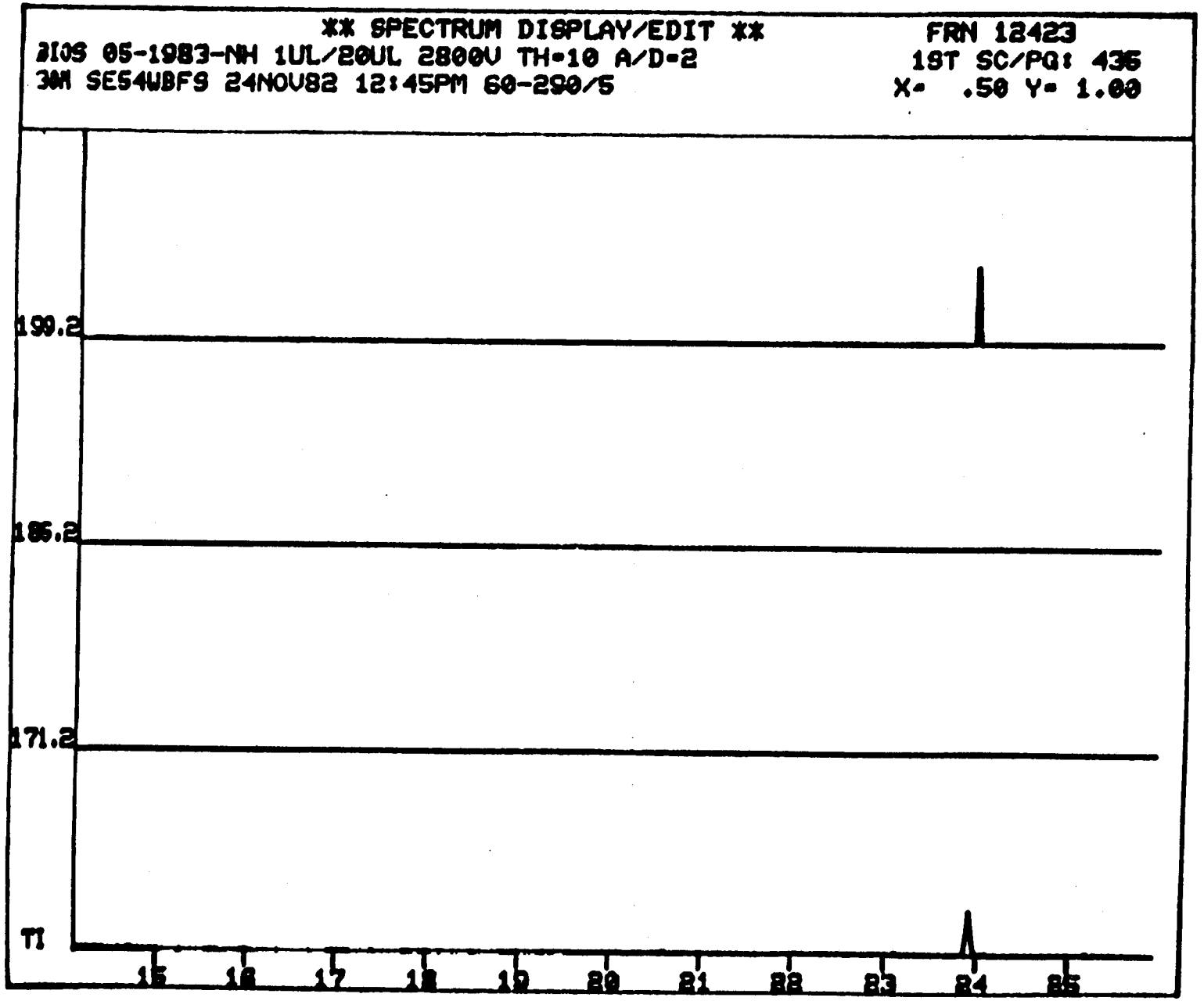
APPENDIX III:

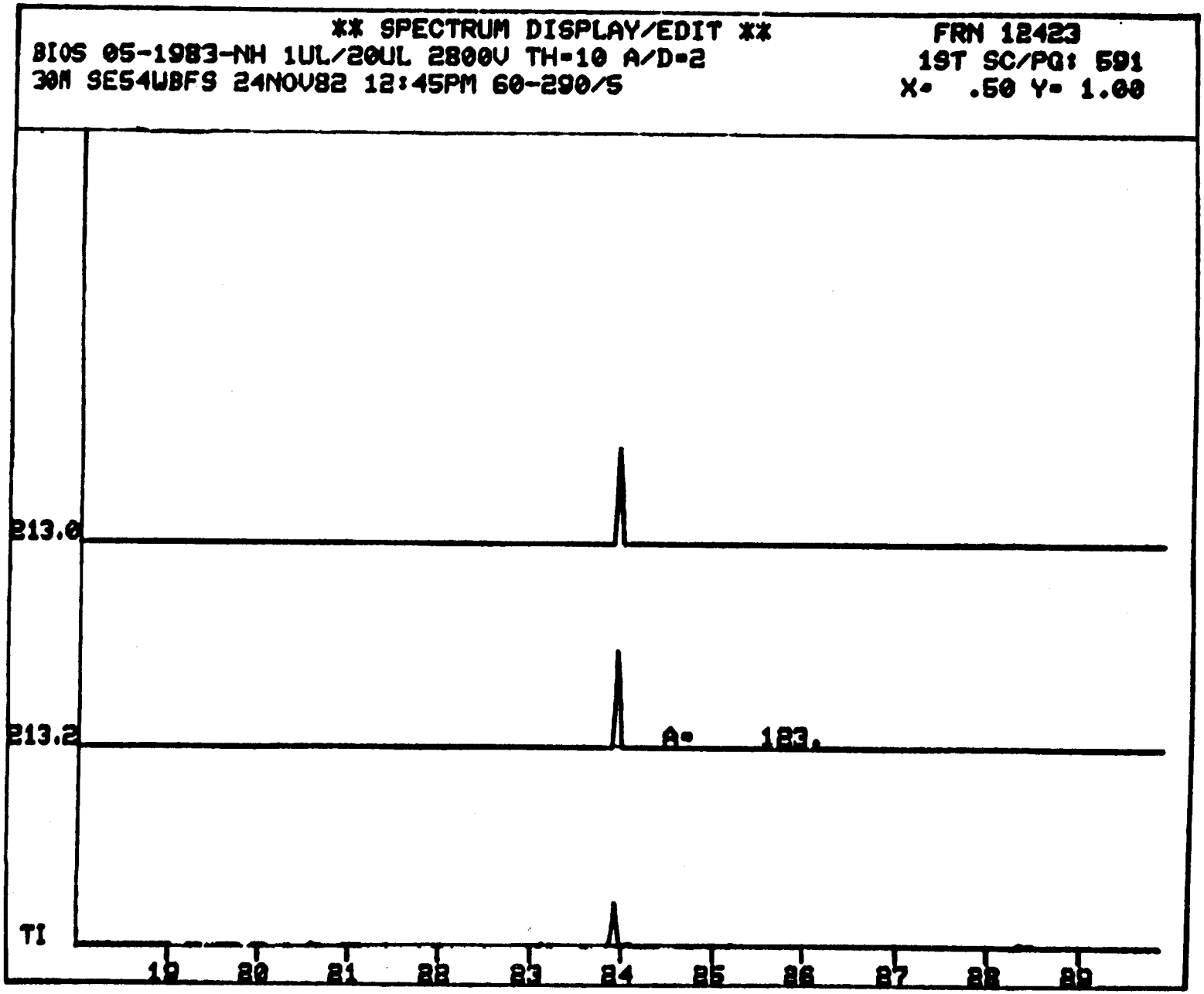
ASTARTE BOREALIS: BAY 9: 2 WEEKS

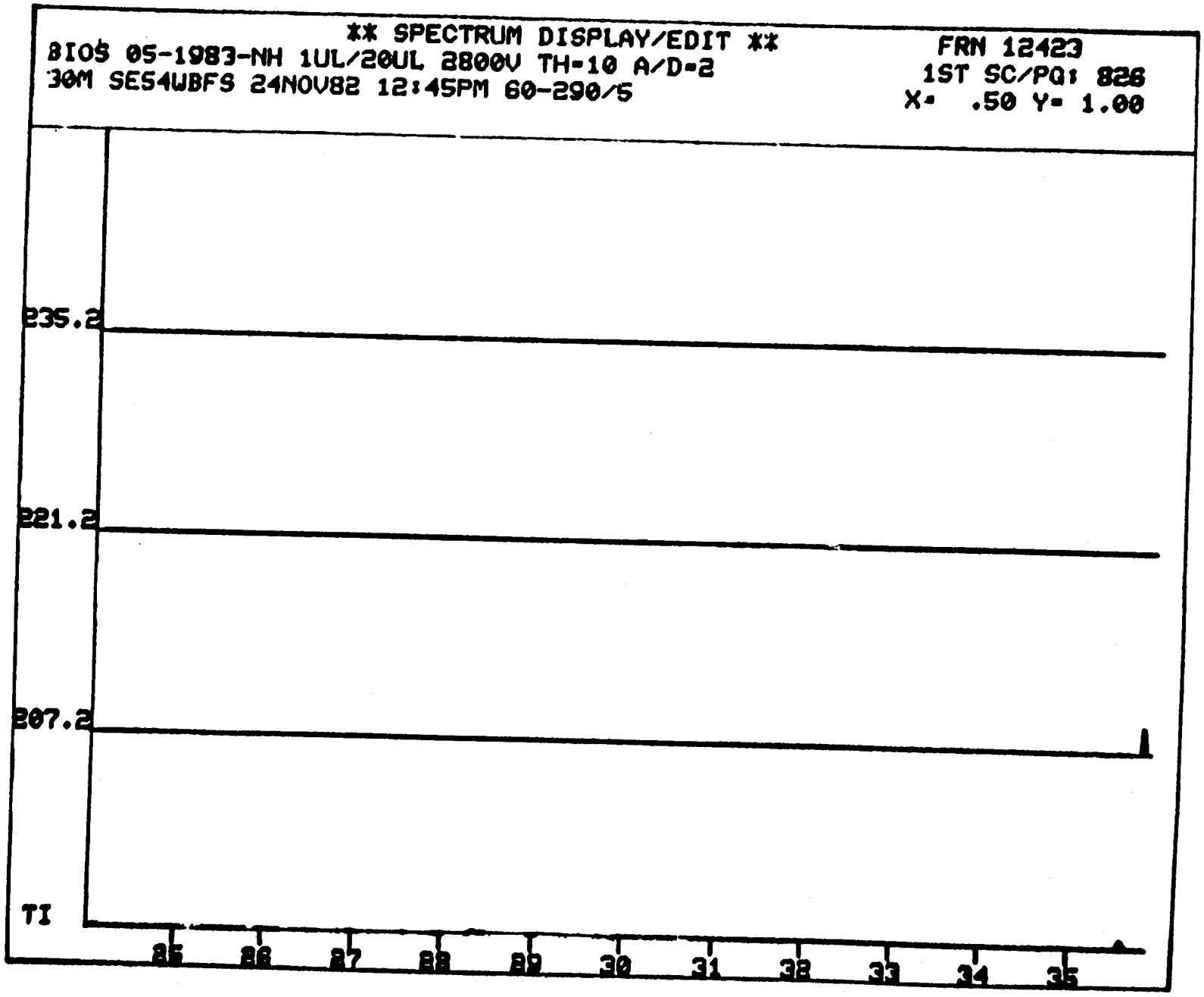

** SPECTRUM DISPLAY/EDIT **
FRN 12423
BIOS 05-1983-NH 1UL/20UL 2800V TH=10 A/D=2
1ST SC/PG: 1
30M SE54WBFS 24NOV82 12:45PM 60-290/5
X= .25 Y= 1.00
TI
5
10
15
20
25

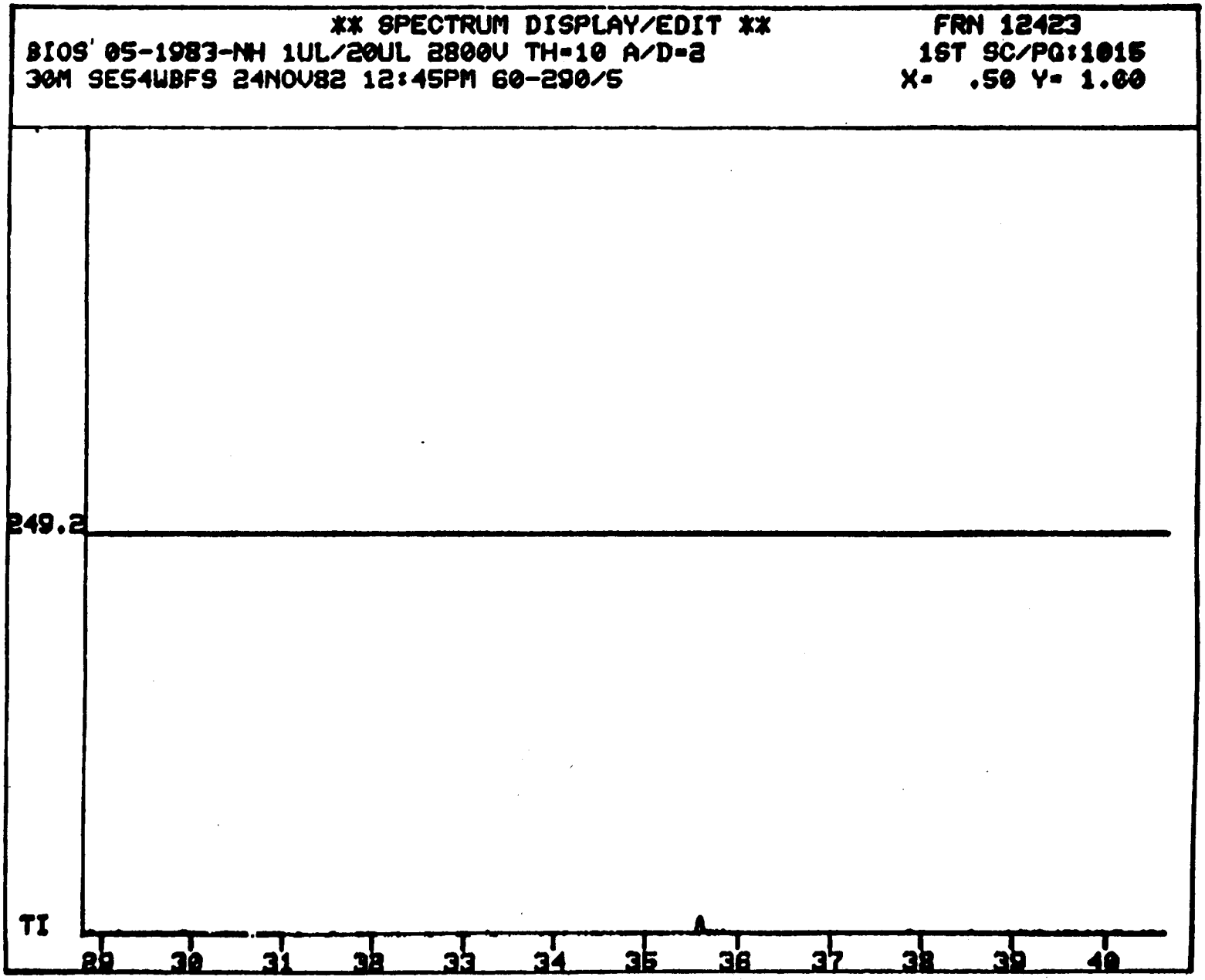

** SPECTRUM DISPLAY/EDIT **
FRN 12423
8IOS 05-1983-NH 1UL/20UL 2800V TH-10 A/D-2
1ST SC/PG: 843
30M SES4WBFS 24NOV82 12:45PM 60-290/5
X= .25 Y= 1.00
TI
25
30
35
40
45

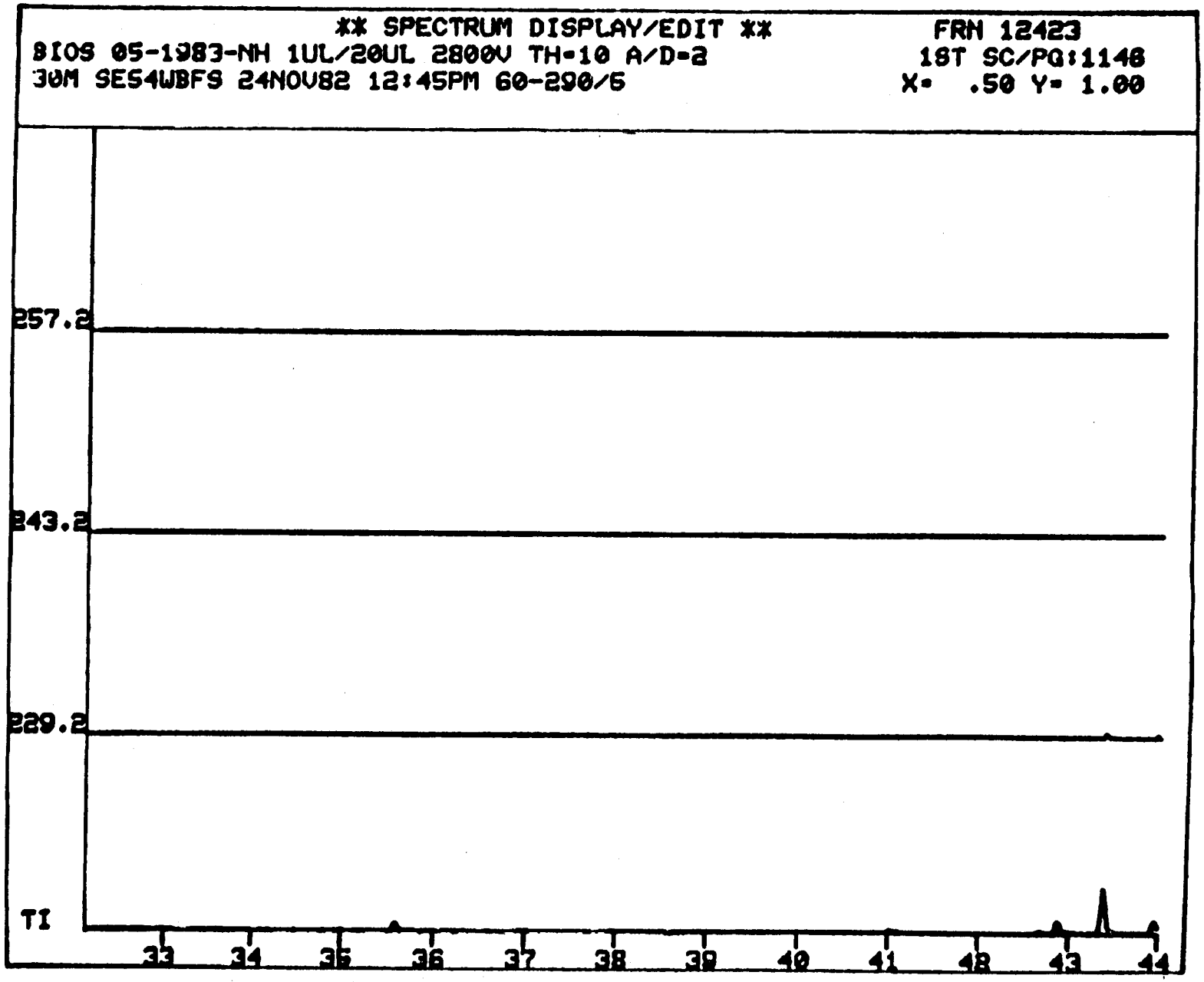

** SPECTRUM DISPLAY/EDIT **
FRN 12423
BIOS 05-1983-NH 1UL/20UL 2800V TH=10 A/D=2
1ST SC/PQ:1684
30M SES4WBFS 24NOV82 12:45PM 60-290/5
X= .25 Y= 1.00
TI
50


** SPECTRUM DISPLAY/EDIT **
FRN 12423
2IOS 05-1983-NH 1UL/20UL 2800V TH=10 A/D=2
1ST SC/PQ: 435
3M SE54WBFS 24NOV82 12:45PM 60-290/5
X= .50 Y= 1.00
199.2
185.2
171.2
TI
15
16
17
18
19
20
21
22
23
24
25


** SPECTRUM DISPLAY/EDIT **
FRN 12423
BIOS 05-1983-NH 1UL/20UL 2800V TH=10 A/D=2
1ST SC/PG: 591
30M SE54WBFS 24NOV82 12:45PM 60-290/5
X= .50 Y= 1.00
213.0
213.2
A= 183.
TI
19
20
21
22
23
24
25
26
27
28
29


** SPECTRUM DISPLAY/EDIT **
BIOS 05-1983-NH 1UL/20UL 2800V TH=10 A/D=2
30M SES4WBFS 24NOV82 12:45PM 60-290/5
FRN 12423
1ST SC/PQ: 826
X= .50 Y= 1.00
235.2
221.2
207.2
TI
35


** SPECTRUM DISPLAY/EDIT **
FRN 12423
BIOS 05-1983-NH 1UL/20UL 2800V TH=10 A/D=2
1ST SC/PQ:1015
30M SES4WBFS 24NOV82 12:45PM 60-290/5
X= .50 Y= 1.00
249.2
TI
29
30
31
32
33
34
35
36
37
38
39
40



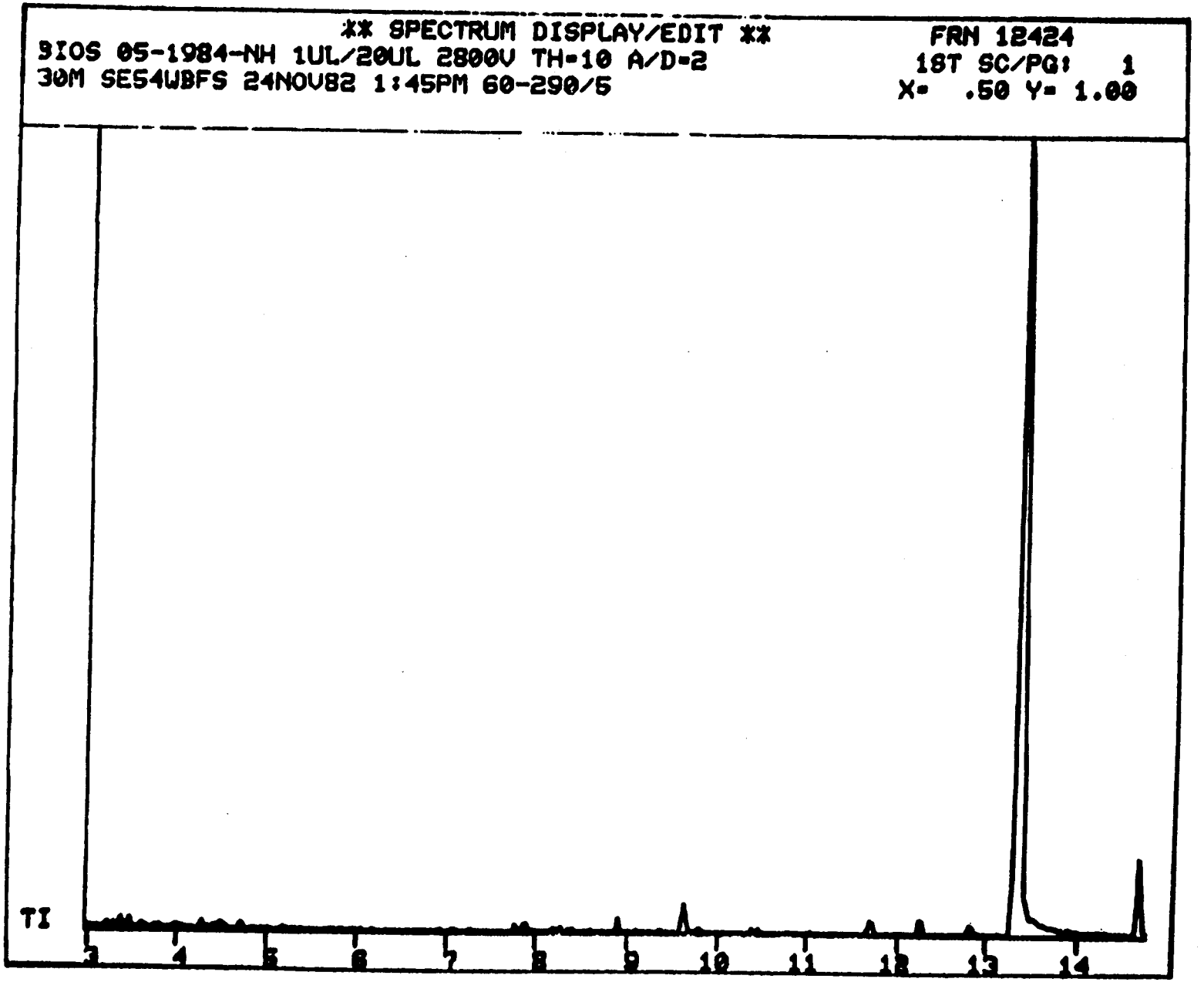
FILE NUMBER 18483

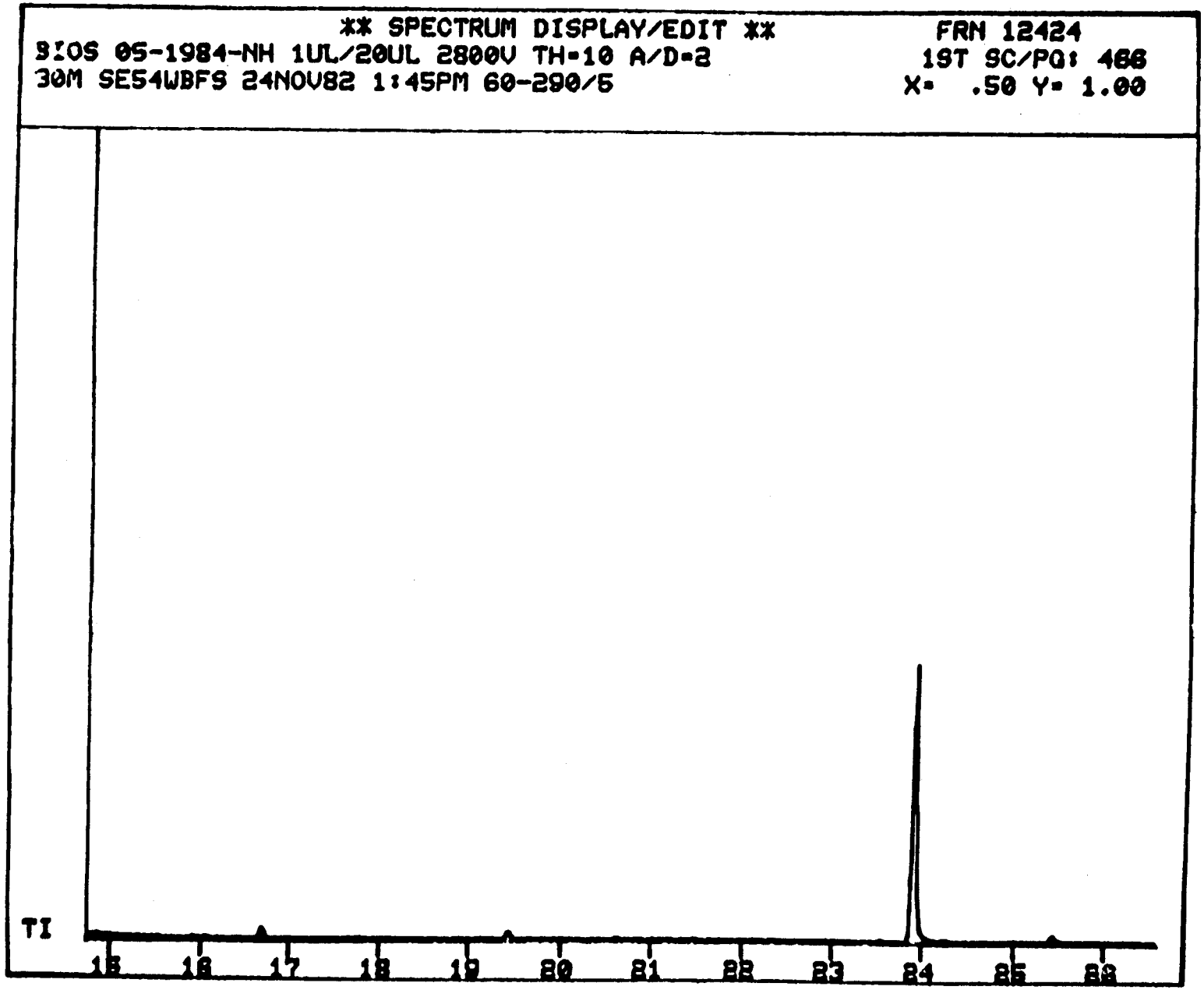
ENTRY	TIME	MASS	AREA	%
1	23.9	213.2	123.	100.00

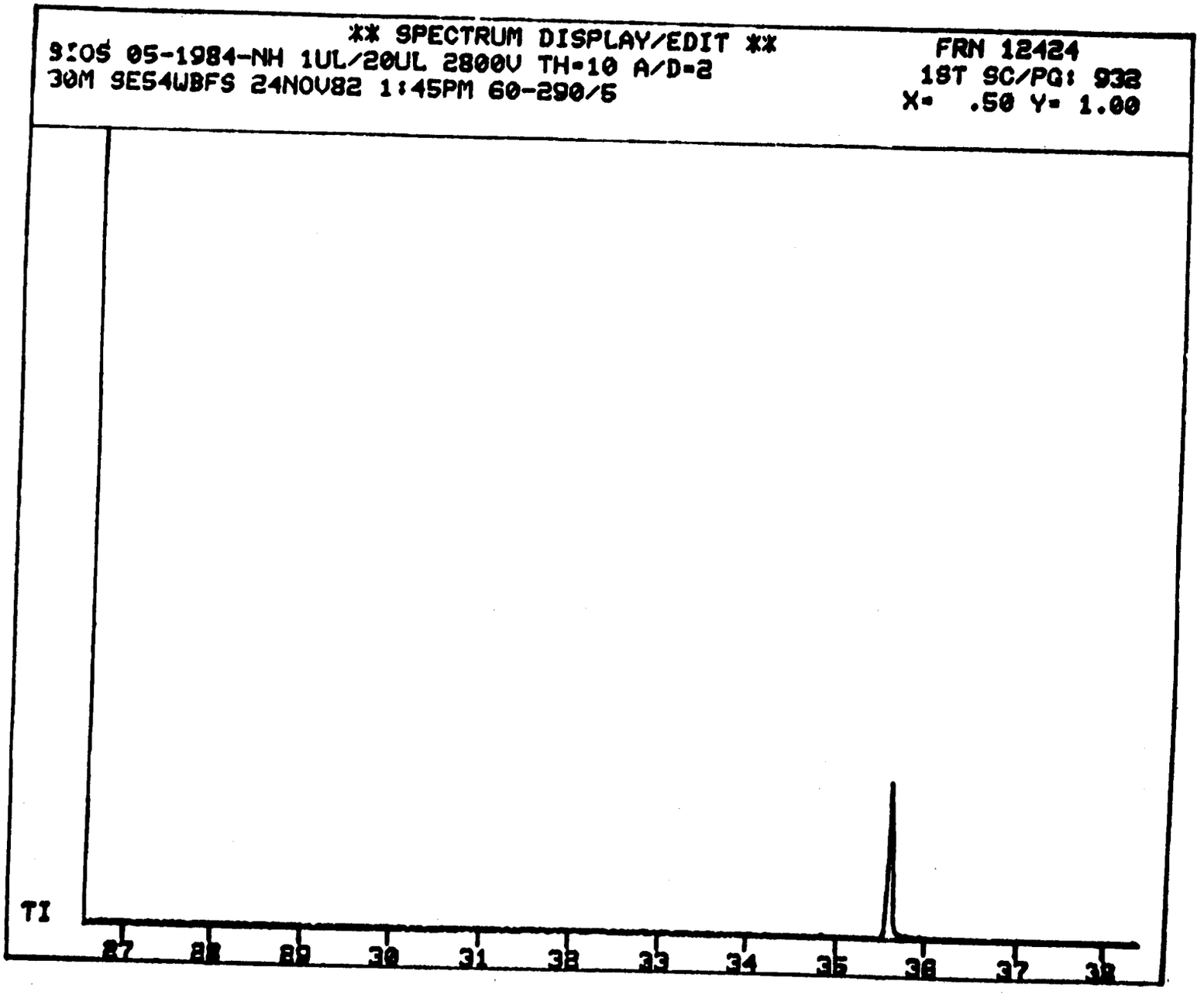
CAL % ON ENTRY?

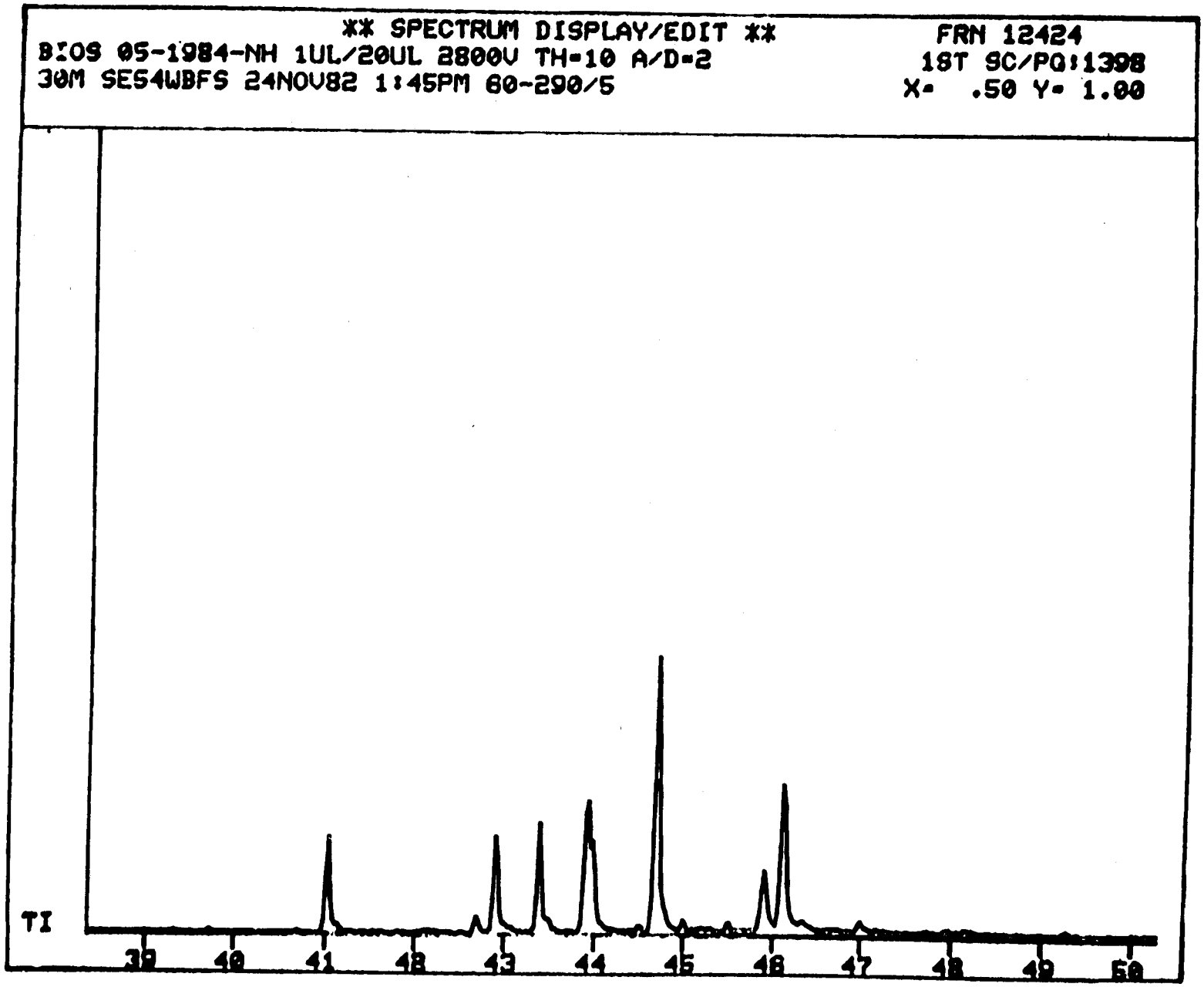
APPENDIX IV:

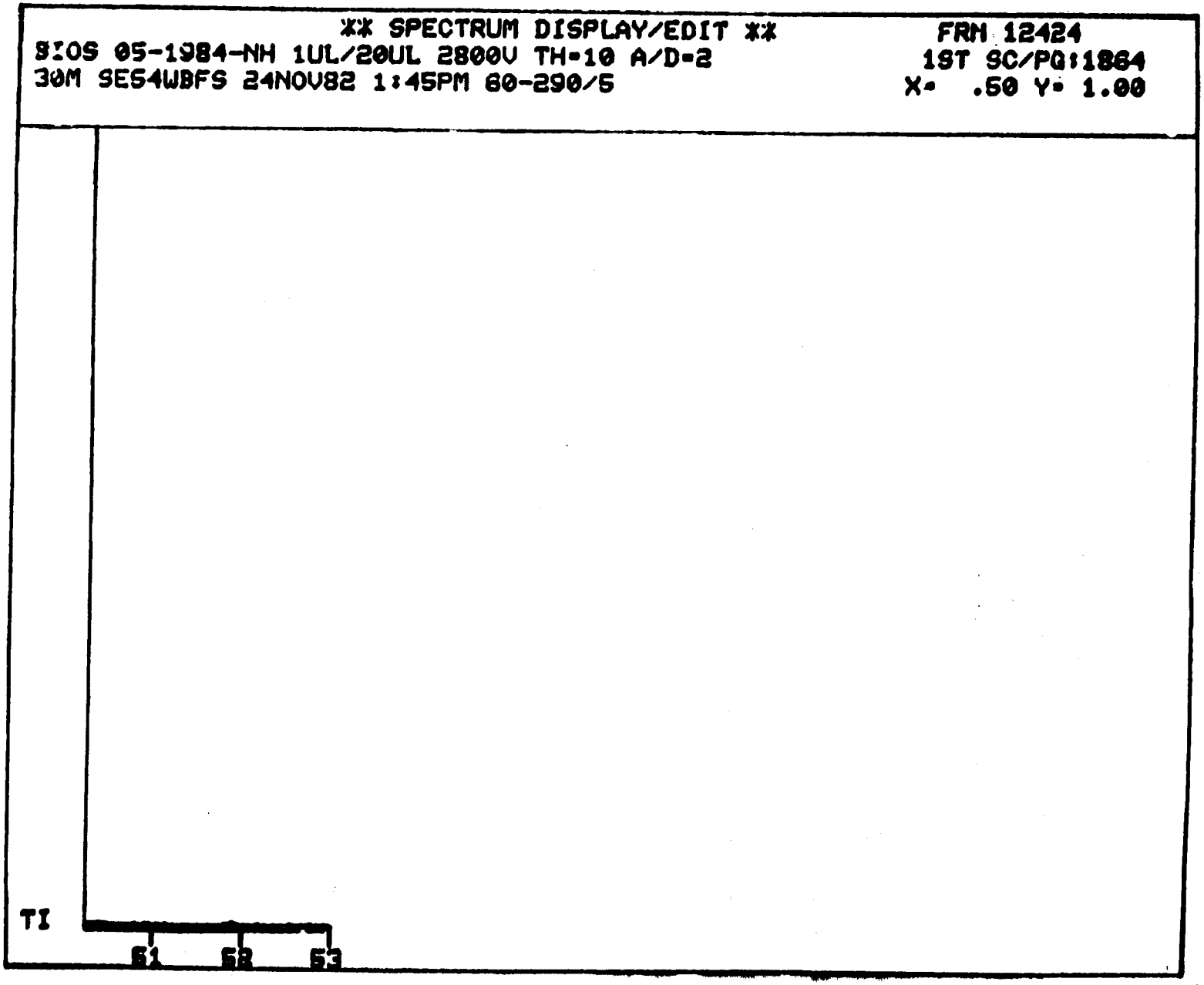
SERRIPES GROENLANDICUS: BAY 10: 1 DAY

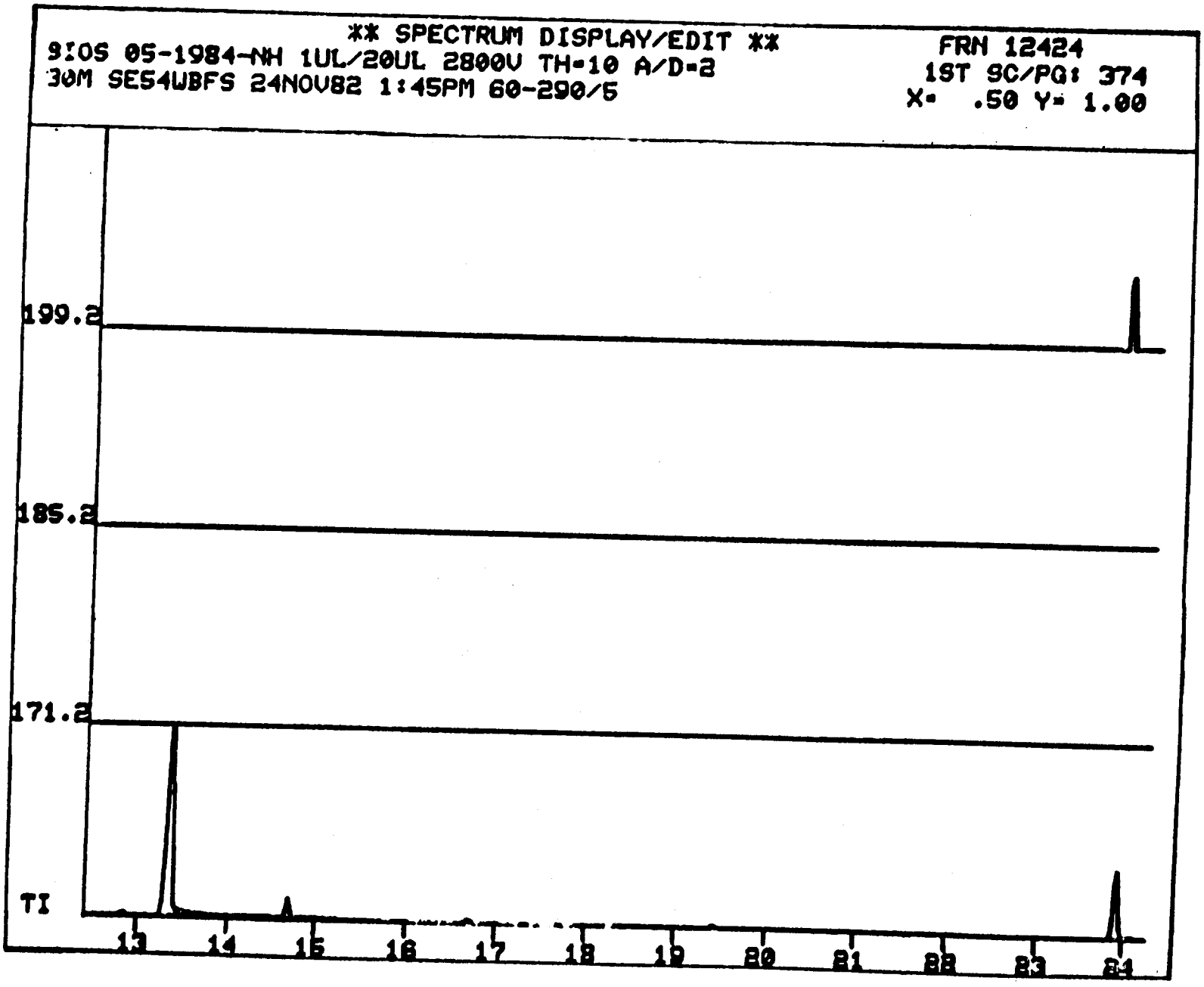

** SPECTRUM DISPLAY/EDIT **
FRN 12424
9IOS 05-1984-NH 1UL/20UL 2800V TH=10 A/D=2
1ST SC/PG: 1
30M SE54WBFS 24NOV82 1:45PM 60-290/5
X= .50 Y= 1.00
TI
3
4
5
6
7
8
9
10
11
12
13
14

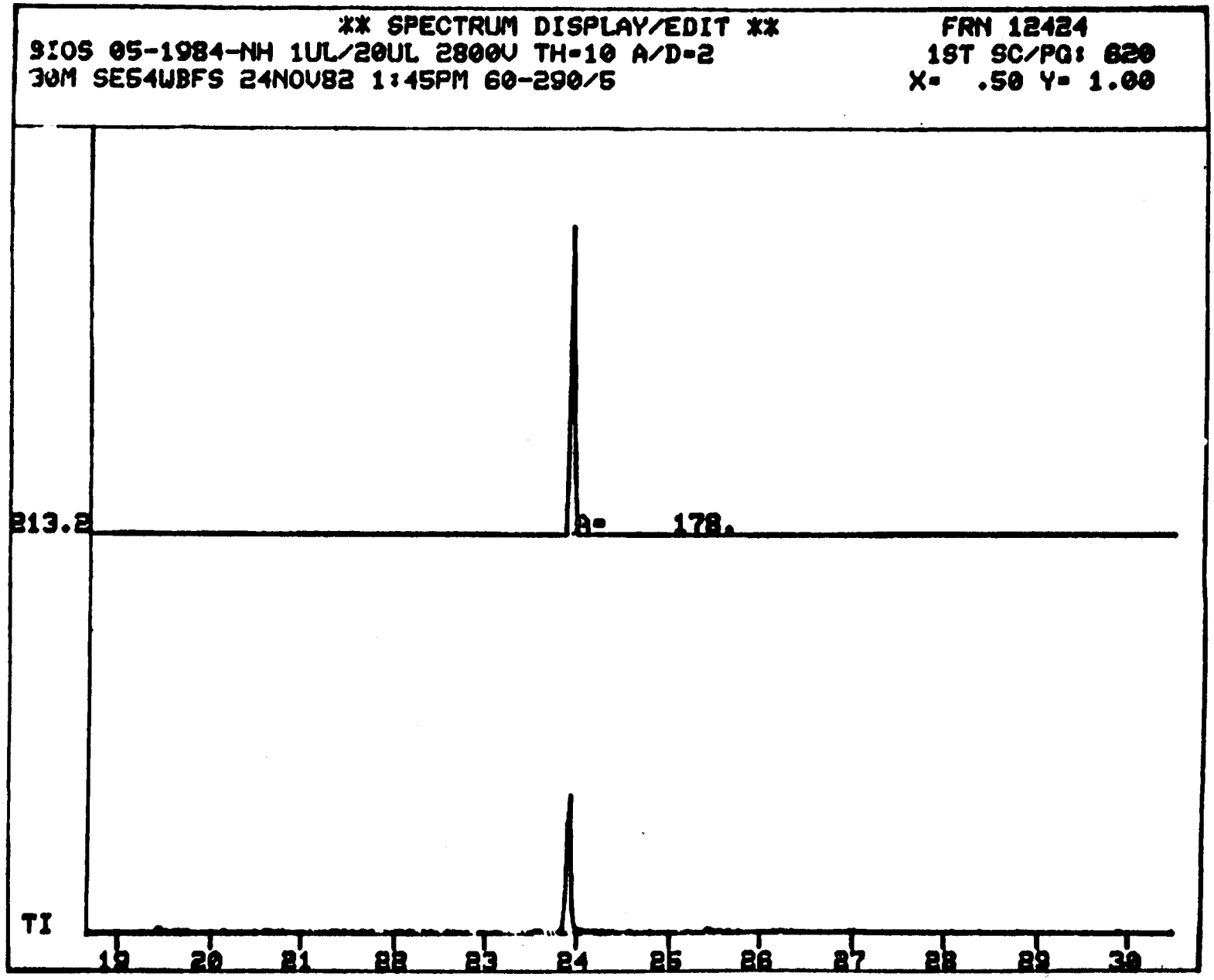

** SPECTRUM DISPLAY/EDIT **
FRN 12424
BIOS 05-1984-NH 1UL/20UL 2800V TH=10 A/D=2
1ST SC/PQ: 466
30M SE54WBFS 24NOV82 1:45PM 60-290/5
X= .50 Y= 1.00
TI
15
16
17
18
19
20
21
22
23
24
25
26


** SPECTRUM DISPLAY/EDIT **
9:05 05-1984-NH 1UL/20UL 2800V TH=10 A/D=2
30M 9E54WBFS 24NOV82 1:45PM 60-290/5
FRN 12424
1ST SC/PQ: 932
X= .50 Y= 1.00
TI
27
28
29
30
31
32
33
34
35
36
37
38


** SPECTRUM DISPLAY/EDIT **
FRN 12424
BIOS 05-1984-NH 1UL/20UL 2800V TH=10 A/D=2
1ST SC/PQ:1398
30M SE54WBFS 24NOV82 1:45PM 60-290/5
X= .50 Y= 1.00
TI
39
40
41
42
43
44
45
46
47
48
49
50


** SPECTRUM DISPLAY/EDIT **
FRM 12424
S:OS 05-1984-NH 1UL/20UL 2800V TH=10 A/D=2
1ST SC/PQ:1864
30M SES4WBFS 24NOV82 1:45PM 60-290/5
X= .50 Y= 1.00
TI
61
62
63


** SPECTRUM DISPLAY/EDIT **
9:05 05-1984-NH 1UL/20UL 2800V TH=10 A/D=2
30M SE54WBFS 24NOV82 1:45PM 60-290/5
FRN 12424
1ST SC/PG: 374
X= .50 Y= 1.00
199.2
185.2
171.2
TI
13
14
15
16
17
18
19
20
21
22
23
24


** SPECTRUM DISPLAY/EDIT **
FRN 12424
9:05 05-1984-NH 1UL/20UL 2800V TH=10 A/D=2
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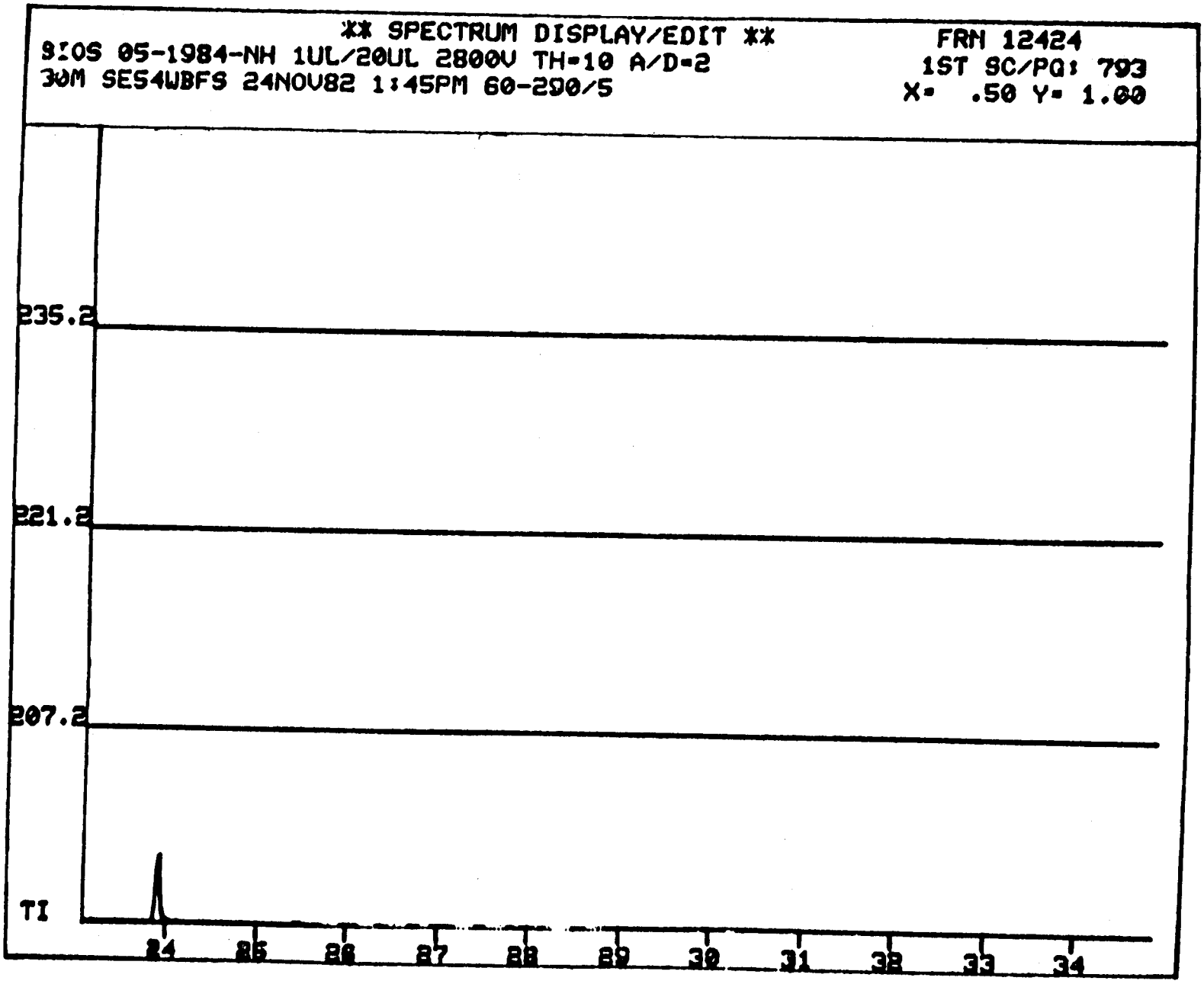
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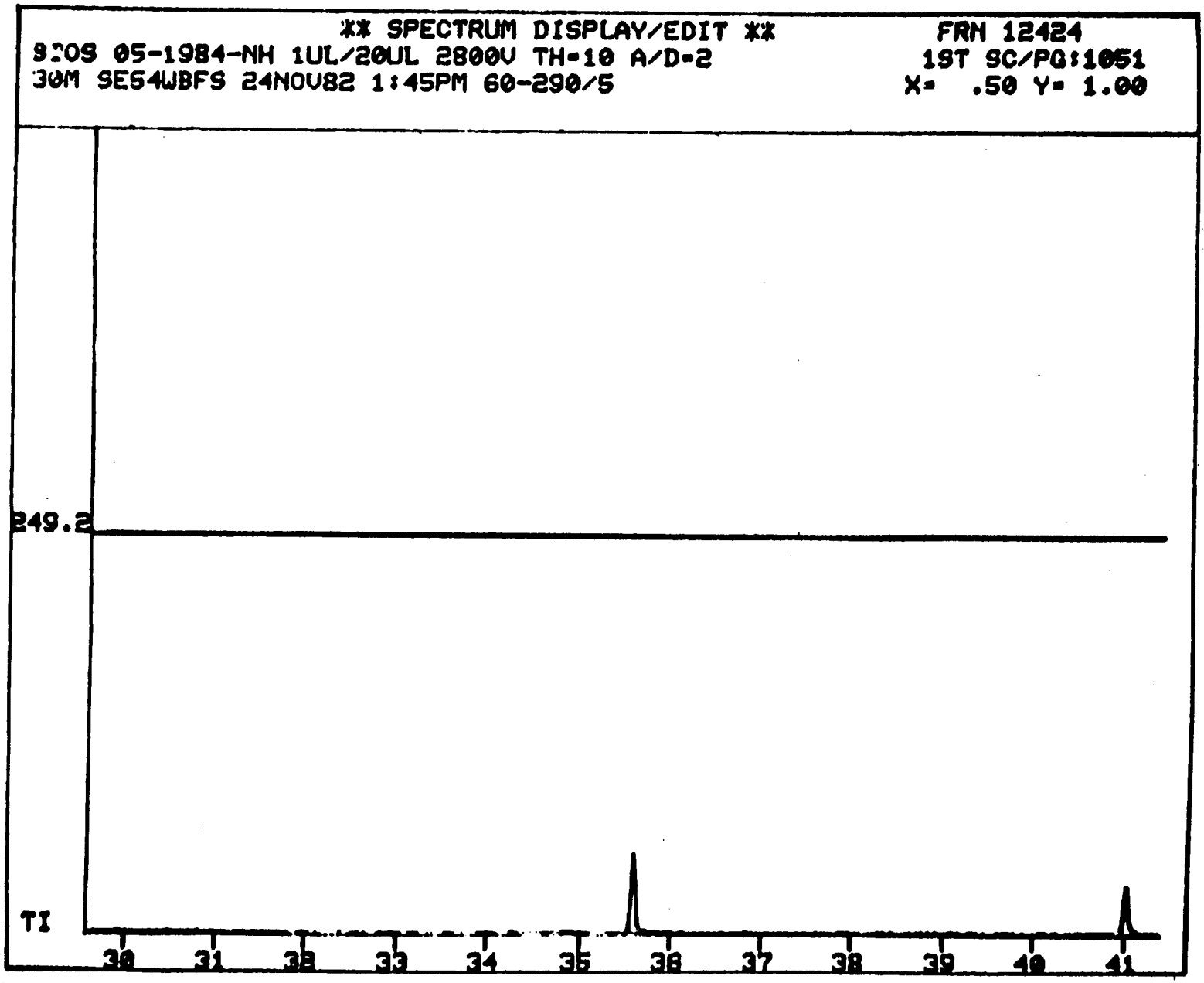
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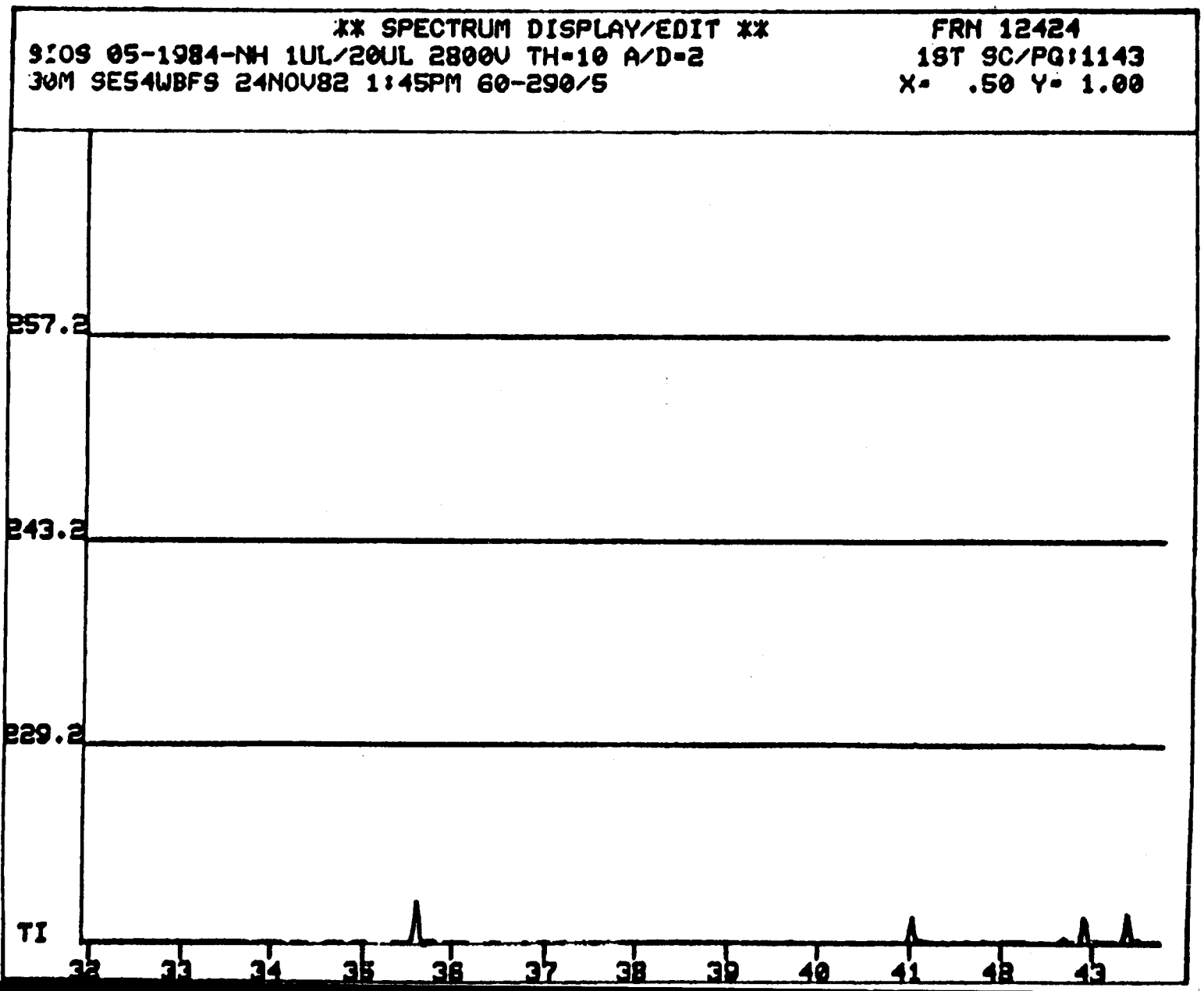

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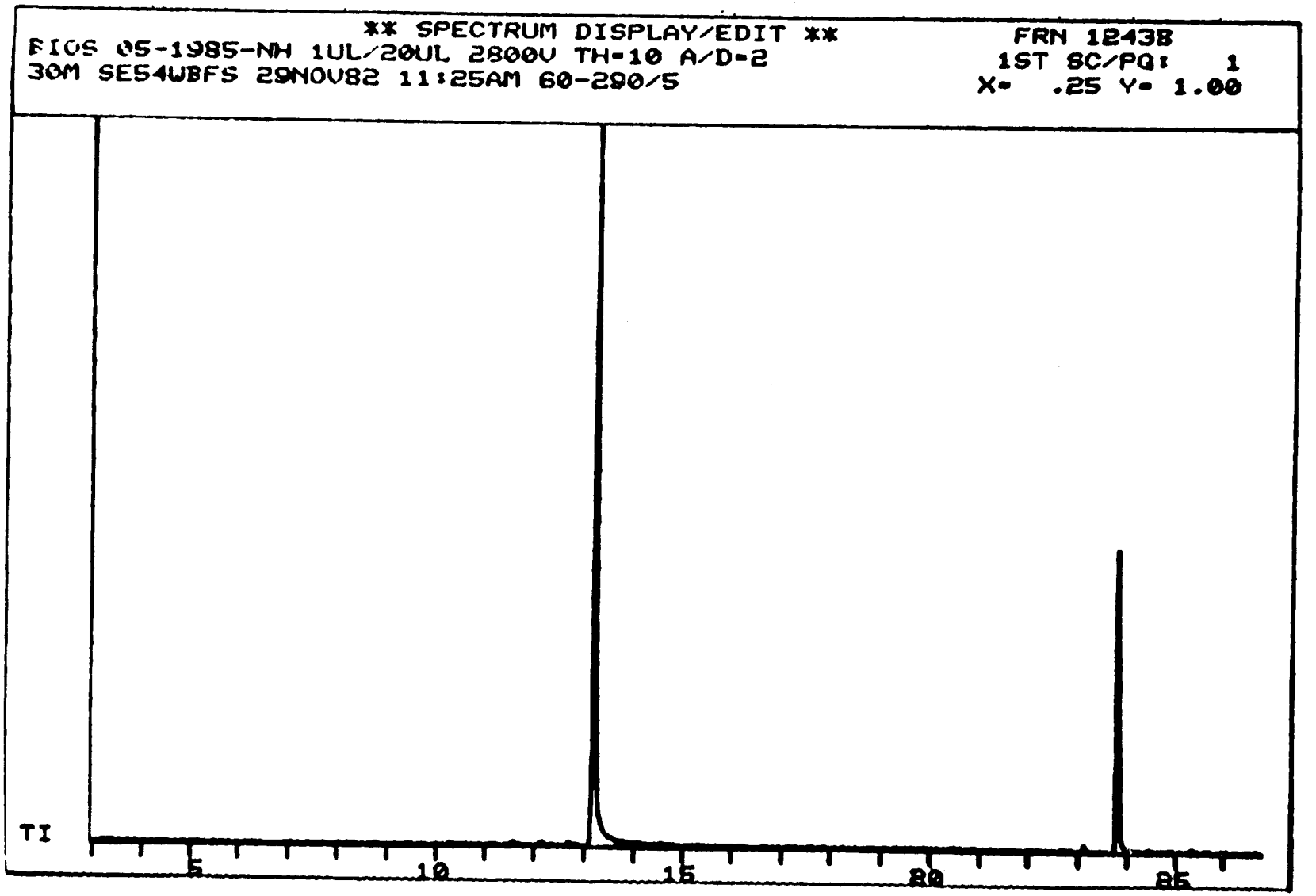
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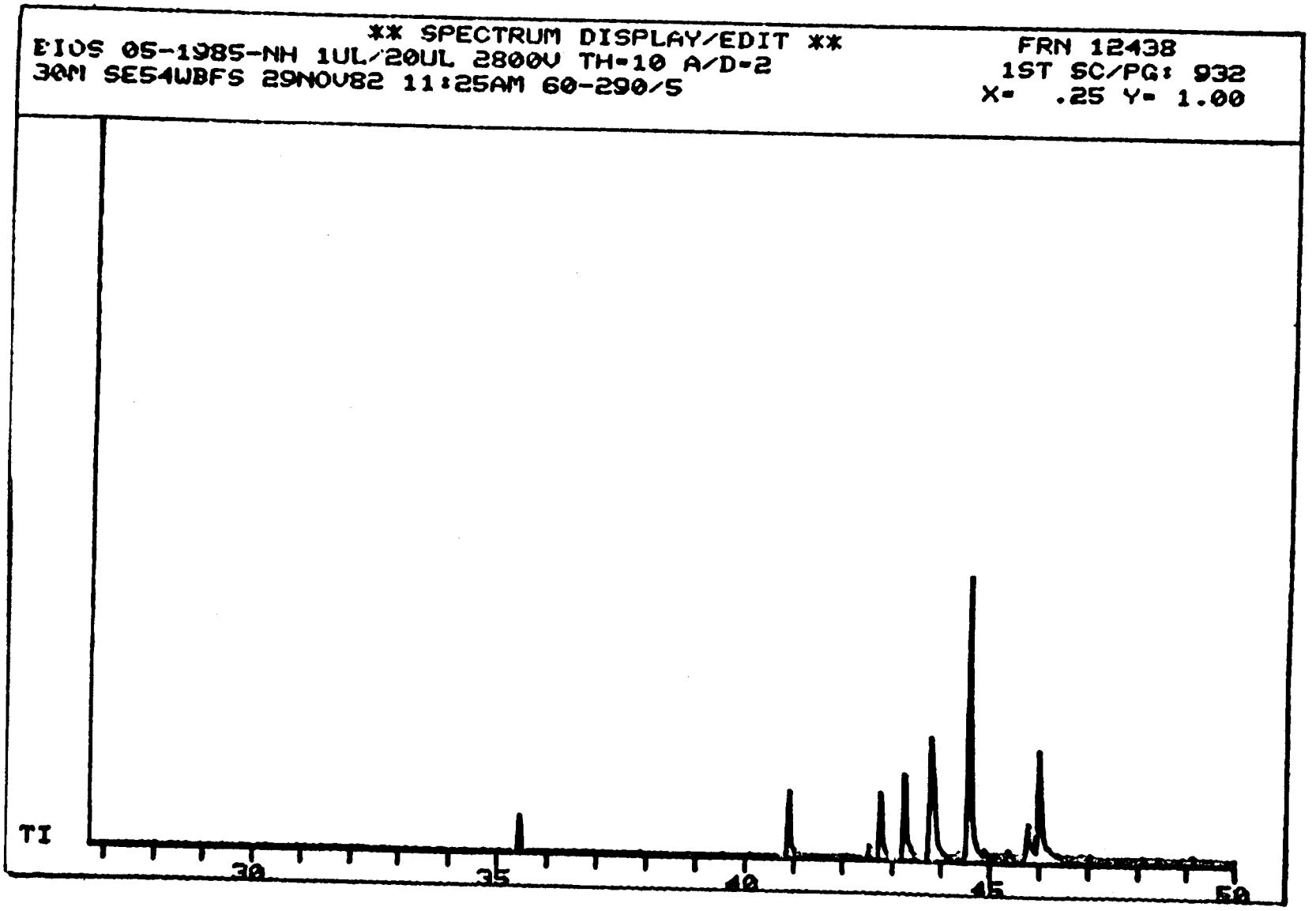
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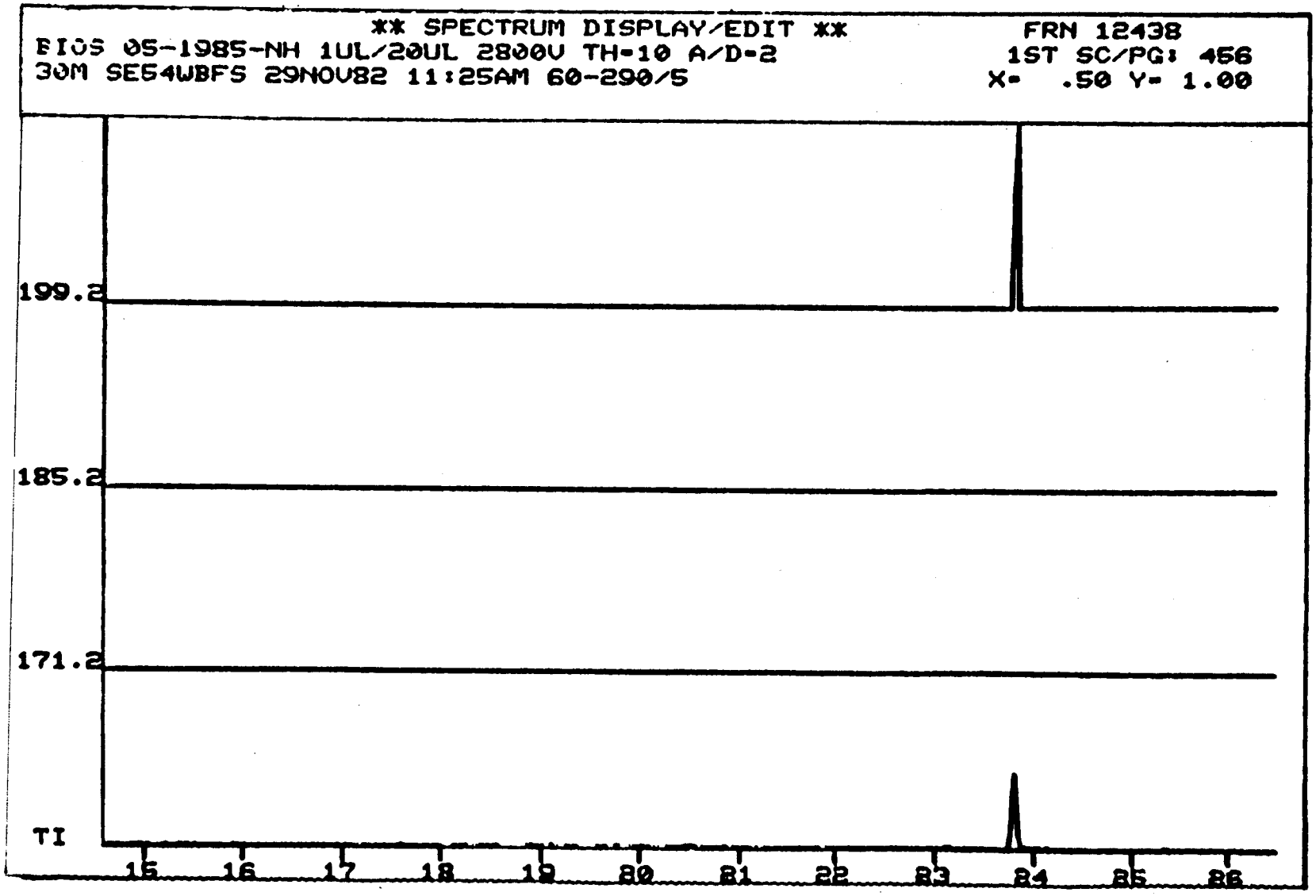
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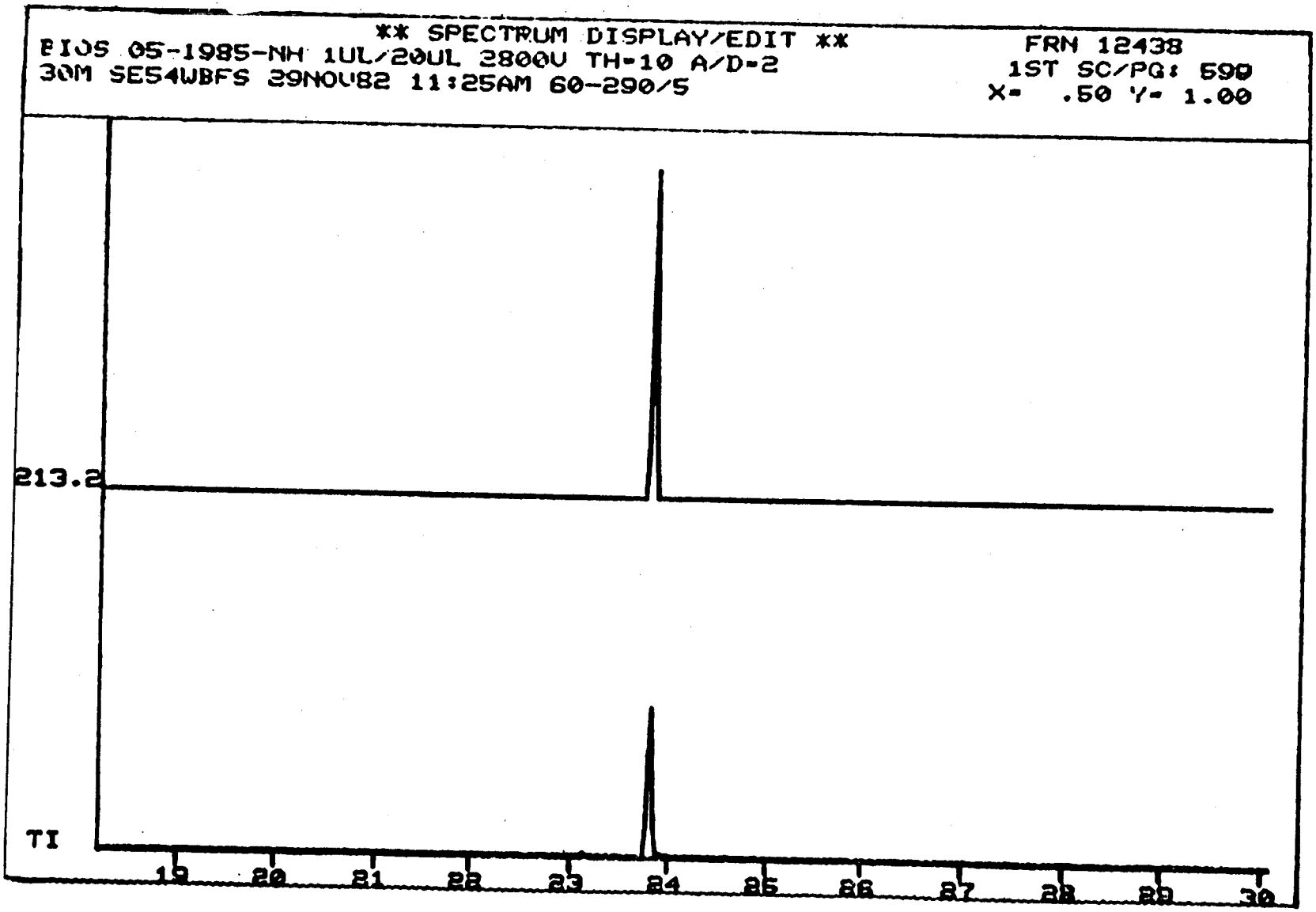
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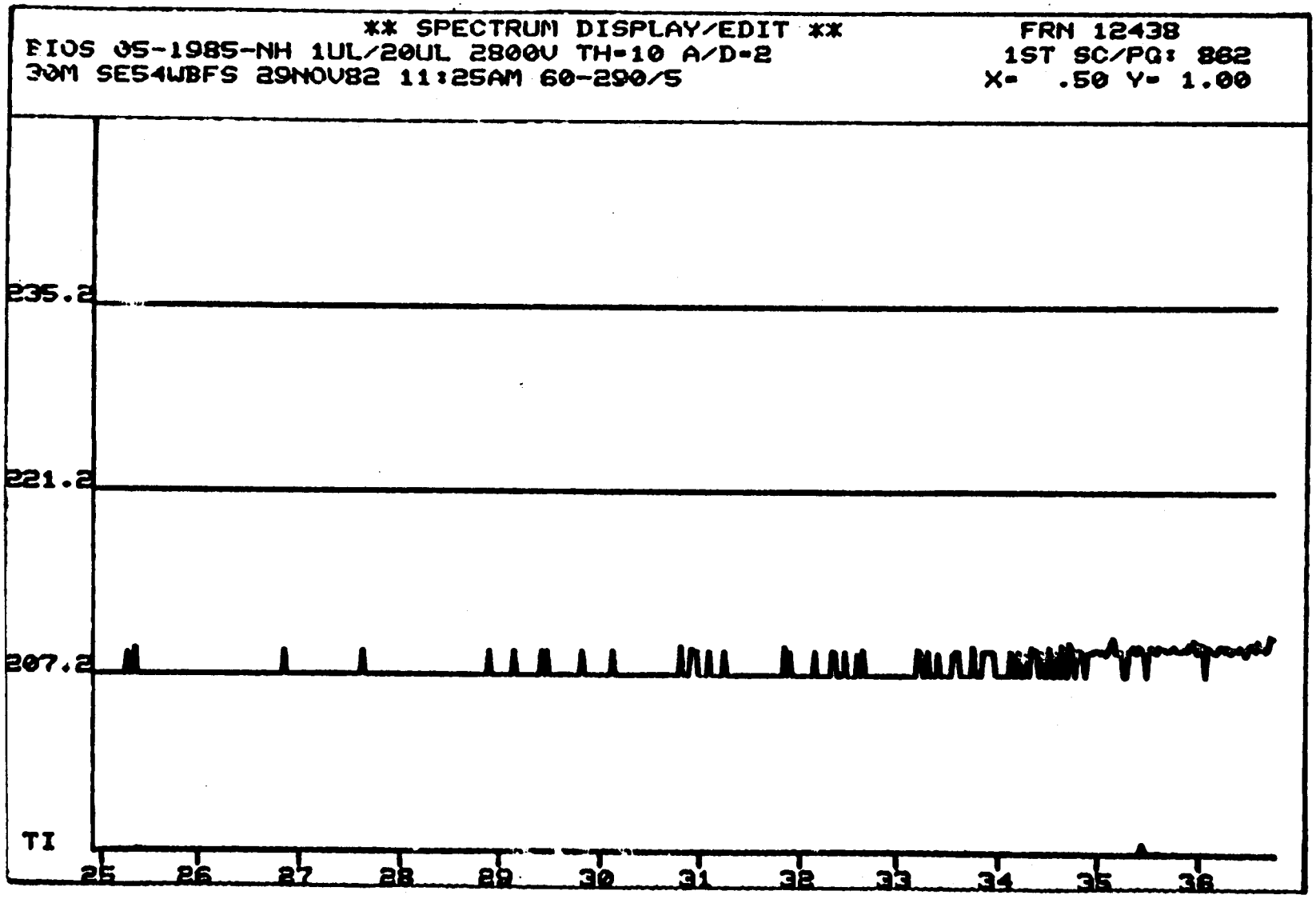
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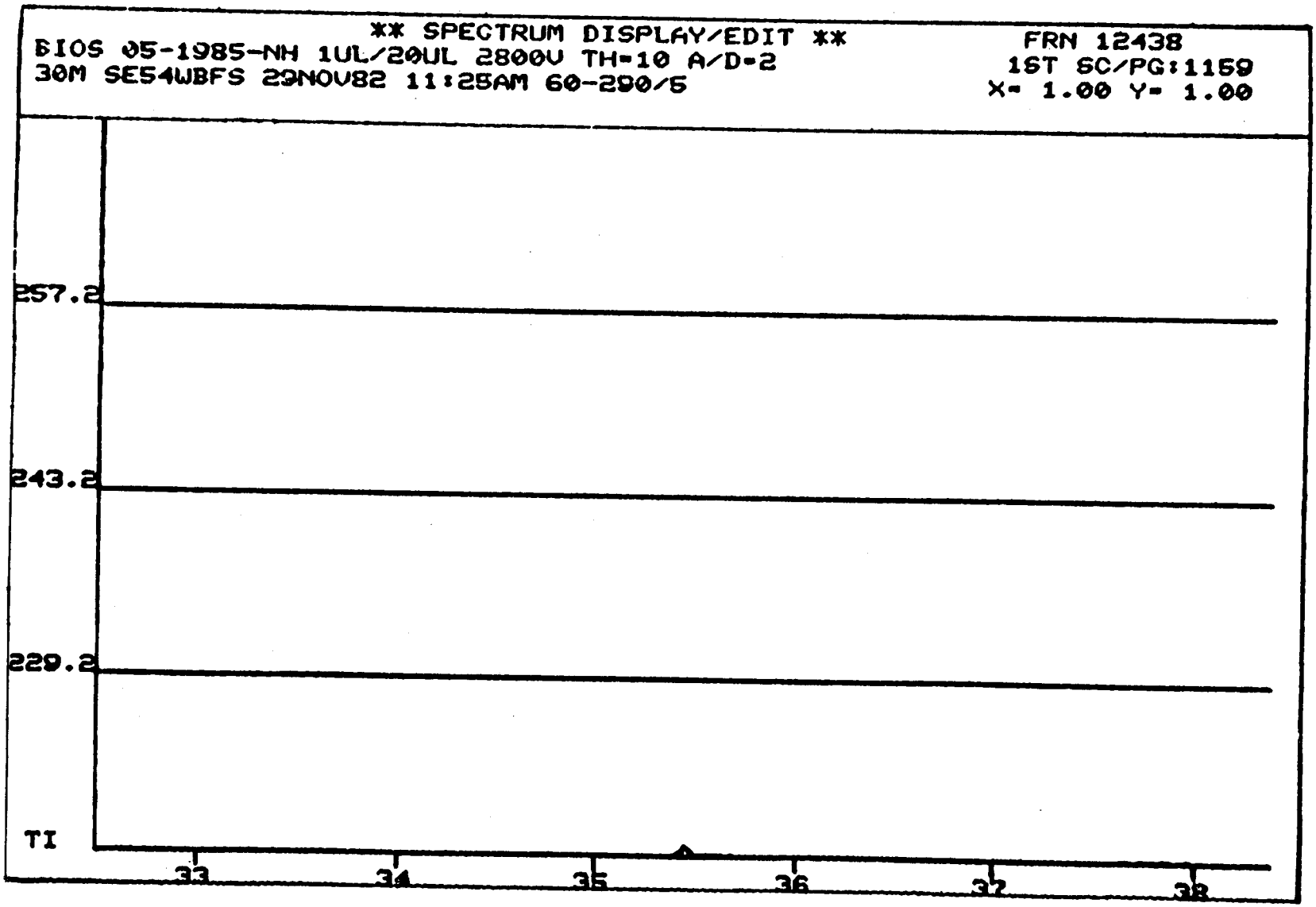
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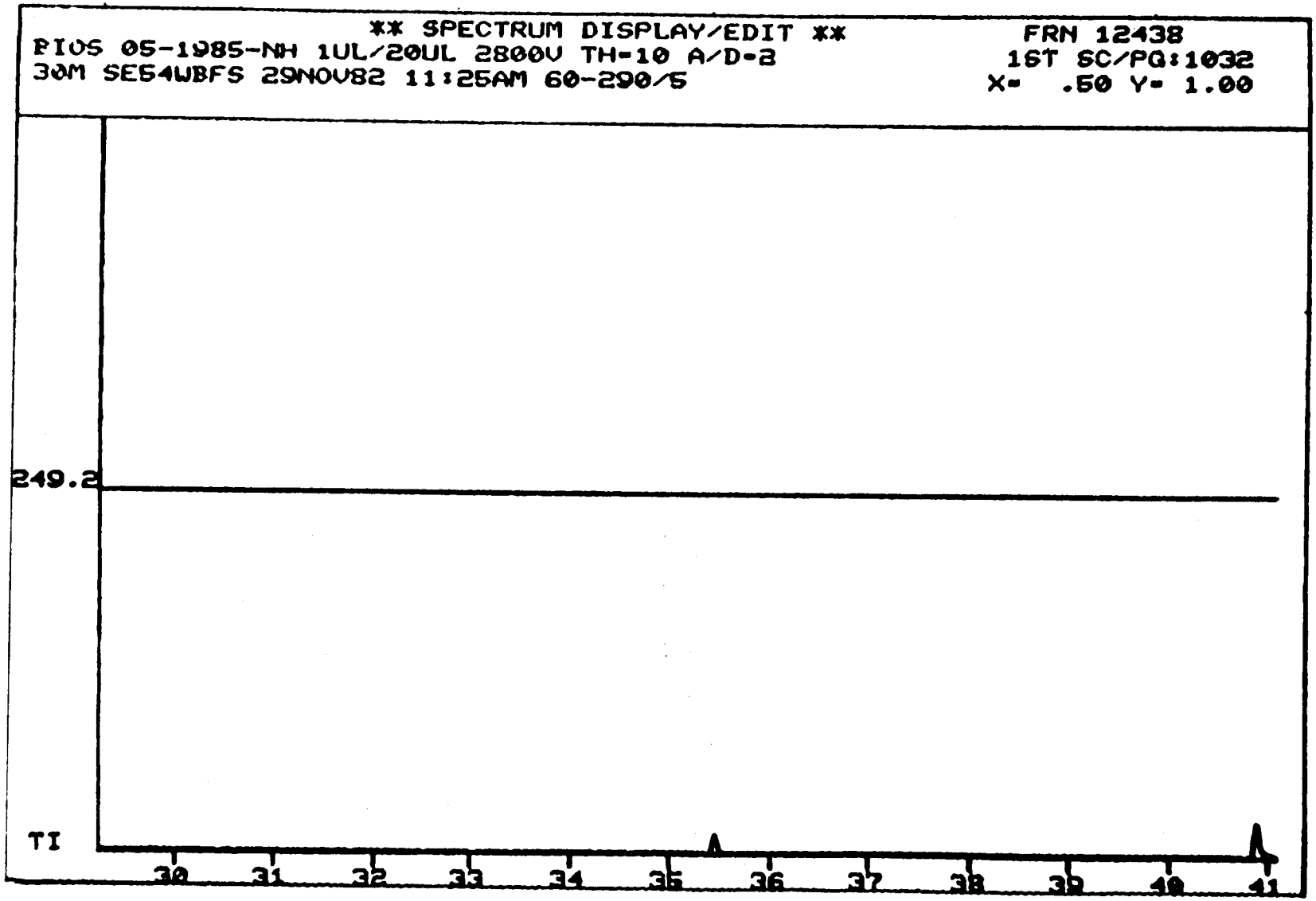
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FEEDING ECOLOGY OF JUVENILE KING AND TANNER CRAB IN THE SOUTHEASTERN BERING SEA

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ABSTRACT

To determine the food requirements of juvenile king and tanner crab and to assess potential impacts on the crab from Outer Continental Shelf oil and gas development, three cruises north of the Alaska Peninsula were conducted by NOAA vessels in June, August and October, 1982. Juvenile red king crab, Paralithodes camtschatica (CL >40 mm), were concentrated off Port Moller whereas juvenile tanner crab, Chionoecetes bairdi (CW <20 mm) were concentrated in the Amak Island-Black Hill Region. Juvenile tanner crab, C. opilio, were not found in the study area. Both the juvenile king and tanner crab, C. bairdi, were in deeper water in August 1982 (65 to 75 m) than in June 1982 (55 to 65 m). The smallest juvenile king crab (CL <30 mm) were found in shallow nearshore areas amongst cobble and rock with abundant epifauna.

Shipboard experiments showed that multi-compartmental exponential decay models described the evacuation of stomach contents in juvenile king crab. Stomach residence times calculated from these models varied with prey type from hours to days. Power laws described the relationships between carapace size and maximum stomach volume in both king and tanner crab.

In the diel feeding chronologies for juvenile king crab (CL = 53-80 mm) in June and August peaks in dry weight of stomach contents indicated two feeding periods, 0000 to 0800 h and 1300 to 1800 h. Using the diel feeding chronologies and a multi-compartmental exponential model for stomach evacuation, the daily rations of juvenile king crab were **calculated to be 6.30 and 11.92 mg dry weight per gram crab wet weight per day in June and August, respectively.**

Visual examination of stomach contents gave dietary composition by frequency of occurrence. Measuring dry weights of the hard parts of prey items and estimating soft tissue intake with appropriate ratios gave a measure of dietary composition by bulk that was converted to calories. Examination of stomach contents alone did not indicate relative importance in the diet because such examinations were biased in favor of prey items with long stomach residence times. After correction for gut residence times, molluscs and echinoderms, whose hard parts dominate stomach contents, became of lesser importance whereas soft bodied polychaete worms became the first-ranking dietary item. Four taxa (two polychaetes, a sand dollar, and a clam) accounted for 92% of the soft tissue dry weight in the overall diet.

The caloric intakes by juvenile king crab (CL = 53-80 mm) were 17.5 and 42.2 calories per gram crab wet weight per day in June and August, respectively. Two polychaetes, Pectinaria sp. and a sabellid, constituted over 50% of the caloric intake in June and August. The sand dollar, Echinarachnius parma, constituted 36% of the caloric intake in June but only 2% in August. Bivalves constituted 3% of the caloric intake in June but 25% in August. The major bivalve in the August diet was a small, thin-shelled clam, Tellina sp. Juvenile king crab appear to be predators of small, poorly motile benthic organisms living at or just beneath the sedimentary surface.

The immunoassay provided evidence that juvenile king crab, especially, the smallest juveniles (CL <30 mm), consume soft-bodied prey types overlooked by conventional analyses of stomach contents. In the smallest juvenile king crab the immunoassay detected polychaetes, oligochaetes and nematodes not detected visually and not observed either visually or immunologically in the stomachs of the larger juvenile crabs. The immunoassay required more refinement than expected to apply it to the analysis of crab stomachs.

Potential impacts from oil and gas development could derive from habitat disturbance and exposure to contaminants from platform discharges and oil spills. Because of the shallow nearshore distribution of the smallest juveniles, impacts from disturbance and platform discharges appear unlikely whereas impacts from oil spills need consideration. Because of the concentration of the larger juveniles off Port Moller in depths of 40 to 70 m, potential effects from disturbance and platform discharges need consideration whereas direct effects from oil spills seem unlikely. Chronic indirect effects could derive from loss or reduction in the food supply of juvenile king crab. An oil spill in the shallow nearshore zone can reasonably be expected to reduce the density of food important to juvenile crabs, but prediction of the extent of such restriction in the crab's food supply requires prediction of the salient features of such a spill. Based on findings with other crustaceans a restriction in food supply can be reasonably expected to retard growth in juvenile king crab if alternative food is not available or taken.

FEEDING ECOLOGY OF JUVENILE KING AND TANNER CRAB IN THE SOUTHEASTERN BERING SEA

INTRODUCTION

This project was initiated by NOAA's Outer Continental Shelf Environmental Assessment Program (OCSEAP) to determine how petroleum contaminants may reach and impact the commercially valuable crab resources of the southeastern Bering Sea. The main objectives of this project were, first, to determine the food requirements of juvenile red king crab, Paralithodes camtschatica, and tanner crab, Chionoecetes bairdi, in the waters north of the Alaska Peninsula and, secondly, to assess potential impacts from Outer Continental Shelf (OCS) development. The project entailed several tasks: the location and collection of crabs; shipboard experiments on stomach clearance rates; 24-h trawling to determine a diel feeding chronology and daily ration; determination of the carapace size - stomach volume relationships; visual examination of stomach contents; calculations of dietary composition; and construction of a caloric intake schedule. Due to grinding of food by the gastric mill, difficulties in identifying prey have confounded other food habits studies of king and tanner crab (Tarverdieva, 1976,1978), but here prey types ordinarily not detectable by traditional gut analysis were identified by an immunoassay of gut contents. This state-of-the-art technique and other techniques were used to assess and correct various biases not normally considered in conventional food habits studies determining the composition of crustacean diets.

This final report gives the diel feeding chronologies and daily rations of juvenile king crab in June and August of 1982. Also reported here is the species composition of the diet of juvenile king crab. Correction of dietary compostion for gut residence times indicated that soft bodied prey, especially polychaete worms, were a considerably greater proportion of the diet of juvenile king crab than conventional uncorrected analyses would indicate. The immunoassay of Feller et al. (1979) modified for the analysis of juvenile king crab stomachs gave evidence for the presence of soft bodied prey undetected by conventional gut analysis. Finally, this report synthesizes the information on the food requirements of juvenile king crab and assesses the potential impacts from OCS oil and gas development.

MATERIALS AND METHODS

CRUISE OPERATIONS

King and tanner crab were collected by trawl and SCUBA diving during three cruises in 1982 along the north Aleutian Shelf (Figures 1 to 3). The NOAA ship MILLER FREEMAN conducted the June and August cruises; the NOAA ship DISCOVERER conducted the October cruise. In June the study area extended from Cape Sarichef on Unimak Island to Cape Seniavin. In August this area was extended to Port Heiden. In June samples were collected from depths up to 70 m along 17 transect lines. In August and October collection efforts were concentrated in areas of high abundance suggested by the June catches. Station locations appear in Figures 1, 2, and 3.

To locate areas of high crab density for later intensive sampling, the search techniques included trawling, TV tows, diver sled tows, and boat-tended drift diving. To locate crabs in depths greater than 20 m, tows of 20 min with an underwater video camera and trawls of 10 min with an 18-foot try net were performed seaward of the 20-m isobath. Shoreward of the 20-m isobath diver sled tows and try net trawling were performed. To collect the smallest king crab and potential prey items, boat-tended drift diving with standard SCUBA was conducted from 1 to 20 m around Amak Island. Additional potential prey items for the immunoassay were taken from bottom grabs. Diving and bottom grabs also provided the large numbers of prey items needed for the clearance rate experiment. CTD casts provided depth profiles of temperature and salinity. Table 1 summarizes the ship operations.

Trawl catches were processed to estimate crab abundances and to obtain samples for several different shipboard and laboratory analyses. For each trawl total weight was measured, and the catch sorted for the crab species and potential prey items needed for the immunoassay. The dominant fish species and the presence of invertebrate species other than crab were noted. King and tanner crab were separated from the catch, counted and measured. Individual king crab were weighed to the nearest g, their carapace length (CL) and width (CW) measured to the nearest mm, and their shell condition qualitatively assessed. After measurement, ovigerous females were either given to Dr. David Armstrong of the University of Washington for further shipboard studies or returned to the sea. In cases where more than 10 king crabs occurred in a trawl, the crabs were flash frozen for later processing. For smaller trawls the crabs were measured

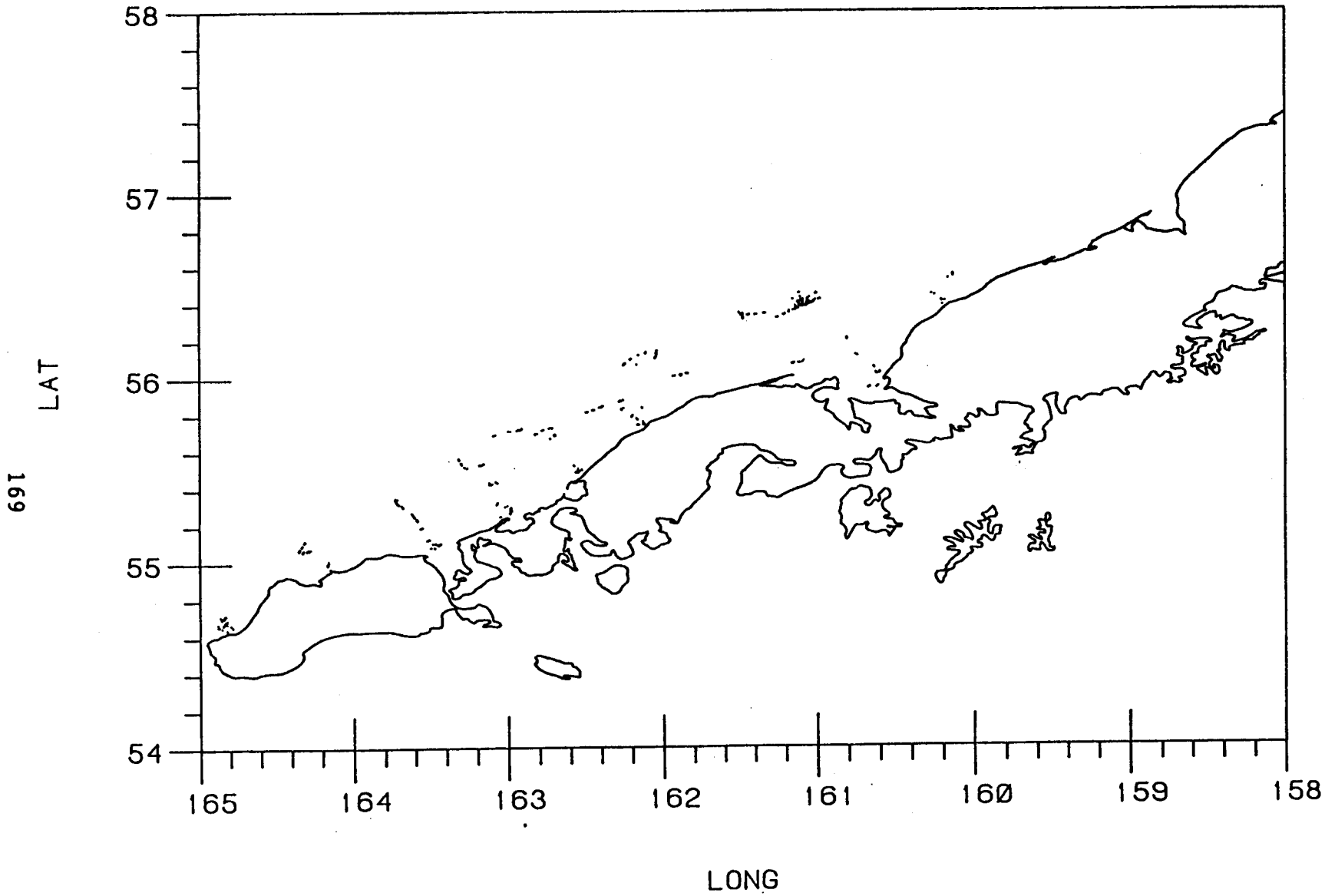


Figure 1.--Station locations during the June 1982 cruise. NOAA ship Miller Freeman.

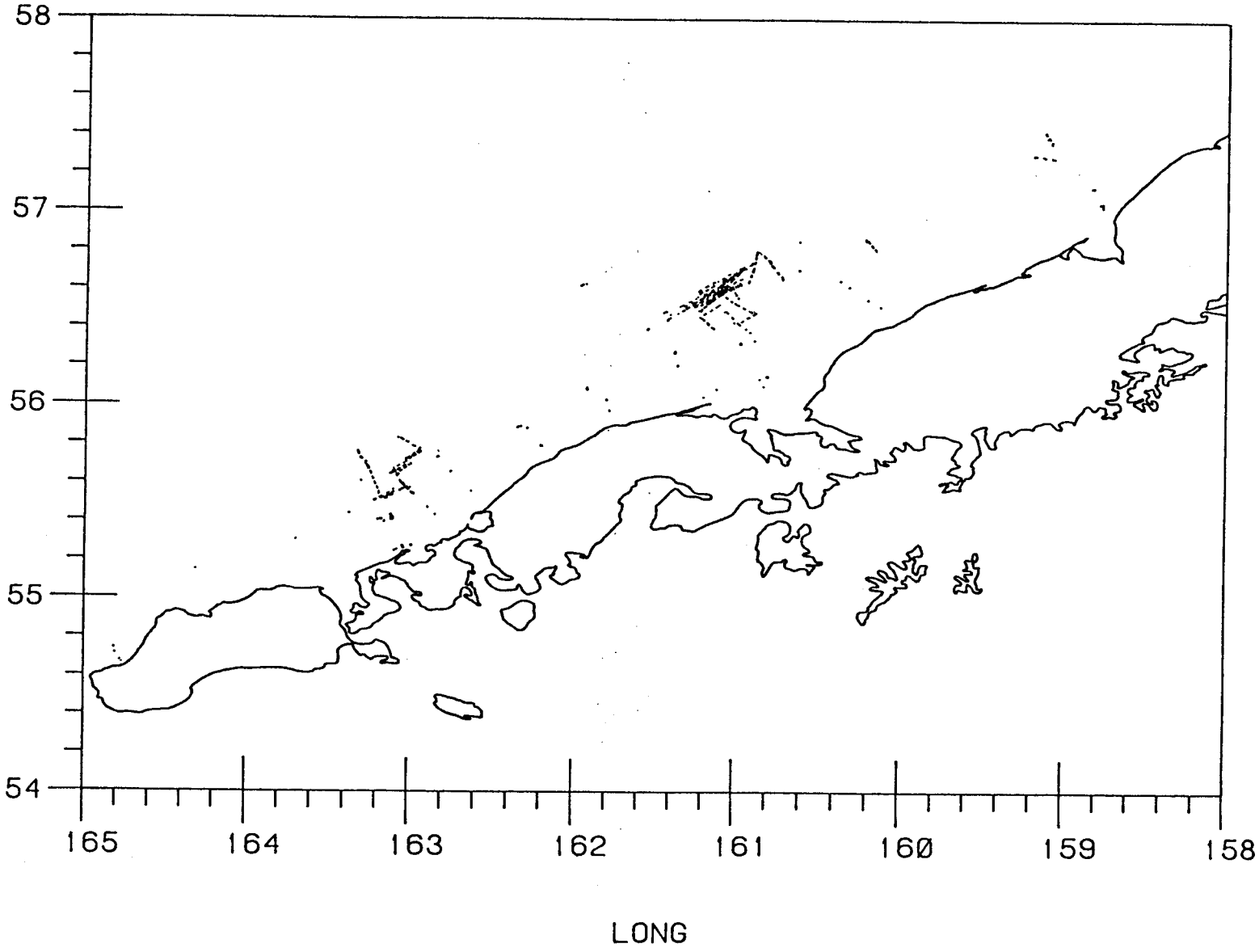


Figure 2.--Station locations during the August 1982 cruise. NOAA ship Miller Freeman.

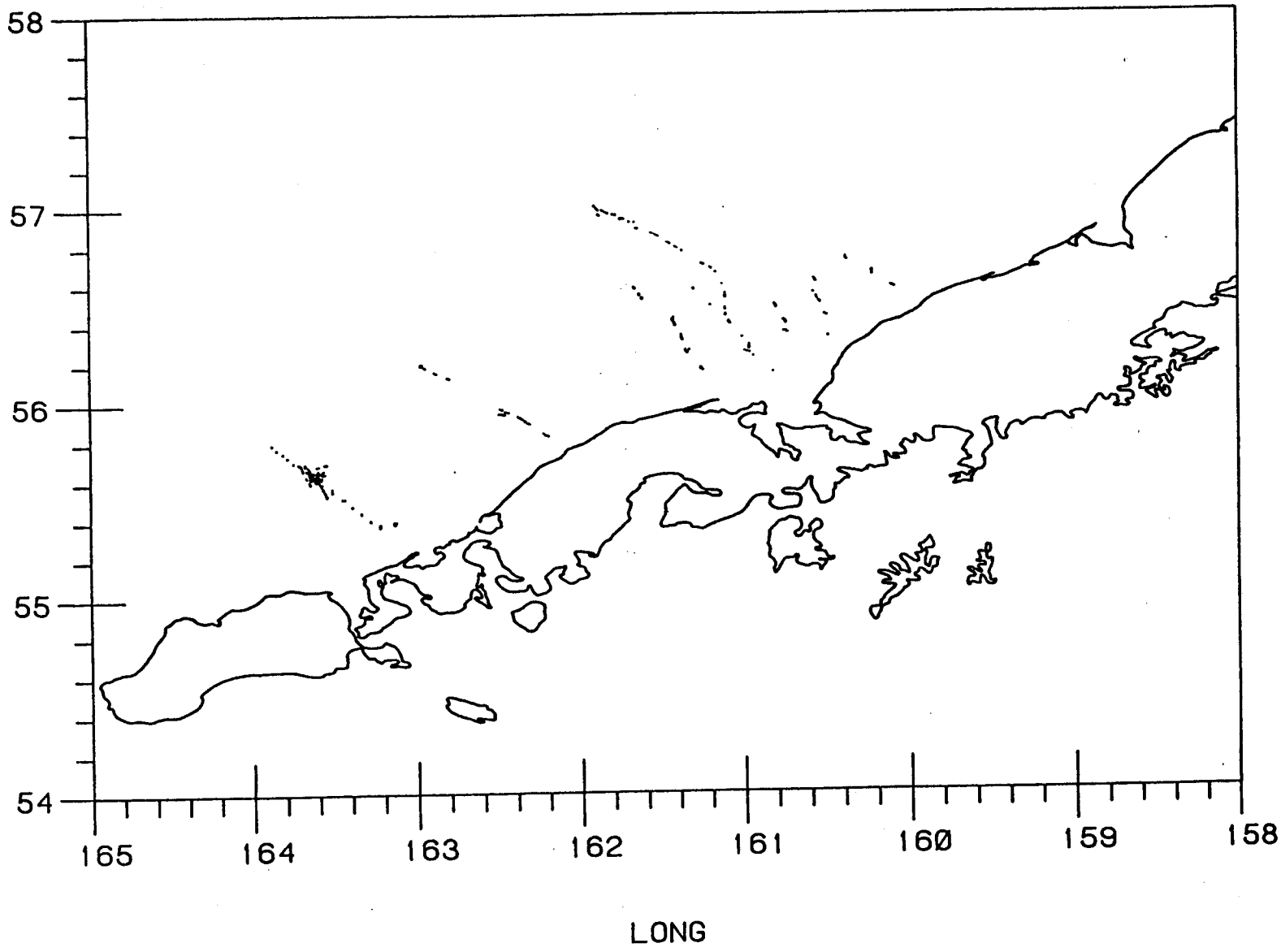


Figure 3. Station locations during the October 1982 cruise. NOAA ship Discoverer.

Table 1. Ship operations accomplished during NOAA/OCSEAP cruises RP-4-MF-82A, LEG I, June, 1982; RP-4-MF-82A, LEG III, August, 1982; RP-4-DI-82B-LEG 1A, October, 1982.

	Number per cruise		
Operation	Jun 82	Aug 82	Oct 82
Try net trawls	93	198	72
Diver sled tows	16	Ø	Ø
Drift dives (no sled)	8	19	5
TV tows	18 (8.3 h)	4 (3 h)	Ø
Grabs	20	35	18
CTD's	18	75	75

before freezing. From large catches on the June and August cruises, portions of juvenile king crabs caught were measured and then maintained in live tanks for shipboard experiments. Because of their extremely small size (CW <20 mm) most tanner crab, C. bairdi, were not measured individually but were counted and weighed as a batch before freezing.

In 1983 juvenile king crab (CL <30 mm) were collected and frozen for Battelle during the NOAA/OCSEAP North Aleutian Shelf cruises. These crab were used in determining dietary composition by visual examination and in the immunoassay. During May, 1983, additional potential prey items were collected near the Pribilof Islands and prepared for the immunoassay.

CARAPACE SIZE/MAXIMUM STOMACH VOLUME RELATIONSHIP

Equations relating the carapace size to the stomach volume were developed for king and tanner crab, C. bairdi, after Hill (1976). These equations were necessary to calculate stomach fullness by volume in later analyses. Before dissection of individual crabs, measurements of wet weight, sex, carapace length, carapace width, and shell condition were made as required for OCSEAP-specified NODC digital data files. After these measurements, the carapace of a thawed crab was carefully dissected from its body. The muscle and other tissue were removed from the outside of the stomach, and the stomach ligatured first at the oesophagus and secondly between the foregut and the midgut posterior to the filter chamber. After cutting of the oesophagus and intestinal tract, the ligatured stomach with its contents was removed. In a graduate cylinder the volume displaced by the stomach with its contents was measured to the nearest 0.5 ml (0.1 ml for smaller stomachs). With a syringe clean seawater was injected into the stomach through the cut end of the filter chamber until the stomach wall became smooth and taut and water began to leak along the syringe. The displacement volume of the stomach with its contents plus injected water was then measured. After opening the stomach and washing the contents into formalin, the displacement volume of the stomach wall alone was measured. The maximum stomach volume, V_{max}, was calculated by subtracting the volume of the stomach wall alone, V_s, from the volume of the stomach with contents and injected water, $V_{s,c,w}$, i.e.,

$$V_{max} = V_{s,c,w} - V_s.$$

Regression analysis was used to relate carapace size to the maximum stomach volume. As a measure of carapace size, carapace length was used for king crab and carapace width for tanner crab.

STOMACH CLEARANCE RATES

Stomach clearance rates for juvenile king crab were determined for several prey types. To determine how quickly the quantity of contents naturally-present in the stomach decreased, juvenile king crabs from large catches in June and August were used. A portion of these large catches were frozen immediately, and the rest held without food in a live tank at ambient seawater temperature (8-9 C). During holding in June, the live tank was periodically siphoned to remove feces and regurgitated shell. In August, the crabs were held in baskets that separated the crabs from any regurgitated or defecated material. At selected time intervals after capture, subsamples of the captive crabs were removed from the live tank and frozen. Later the volume and dryweight of the gut contents of these crabs were determined.

The volume of stomach contents was determined by subtracting the displacement volume of the stomach wall alone, V_s, from that of the intact, ligatured stomach with its contents, $V_{s,c}$. Dividing the resulting volume by the maximum stomach volume, V_{max}, and multiplying by 100, gave the percentage stomach fullness, F, by volume. Thus,

$$F = \frac{V_{s,c} - V_s}{V_{max}} 100.$$

For June samples determination of clearance rates by plotting percentage stomach fullness against time was confounded by the large volumes of clear liquid that still occurred in stomachs after solid material disappeared, and to avoid this confounding the dry weight of the stomach contents and the volume of the solid material alone were determined. After determining sex, wet weight, and carapace length, of thawed crabs from August, the stomachs and their contents were transferred to graduated and tared centrifuge tubes. After 1 h of settling, the total volume of liquid and solids and the volume of solids alone were recorded. Settling for 16 h did not change the volume noted after 1 h. After noting the volumes and the occurrence of sand, floc, soft tissue, or hard parts, the stomach contents were dried at 60 C to constant weight. The

percentage of the maximum stomach volume occupied by solid material was calculated, and the dry weight standardized by dividing it by the crab's wet weight. The stomach contents preserved in June were similiarly reanalyzed, except that the addition of preservative precluded measurement of total volume including the liquid.

To determine stomach clearance rates for specific prey items, crabs from large trawls in August were held without food in the ship's live tank. Seven days after isolation examination of the stomachs of 5 crabs confirmed that all were empty except for liquid and that crabs held at least 7 days could be used in the experiment. After 7-12 days without food crabs were removed and their sex, wet weight, carapace length and width, and shell condition determined. Individual juvenile king crab were tagged and placed into individual containers with seawater to be given a specific prey item. Individual crabs were presented with one of the following: pandalid shrimp, juvenile gadid fish (2-3 cm), barnacles (Balanus sp), small mussels (Mytilus edulis, <2 cm long), shucked and diced clam (Spisula polynyma: siphon, foot, and adductor), tube worms (Sabellidae), and snails. With the exception of the mussels these or similar prey types had been identified in crab stomachs in June. Whole mussels were used in place of the small clams, e.g., Tellina sp, which were preferred but not obtained in sufficient number during the survey.

The protocol was as follows: During daylight a tagged and measured crab was transferred from isolation to an individual container with seawater. After 0.5 h of acclimation, a known number and volume of a specific prey item were added. The containers were examined every 10 to 15 min. If a crab had eaten more than half the food, the crab was removed and it was determined by formal randomization whether to freeze the crab immediately or transfer it to isolation for a prespecified time interval. Any crabs that had not eaten within 1.5 h after food introduction did not enter the analysis for that food. After removing a crab, the remaining food was recovered and its volume measured to confirm that the crab had, indeed, ingested the food.

The live tank had flowing seawater at 0.0 to 0.3 C above ambient sea surface temperature (8-9 C). After 1.5 h, seawater in the static feeding containers rose less than 0.9 C. The bottom temperature at capture varied between 5 and 6 C.

In the laboratory, the stomachs from thawed crabs were removed and the contents transferred to graduated and tared centrifuge tubes. As described above the total volume of liquid and solids and that of solids alone were determined before drying the contents to constant weight.

SHIPBOARD OBSERVATIONS OF FEEDING BEHAVIOR

On shipboard the feeding behavior of juvenile king crab was observed during the clearance rate experiment and later filmed in a large glass-fronted aquarium with flowing ambient seawater. Special note was taken of how crabs handled prey items during ingestion.

DIEL FEEDING CHRONOLOGY

In areas of high crab density continuous trawling from 23 to 72 hours was conducted to collect crabs for determination of diel feeding chronologies. Generally, two or three trawls took place within 2 h, and the samples taken within each 2-h period of the 24-h cycle were pooled.

Stomach fullness determined as described above was plotted against time of day and the plot examined for periods of high fullness. Because this method proved inadequate due to high volumes of liquid in otherwise empty stomachs, preserved and frozen stomachs were analyzed as decribed above to obtain the percentage of maximum stomach volume occupied by solids and dry weight of stomach contents standardized by the wet weight of the crab. Plots of these two variables against time of day were examined for periods of high stomach contents.

DAILY RATION

Using the diel feeding chronologies and equations for the clearance rates of all items naturally present in the king crab stomachs, daily rations for June and August were calculated following a modification of the technique of Elliott and Persson (1978). The diel feeding chronologies gave the dry weight (mg/g crab wet weight) of stomach contents for each 2 h period of the 24 h cycle. To determine the amount of food consumed during each 2-hour interval, the following equation from Elliott and Persson (1978) was used.

$$C_t = S_t - S_o + A$$

where t = midpoint of the 2-h interval,

C_t = amount of food consumed,
S_o = amount of food at the beginning of the interval,
S_t = amount of food at the end,
and A = the amount of food evacuated from the stomach during the interval.

The amount evacuated is given by the following equation:

$$A = 1/2 (S_o + S_t) - S_r,$$

where $S_r = 1/2 (S_o + S_t) e^{-Rt}$
R = the decay constant
and t = 2 h.

Values for S_o and S_t were taken from the dry weight data in the diel feeding chronologies, and A was calculated using the multi-compartmental clearance rate equation given in Table 2 in place of the term, e^{-Rt}, used by Elliott and Persson (1978). By summing the twelve C_t values for each 2-hour period of the day the daily ration was calculated. Later the daily ration was converted to caloric equivalents using the dietary composition data and caloric values of prey items.

DIETARY COMPOSITION

The Frequency of Newly Discovered Prey as a Function of the Number of Stomachs Examined

To determine the optimal number of stomachs to examine in detail for dietary composition, 25 stomachs were examined from one station with a large catch of 192 juvenile king crabs. Following Vesin et al. (1981) the number of newly discovered prey items was plotted against the number of additional stomachs examined.

Dietary composition from Visual Examination of Stomach Contents

Stations for the examination of stomach contents of juvenile king crab (CL = 53–80 mm) were chosen by two criteria. First, the stations were occupied at or near a feeding peak evidenced in the diel feeding chronology. Secondly, the number of crabs at the stations approached the optimal number determined from above. Most juvenile crabs visually

Table 2. Clearance rates for all items naturally present in the stomachs of juvenile king crab. V = proportion of the initial value for the volume of solids as a percentage of maximum stomach volume. This average initial value of solids volume was 23.1 (± 2.4 SD) %. W = proportion of the initial value for the gram dry weight of stomach contents per gram crab wet weight. The average initial value for the dry weight was 2.91 (± 1.51) mg dry weight/g crab wet weight. T = time in hours after isolation. $\bar{T}$ = mean life, the reciprocal of the decay constant.

Basis	No. of time intervals	Equation	R^2	$\bar{T}$ in the compartments	Time (h) to 10% of initial	Time (h) to 5% of initial
Volume	14	$V=0.191e^{-1.190T}+0.856e^{-0.0930T}$	87.9	0.84 10.8	23.2	30.6
Dry weight	18	$W=0.287e^{-1.134T}+0.551e^{-0.148T}+0.226e^{-0.0217T}$	93.1	0.88 6.8 46.1	38.0	69.5

examined entered the dry weight analysis discussed below, and in some cases also entered the immunoassay. Thus, for larger juveniles both visual and immunological analyses were performed on the same stomachs. The smallest juvenile king crab (CL <30 mm) from both 1982 and 1983 were randomly assigned either to visual examination or to the immunoassay because the stomach volumes of the smallest juveniles proved too small for both analyses to be done on the same stomach.

Stomach contents were examined under a dissecting scope, sorted, and the prey items identified to the lowest taxa possible. For stomachs entering dry weight analyses all items were sorted and added to a pooled sample in a tared vial for drying to constant weight. Because of grinding by the crab's gastric mill, counting the number of prey items proved impossible.

The percentage frequency of occurrence was calculated by dividing the number of stomachs in which a prey item was observed by the number of stomachs examined and multiplying by 100. Another measurement of dietary importance calculated was the percentage of all occurrences for each prey item, i.e., the number of occurrences of a prey item divided by the total number of all occurrences of all prey items multiplied by 100.

To correct estimates of dietary composition for overestimation of the importance of items with hard tissue and, therefore, long gut residence times, the percentage of all observed occurrences were corrected following Peterson and Bradley (1978). Estimates of gut residence time came from the shipboard clearance rate experiments. Residence times for items not determined experimentally were estimated by their similarity to those so determined. From the number of stomachs containing floc during the clearance rate experiments, the residence time for floc was found to be 90 h. To correct for gut residence times, the percentage of all occurrences of each item was divided by its gut residence time to determine the relative dietary proportion. Summing the relative proportions and then dividing individual relative proportions for each item by the resulting sum gave the corrected proportion of the diet each item represents. In calculating the percentage of diet totals that both included and excluded floc and sand were used.

Dietary Composition from Dry Weights of Prey Items

Because dry weights are the appropriate measure of bulk for conversion to caloric intake (Hyslop, 1980), the percentage of the diet of juvenile king crab contributed by each prey item was determined by dry weight of each prey item. From the stomachs visually examined above, prey items were sorted into tared vials for drying at 60 C to constant weight. To

obtain sufficient weights all the stomachs at a station were pooled into one sample. Dividing the dry weights of individual prey items by the total dry weight of all items and multiplying by 100 gave dietary composition as a percentage of total dry weight. Because floc and sand proved a substantial proportion of the dry weight, calculations were done both including and excluding floc and sand.

CALORIC INTAKE

To determine caloric intake the dry weights for each item needed to be converted to caloric equivalents. However, simple conversion of dry weights of stomach contents to calories was not possible without an estimate of the intake of soft tissue. Caloric values are determined on the soft tissue of marine invertebrates after the shell or other hard parts have been removed. Because the dry weights of prey items were determined almost exclusively by weighing hard tissue, such as shell, estimating the dry weight of soft tissue ingested from the dry weights of hard parts was necessary before conversion to calories was possible. For a number of potential prey items collected from the Bering Sea, the soft tissue was separated from the hard tissue, and both dried at 60 C in tared containers to constant weight. Soft tissue/hard tissue conversion factors were calculated by dividing the dry weight of the soft tissue by the dry weight of the hard tissue. Conversion factors for prey items not determined experimentally were estimated by their similarity to those items for which data exists. Floc was assumed to be essentially soft tissue and assigned a soft tissue/hard tissue ratio of 1.000.

To obtain dietary composition on the basis of soft tissue dry weights, the dry weight for each prey item was multiplied by its soft tissue/hard tissue ratio, the resulting soft tissue dry weights summed to obtain a total, and the percentage of the diet calculated based on that total. Correction for gut residence time followed the same procedure described above for dietary composition as percentage of all occurrences.

To obtain the energetic contribution to the diet made by each prey item, the corrected percentage of diet on the basis of total soft tissue dry weight was multiplied by the daily ration (mg/g crab wet weight) to yield the soft tissue dry weight for each item. Then these soft tissue dry weights were multiplied by the caloric values (calories/mg dry weight) to obtain the calories ingested from each prey item. Caloric values came either from the literature or from new determinations done on specimens collected from the Bering Sea. These new determinations of caloric value were done by standard bomb calorimetry with benzoic acid standards at

Battelle's Pacific Northwest Division in Richland, Washington.

After multiplication of the soft tissue dry weights by the caloric values, summing the caloric intakes for all items gave the daily ration in calories per g crab wet weight per day. The percentage of this total caloric intake that each item contributed was then calculated.

IMMUNOASSAY

Because the grinding of the crab's food by the gastric mill (Warner, 1977) renders prey unidentifiable, visual examination of gut contents suffers bias. To identify prey entirely missed by conventional analysis, immunological examination of gut contents modified from Feller et al (1979) was performed. Briefly, probable macro and meiofaunal prey items were collected as described above. On shipboard these organisms were isolated in seawater filtered to 45 microns. After up to 7 days to clear their stomachs of foreign protein the isolated organisms were flash frozen. In the laboratory, whole organism extracts were prepared by grinding frozen prey in a chilled buffer solution. Protein concentrations in the extracts were determined spectrophotometrically against albumin standards. Following standard protocols (Kenny, 1971) extracts of known protein concentration were injected into rabbits to produce antisera of varying specificity.

To determine self and cross reactions and reactions between the antisera and gut contents, standard Ouchterlony (double immuno diffusion precipitin) tests were performed. In this test the antigen and the antisera were allowed to diffuse towards each other through a supporting medium of 0.5 percent agarose gel on glass microscope slides for 48 hours. When a soluble antigen (prey organism extract or stomach contents) reacted with its specific antibody (antisera to prey organisms), a precipitate was formed where they met in optimal proportions. The opaque precipitin lines were then stained with Coomassie Brilliant Blue R and counted. Based on the number of precipitin reaction lines encountered, a matrix table of self and cross reactions was developed similar to Feller's.

RESULTS

LOCATION AND COLLECTION OF JUVENILE CRABS

Juvenile king and tanner crabs varied in their spatial and temporal distribution. In June, August, and October, no juveniles of the tanner crab, C. opilio, and only minimal numbers of adults were captured. In June trawling produced only 56 adult C. opilio, 50 of which occurred in one trawl at the extreme western end of the study area near Unimak Pass. The study area apparently does not contain juvenile C. opilio, and the tanner crab mentioned in the rest of this report are C. bairdi.

Juvenile tanner crab, C. bairdi (CW <20 mm), were most abundant near Amak Island at depths of 55–65 m in June, 65–75 m in August, and over 80 m in October. Over 2000 of C. bairdi were less than 20 mm CW whereas less than 50 were greater than 20 mm CW.

Juvenile king crab were concentrated off Port Moller and Cape Seniavin. In June, August, and October only adult king crab occurred west of Nelson Lagoon. Off Port Moller, juvenile king crab were deeper in August (65 to 75 m) than in June (55 to 65 m). In contrast to the hundreds of juvenile king crab taken off Port Moller in June and August, only one juvenile king crab was taken in October.

Diver sled tows covered the areas shoreward of 20 m in June, but divers sighted no pods or solitary king crab or tanner crab. The high-energy sandy nearshore areas along the north side of the Alaska Peninsula do not appear to offer good habitat for juvenile crab. Among boulders divers did find 4 juvenile king crab (CL <20 mm) at approximately 18 m near Amak Island.

TV tows off Cape Seniavin and Port Moller revealed that juvenile king crab occurred on sandy bottoms where large numbers of ascidians and sponges were growing on the large tubes of polychaete worms. The crabs were not aggregated or podded, but solitary. All TV tows occurred during daylight. Because this survey was not specifically designed to compare TV

tows and trawling as techniques for assessing distribution and abundance, little can be said concerning the relative effectiveness of the two techniques in determining distribution. Clearly, the TV tows were most valuable in giving a visual record for characterizing the habitat of the juvenile king crab and should be considered capable of providing information not obtainable from trawling.

Most of the juvenile king crab collected were between 50 and 80 mm CL. King crab less than 20 mm CL were collected by divers or trawls in rocky areas off Nelson Lagoon and near Amak Island. Trawls in these rocky areas tore the nets, and the small juveniles were picked off the torn netting. Of king crab less than 20 mm CL one was taken in June; eight, in August; and one, in October. Two additional king crabs collected were between 20 and 40 mm CL; the remaining king crab were above 48 mm CL. During 1983 other NOAA/OCSEAP investigators collected and froze 63 specimens of juvenile king crab (CL = 5-29 mm) for use in the immunoassay.

The lack of juvenile king crab off Port Moller in October was unexpected but may have been related to oceanographic events. In October warm water (>7 C) extended to the 75-m isobath due to storms with west winds in September. The crabs may have moved in response to the extension of the warm water mass. The smaller shifts of juvenile king and tanner crab from 55-65 m in June to 65-75 m in August may also have been due to seaward extension of the frontal zone in August. A more systematic effort would be necessary to demonstrate that the juvenile crabs migrate seaward and shoreward before the frontal zone of the coastal water mass located approximately at the 50-m isobath.

CARAPACE SIZE - MAXIMUM STOMACH VOLUME RELATIONSHIP

In June, 262 of the 319 king crabs (CL = 33-129 mm) that were dissected had intact stomachs and were used in the regression analysis. The following power function proved to relate the maximum stomach volume, V (ml), to the carapace length, L (mm):

$$V = 2.22 \times 10^{-5} L^{2.87}$$

$$\text{or } \ln V = -10.716 + 2.87 \ln L.$$

The R-squared was 76.6%. Equations for the separate sexes did not differ significantly so that data from both sexes were pooled to produce the above equation. Shell condition also did not prove to be a significant variable.

For tanner crab, C. bairdi, the following power function related maximum stomach volume, V (ml), to carapace width, W (mm):

$$V = 2.68 \times 10^{-5} W^{2.69}$$

$$\text{or } \ln V = -10.527 + 2.69 \ln W.$$

Ninety-two out of 133 tanner crabs (CW = 27-153 mm) were successfully dissected and entered the analysis. The R-squared was 79.8%.

These equations differ substantially in mathematical form from that given by Cummingham (1969) and cited and used by Jewett and Feder (1982) for adult king crab. The equation appearing in Jewett and Feder (1982) has a typographical error and is really a second order quadratic. Thus, Jewett and Feder's equation is only a good fit over a specific size range, and for king crabs below 70 mm CL actually gives increasing stomach volumes for decreasing carapace lengths. Most allometric relationships in crustaceans are power functions so that it was not surprising that regression analysis confirmed a power function relating carapace size and stomach volume. The power functions presented here are more appropriate models than the quadratic best fit model given by Cummingham (1969) and used by Jewett and Feder (1982).

The above equations were used to calculate the maximum stomach volume from the carapace size of crabs measured in the laboratory. The maximum stomach volume was then used in calculations of percentage stomach fullness and other statistics.

STOMACH CLEARANCE RATES

Clearance Rate for all Items Naturally Present

To obtain a decay curve describing the passage of food from the gut, 85 juvenile king crab, 61.3 (± 6.6 SD) mm CL, were kept in June without food in ship's live tank and sacrificed at intervals of T = 0, 1, 2, 4, 8, 12, 16, 24, 40, 72, and 121 h. In August 58 juvenile king crabs, 64.3 (±8.1) mm CL, were sacrificed at T = 0, 8, 12, 24, and 48 h. Stomach fullness as a percentage of the maximum stomach volume was determined for the June samples using the total volume of the gut and its contents.

Stomach fullness plotted against time after isolation proved not to describe adequately the passage of solid material from the gut because large amounts of liquid were still present in otherwise empty stomachs. In fact, the volume of liquid actually increased with time after isolation (Table 3), and otherwise empty stomachs contained enough liquid to maintain 25 to 30% stomach fullness after 130 h. The liquid was clear to light brown and without floc or the cloudiness indicating fine particulate matter. Apparently the crab maintains a minimum level of digestive fluid in its gut. To avoid confounding the determination of clearance rates by this liquid, the volume of solid material in the stomach and the dry weight of the stomach contents were determined.

Both the volume of solids and the dry weight of stomach contents fell exponentially with time after isolation (Figure 4, Table 2). A two-compartmental model described the decrease in the volume of solids and a three-compartmental model, the loss of dry weight (Table 2). The exponential decay curves were used later to calculate daily ration following Elliott and Persson (1978). Dry weight of stomach contents proved to be a better measure of stomach clearance rates than volume.

Evidence for several compartments rather than one in the exponential decay curves comes from two sources: information concerning variation in gut residence times of different materials (Hill, 1976; Carter and Steele, 1982) and graphical analysis of the data here. Whereas many models of stomach clearance assume a one-compartmental exponential decay curve, it is not reasonable to accept the implication of a one-compartmental model that all the materials in the stomach are digested and passed out at the same rate. Hill (1976) and Carter and Steele (1982) reported that in the stomachs of crabs and lobsters soft tissue is lost in hours while hard parts from bivalves and echinoderms remain for days. Thus knowing that clearance rates do vary among different tissues, it is reasonable to expect that a decay curve describing the passage of a mixture of materials from the stomach would be the outcome of different clearance rates acting on different materials initially present in different proportions. The king crab stomachs examined for this analysis contained floc, sand, soft tissue, shell fragments from small bivalves and gastropods, and sand dollar tests. Finding multi-compartmental exponential models for stomach clearance meets this reasonable expectation.

Graphical analysis indicated the number of compartments in the specific decay curves. If the appropriate model for the exponential decay had only one compartment, then plotting natural logarithm of the dependent variable, e.g., the dry weight, against time would give a straight line. For a two-compartmental model such a plot would show a straight line

Table 3. Stomach fullness as a function of time after isolation. Stomach fullness is expressed as the percentage of maximum stomach volume occupied by the total or liquid portion of stomach contents.

Time after isolation (h)	Stomach fullness by volume %	
	Total contents	Liquid contents
Ø	48.3	30.1
8	30.9	22.0
12	23.7	16.2
24	24.9	24.4
48	28.3	28.3

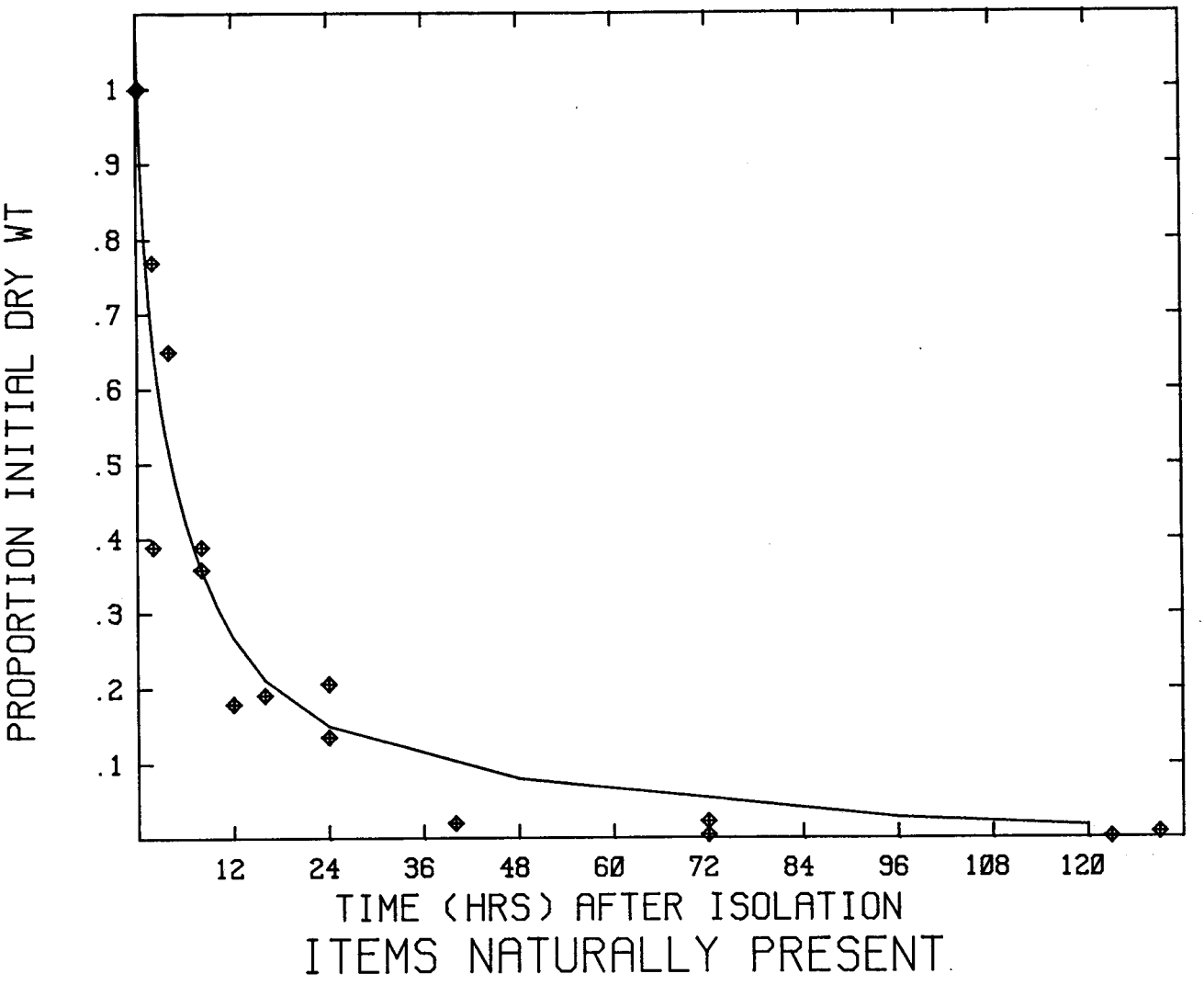


Figure 4. Decay curve for the clearance of all items naturally present in the stomachs of juvenile king crab. The proportion of the initial value for grams dry weight of stomach contents per grams crab wet weight vs. the time in hours after isolation.

falling to an inflection point where another straight line of shallower slope would continue. Similarly, for a three-compartmental model the plot would show three straight lines meeting at two inflection points. For clearance rates of all items naturally present and of specific prey items such plots were used to indicate the appropriate number of compartments and to estimate starting values for a reiterative curve fitting program. The FIT program developed by Battelle Pacific Northwest Laboratories was then used to evaluate the parameters of multi-compartmental exponential decay curves.

Beyond 48 h the volume of solids had fallen below the minimum measurable volume (0.1 ml). If smaller volumes could have been measured, a three-compartmental exponential model might also have described the volume decay curve. In contrast to volume, the dry weight of stomach contents did not fall below the minimum measurable amount. The coefficient and decay constant for the first compartment in the volume curve agree well with those in the dry weight curve. Also, the parameters of the second compartment in the volume curve approximate a combination of the parameters of the second and third compartments of the dry weight curve. Given this agreement, dry weight of stomach contents is the better basis for determining clearance rates than volume on two counts: the better measurements for dry weight than solids volume with extremely low stomach contents and the better fit of the dry weight curve. Similarly, dry weight also proved a better measure for determining clearance rates for specific prey items and the diel feeding chronology described in the next sections.

The parameters of the exponential model have definite biological meaning. The decay constants and their reciprocals, the mean life, indicate how long material remains in a given compartment. Thus from Table 2, material remains in the first compartment less than 1 h; in the second compartment, about 7 h; in the third, 46 h. The coefficients also can be interpreted. Because the dry weight is expressed as a proportion of the standardized dry weight initially present, $W = 1.000$ at $T = 0$ by definition. Note that the coefficients of the three compartments in Table 2 sum to 1.064. The coefficients represent the proportion of total dry weight that is in each compartment at $T = 0$. There are three possible biological interpretations of the coefficients. Under the first interpretation, the coefficients represent the proportions at $T = 0$ of different classes of material (either tissue types, e.g., soft tissue, hard tissue, or prey types, e.g., worms, crustaceans, molluscs). Under this first interpretation then soft tissue would be assigned to the first compartment. Soft tissue would have been slightly less than 30% of the original material and have essentially disappeared after 0.9 h, the mean

life of the compartment. Similarly, hard tissue would be assigned to the third compartment. This third compartment would have constituted 23% of the material originally present and had a mean life of 46 h. Under the second interpretation, the compartments represent processes, such as, digestion and active passage of indigestible material, rather than kinds of materials or tissues. Here the compartments might represent the order of the dominant processes, e.g. first the digestion of soft tissue, then the breakdown of more refractory material and finally the evacuation of indigestible material. Under the third interpretation the compartments are seen to represent some combination of process and material.

More experimental work would be necessary to confirm one or the other of these interpretations. They are presented because all three have practical implications. If the compartmental coefficients indicate the proportion of tissue type initially present, or the predominant digestive process. then a potential method exists for estimating the time at which the crabs fed from a decay curve such as in Figure 4 and Table 2. A high proportion (high coefficient) in the first compartment would indicate recent feeding whereas a low proportion in the first compartment would indicate less recent feeding.

Clearance Rates for Specific Prey Items

On shipboard starved juvenile king crabs fed readily on shucked and diced clam, juvenile fish, shrimp and barnacles, less readily on tube worms, only slightly on mussels. Crabs did not eat the snails. For mussels the number of crabs eating was not sufficient to determine clearance rate. The clearance rate for the sabellid worm is based on much fewer data points than those for the other items and, therefore, should be considered tentative.

For the proportion of the initial grams dry weight of stomach contents per gram crab wet weight, multi-compartmental models described the exponential decay (Figures 5-8, Table 4). As previously described, graphical analysis indicated the number of compartments and Battelle's FIT program evaluated the parameters. Because only a small number of crabs consumed tube worms, the exponential decay model for tube worms (Table 4) is based on data only to 12 h and may have shown more than one compartment if it could have been followed longer. An example of how the individual compartments combine to give an overall decay curve appears in Figure 8.

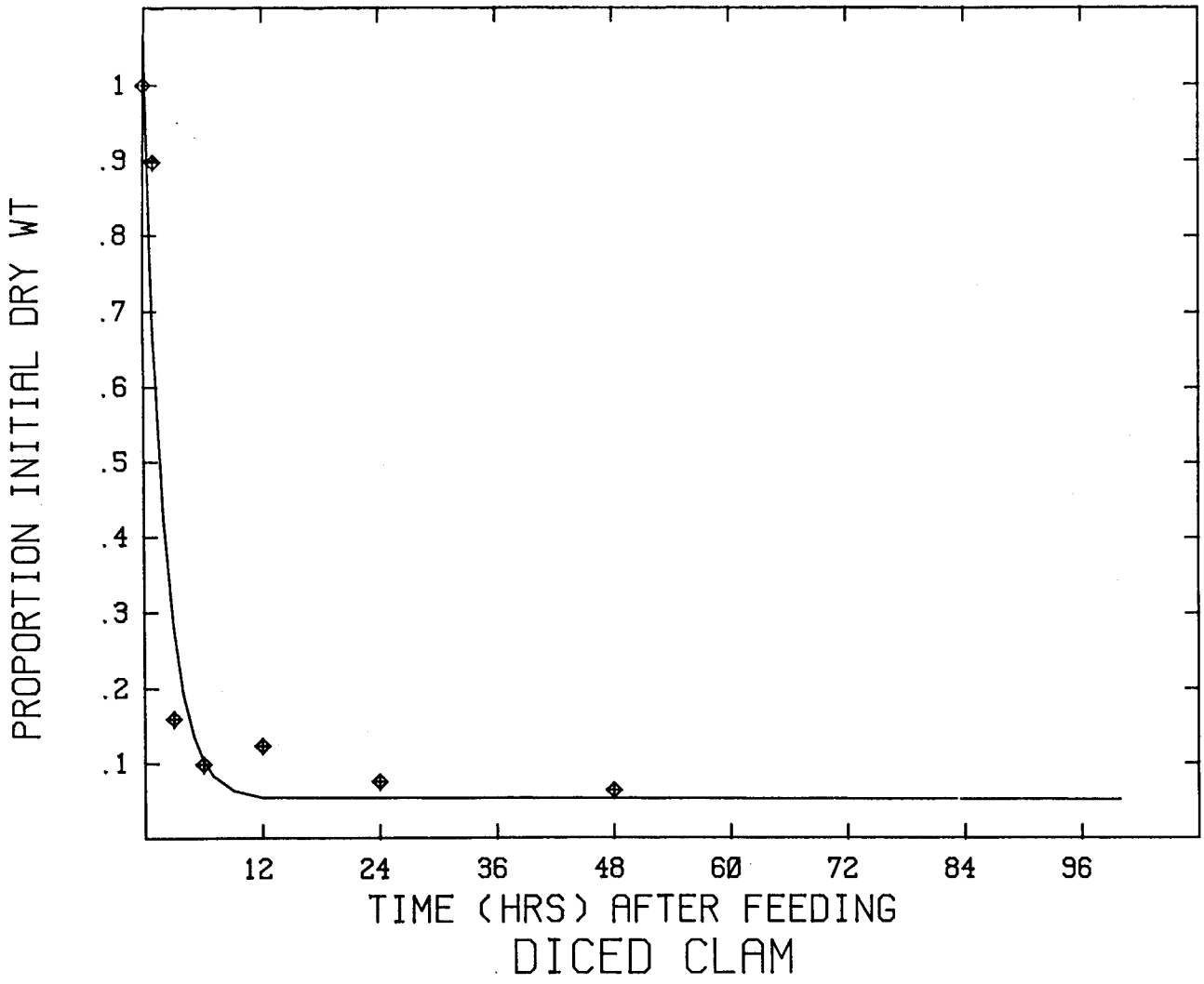


Figure 5. Exponential decay curve for stomach contents in juvenile king crab fed diced clam. The dependent variable is the proportion of the grams dry weight of stomach contents per gram crab wet weight at time = 0. See Table 4 for equations.

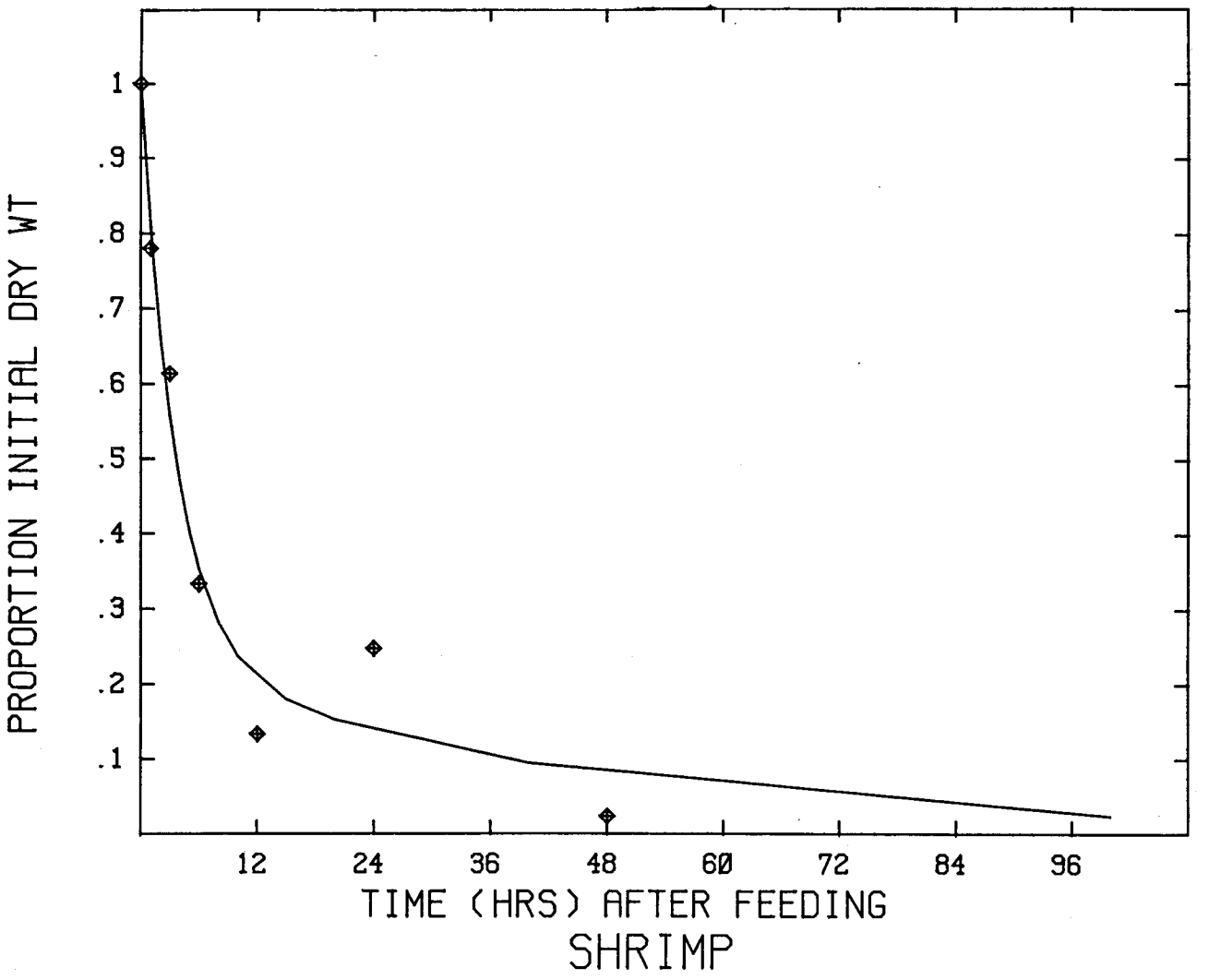


Figure 6. Exponential decay curve for stomach contents in juvenile king crab fed shrimp. The dependent variable is the proportion of the grams dry weight of stomach contents per gram crab wet weight at time = 0. See Table 4 for equations.

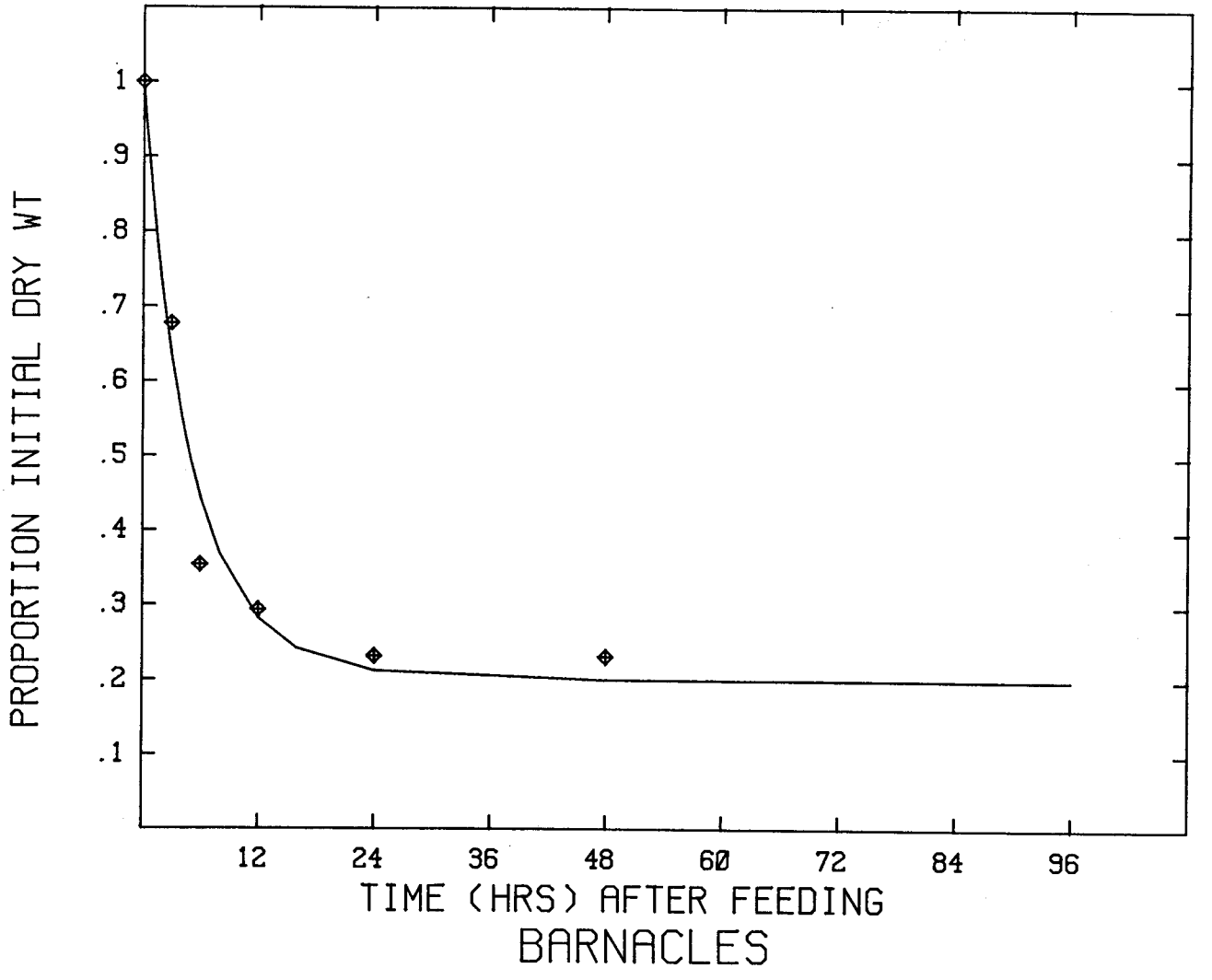


Figure 7. Exponential decay curve for stomach contents of juvenile king crab fed barnacles. The dependent variable is the proportion of grams dry weight of stomach contents per gram crab wet weight at time = 0. See Table 4 for equations.

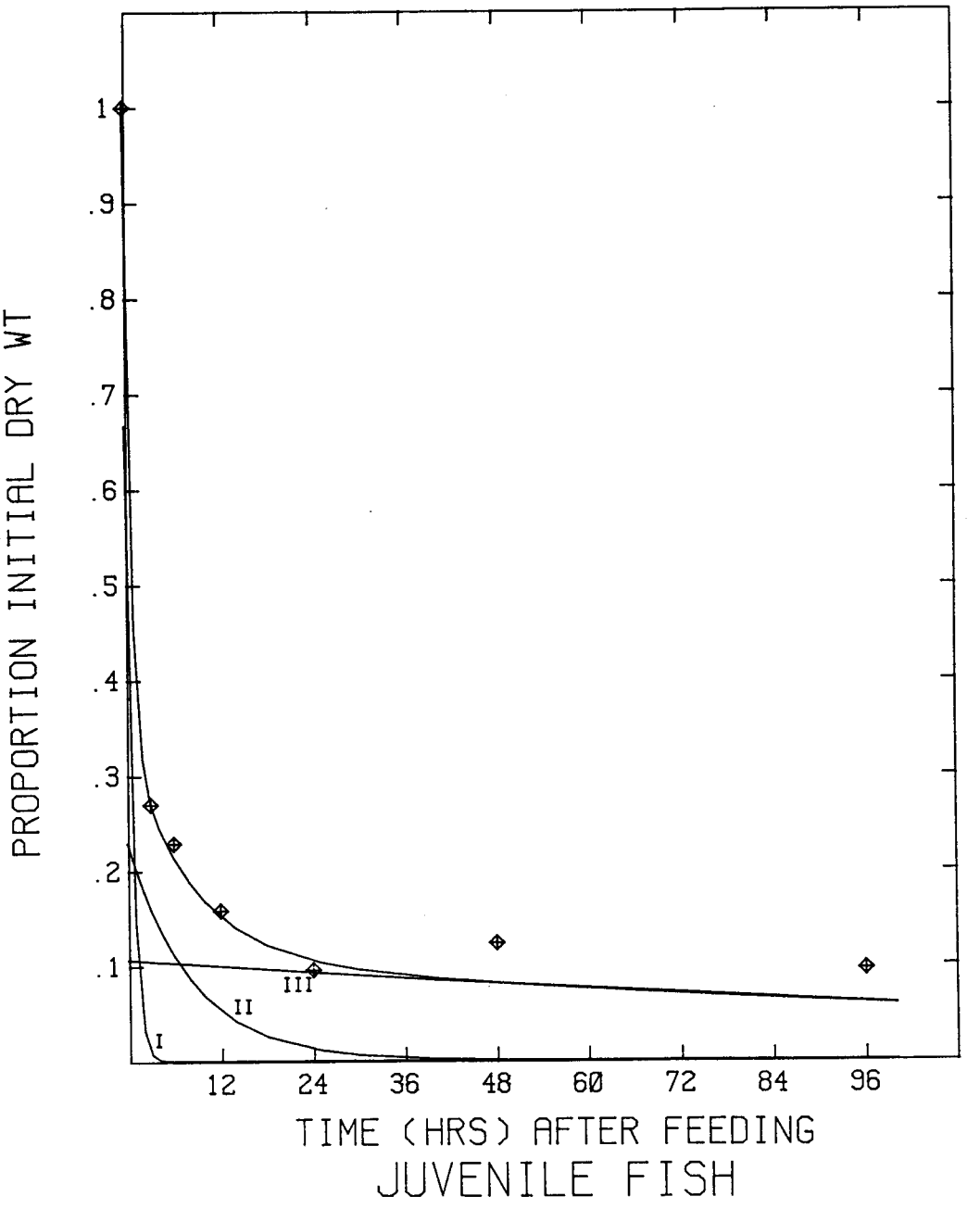


Figure 8. Exponential decay curve for stomach contents of juvenile king crab fed juvenile fish. The dependent variable is the proportion of grams dry weight of stomach contents per gram crab wet weight at time = 0. Decay curves for each compartment are plotted individually and labelled with Roman numerals. See Table 4 for equations.

Table 4. Stomach clearance rates for specific prey items fed to juvenile king crab. W = proportion of initial g dry weight/g crab wet weight, T = time in h after feeding or isolation, $\bar{T}$ = mean life, the reciprocal of the decay constant.

Prey	Avg. dry wt (g) @ t = 0	Equation	R^2	$\bar{T}$ by (h) compartment	Time (h) to 10% of initial	Time (h) to 5% of initial
Diced clam	0.425	$W=1.003e^{-0.494T}+0.0518e^{-0.0000022T}$	92.9	2.0 4.5×10^5	6.1	asymptotic to 5% @ 11 h
Shrimp	0.212	$W=0.763e^{-0.0271T}+0.233e^{-0.0224T}$	96.6	3.69 44.5	37.5	68.5
Barnacles	0.180	$W=0.598e^{-0.225T}+0.192e^{-0.128T}+0.200e^{-0.000033T}$	97.6	4.45 7.84 3.0×10^4	asymptotic to 20% @ 48 h	
Juvenile fish	0.525	$W=0.666e^{-1.518T}+0.229e^{-0.121T}+0.106e^{-0.0058T}$	99.8	0.66 8.23 172.0	26.5	129.5
Tube worm	0.502	$W=0.912e^{-0.204T}$	99.5	4.9	10.8	14.2

A comparison of the equations in Table 4 shows that the overall clearance rates, the number of compartments, and the relative size and mean life of the compartments clearly varied with prey type. The diced clam represented soft tissue with no hard parts and had by far the fastest clearance rate. The decay model for diced clam shows that the first compartment contains almost 100% of the material and has a very low mean life, 2.0 h. Other items showed substantial amounts of material in their second and third compartments and lower clearance rates due primarily to longer mean life in the second and third compartments. Shrimp with an exoskeleton but no heavily calcified parts had two compartments whereas barnacles and juvenile fish with calcified parts (barnacle plates and fish bone) had three compartments. Note that the decay constants in the first compartments (Table 4) are quite comparable for shrimp and barnacles but are much higher for clam and fish. If the first compartment represents digestion of soft tissue, shrimp and barnacles with their crustacean exoskeleton might be expected to have similar decay constants when compared to each other but slower decay constants when compared with prey types having more exposed soft tissue.

If the coefficients for each compartment represent the proportions of tissue types present at T = 0, then for barnacles and fish 20% and 10%, respectively, of the ingested material have very long stomach residence times. For lobsters, Homarus americanus, Carter and Steele (1982) found that barnacle plates and bivalve shells remain in the stomach for 180 days. Because the stomach clearances for the king crab were studied for only 4 days, the third compartment for barnacles appears almost indefinite (mean life = about 1000 d). Even so, this estimate for barnacles is not totally unimaginable given Carter and Steele's (1982) findings.

Conventional determinations of dietary composition are biased in favor of those items with long stomach residence times (Peterson and Bradley, 1978)., and clearance rates for specific prey items were needed to provide gut residence times for corrections of the relative importance of prey items in the diet of juvenile king crab. The occurrence of multi-compartmental models makes it inappropriate to use mean life, the reciprocal of the decay constant, as a measure of stomach residence time because no legitimate way is known to combine the mean lives from several compartments into one number. Instead, the time required for the dry weight to fall to 5% of initial value was taken as a measure of stomach residence time. Such estimates can be readily calculated from the exponential equations and appear in Table 4. Stomach residence times of prey items not studied were estimated by their similarity to those studied.

Estimating an appropriate residence time for shell fragments appears problematic but a reasonable estimate is possible. Carter and Steele (1982) found that shell fragments remained in lobster stomachs 90 to 180 d (2160 to 4320 h). Hill (1976) observed no decrease in the weight of shell fragments in the stomachs of the crab, Scylla serrata, during 8 days of observations while soft tissue fell to 5% of its initial level in 12 h and fishbone, to less than 5% in about 3.5 days (about 84 h). Here barnacle tissue reached 5% of its initial dry weight at 3.0×10^4h, i.e., 1250 days. Hard tissue, such as barnacle plates and molluscan shell fragments, appear to remain indefinitely in crab stomachs. Hill suggests that crabs regurgitate shell rather than evacuate it into the lower digestive system. Pearson and Olla (1977) and Pearson et al (1979) have seen captive blue crab, Callinectes sapidus, and Dungeness crab, Cancer magister, periodically regurgitate shell when held on an ad libitum diet of blue mussels. During shipboard holding of juvenile king crab regurgitation of shell and sand dollar test fragments was observed. These observations suggest that shell fragments and other hard tissue remain indefinitely in crab stomachs accumulating to some threshold volume at which point the crab regurgitates the entire volume. If so, the problem becomes one of determining the time frame within which the regurgitation will normally occur. On shipboard juvenile king crabs held without food regurgitated shell beginning 4 days after capture and continuing each night until the crabs were used in an experiment at 12 days after isolation. Five crabs sacrificed 7 days after isolation had no visible shell fragments in their guts, but dry weights of stomach contents for these individuals were not determined. Both Hill's (1976) data and that presented here indicate shell fragments have a longer stomach residence time than fish bone. In light of the available information, a stomach residence time for hard tissue such as shell fragments appears to be more than 5.4 days and could be on the order of 135 days for crustaceans continuing to feed on soft tissue. The shipboard observations on regurgitation and visual examination of the stomachs would indicate a residence time between 4 and 7 days. The exponential model would indicate one of 1250 days. The harmonic mean of these four estimates is 10.7 days. This latter value was used in corrections for gut residence times.

SHIPBOARD OBSERVATIONS OF FEEDING BEHAVIOR

On shipboard, juvenile king crabs selectively ingested only certain parts of some prey. Crabs ate the fleshy portions of the shrimp and juvenile fish, leaving the heads. Similarly, crabs ingested little of the barnacle plates and mussel shell. Crabs scraped the soft tissue from the

hard parts with the palps and then dropped the cleaned hard parts. Only small fragments of plate or shell were ingested. Previously Pearson et al (1979,1981) have seen similar selective feeding on soft tissue and discarding of hard parts by the Dungeness crab, C. magister. The implication of the selective ingestion observed in the juvnenile king crab is that in actively selecting soft tissue and rejecting hard tissue, the crab is not ingesting prey items in proportion to the occurrence of hard parts of those items in the stomach. For example, juvenile king crab could well be consuming more clams than the presence of shell fragments indicates.

DIEL FEEDING CHRONOLOGY

Diel feeding chronologies were determined for June and August (Figures 9, 10 and 11). In June juvenile king crab were not sampled at every hour of the day, but in August 25 crabs were obtained in each 2-h period of the 24-h cycle. In October only one juvenile king crab greater than 20 mm CL was collected. Consequently, the best estimate of the diel feeding chronology for juvenile king crab came from August. For tanner crab the sample sizes for crabs greater than 20 mm CW were inadequate to construct a diel feeding chronology. Tanner crab less than 20mm CW had extremely small stomach volumes (<0.08 ml) that precluded this type of analysis.

In June the volume of solid material in the stomachs of juvenile king crab averaged 18% of the maximum stomach volume, and the dry weight of the stomach contents, 1.63 mg dry weight per g crab wet weight (Table 5). In August the volume of solids in the stomach averaged 10% of the maximum stomach volume and the dry weight of the stomach contents, 2.89 mg dry weight per g crab wet weight (Table 6). Because of the low sample size and consequent high variance, there was no significant difference in June with time of day for the volume of solid stomach contents or the dry weight. Ignoring those times of day with less than 10 samples stomach fullness decreased during mid-day in June but again not significantly. In August the volume and dry weight of stomach contents both varied significantly with time of day. In June and August volume and dry weight of stomach contents did not vary significantly with sex.

Patterns in the diel feeding chronologies were similar in June and August. The average amount of food in the stomach was higher in August (Figures 9, 10, and 11). Two feeding peaks occurred. The feeding period between 1300 and 1800 h showed higher amounts of stomach contents than that between 0000 and 0800 h.

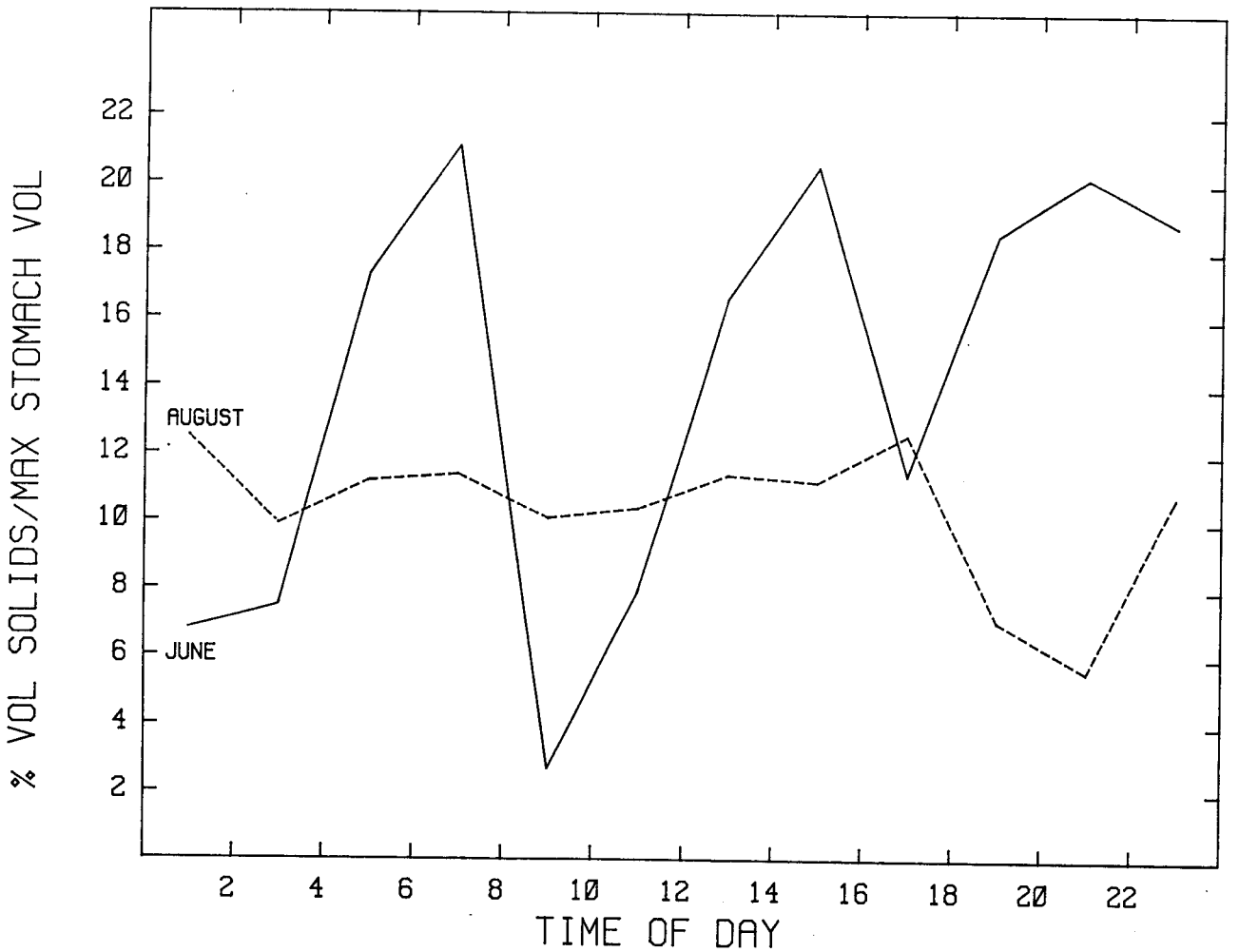


Figure 9. Volume of solids in stomach as a percentage of maximum stomach volume vs. time of day for juvenile king crab.

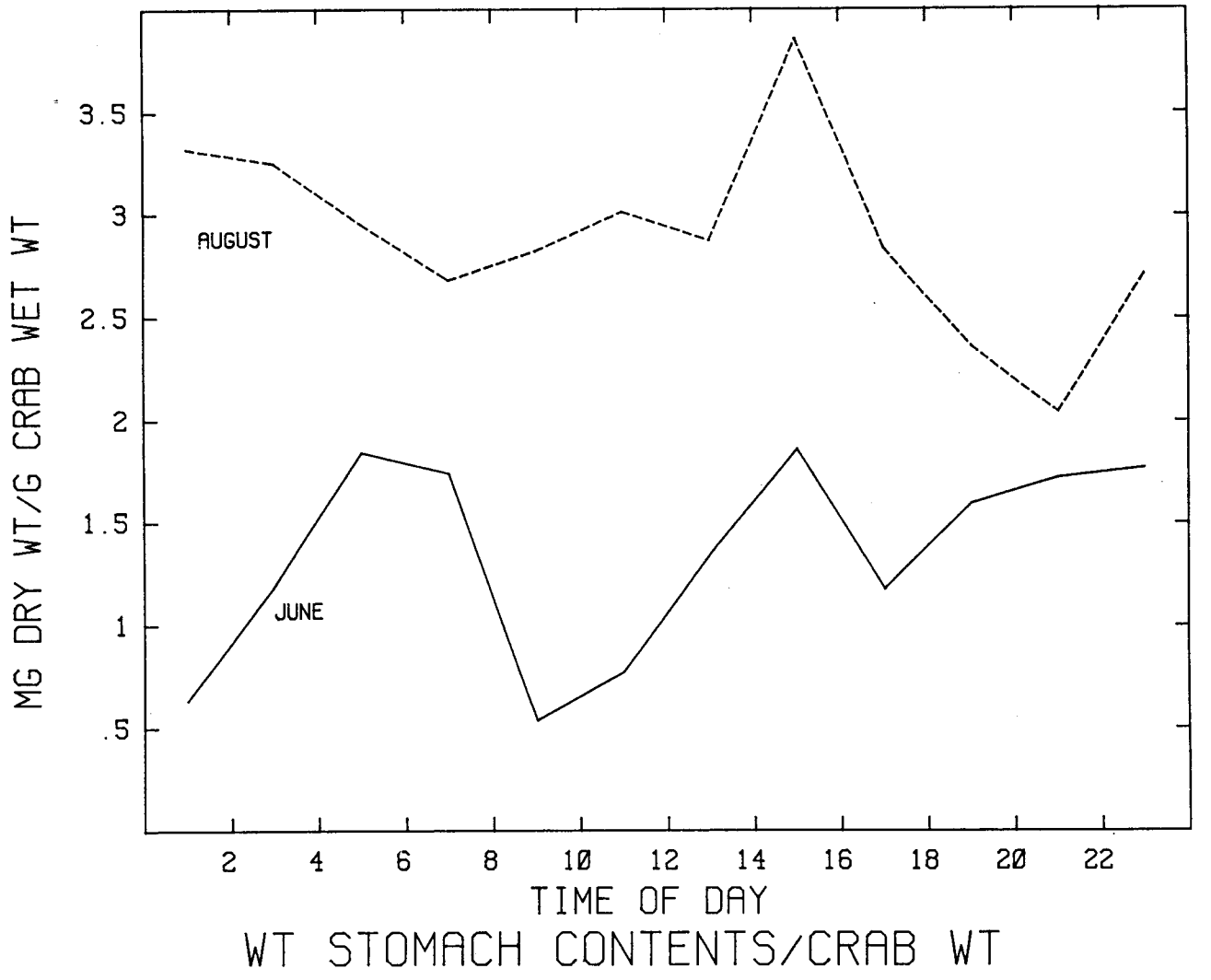


Figure 10. Standardized dry weight of stomach contents (mg dry weight/g crab wet weight) vs. time of day for juvenile king crab.

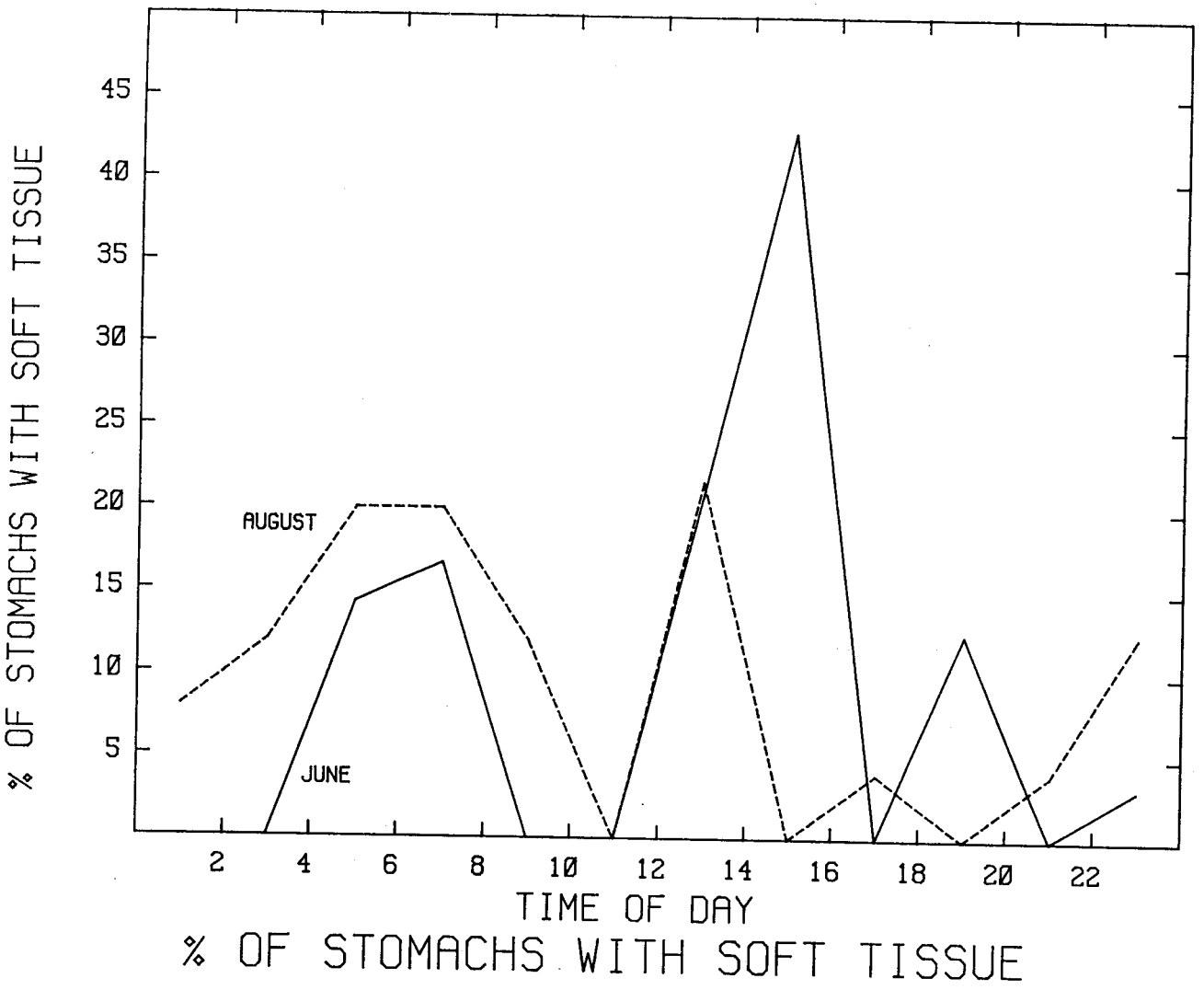


Figure 11. Percentage of stomachs with soft tissue vs. time of day for juvenile king crab.

Table 5. Diel feeding chronology from June, 1982, for juvenile king crab ($\leq$ 90 mm CL). Mean carapace length 64.5 (± 8.8) mm. Time of day is midpoint of 2-h period. Duration of trawling was 24 h.

Time of day	N	Volume of solids as % maximum stomach volume x ± SD		mg dry weight stomach contents per g crab wet weight x ± SD	
0100	4	6.8	3.0	0.635	0.230
0300	1	7.5	-	1.195	-
0500	28	17.3	12.9	1.845	1.480
0700	18	21.1	13.3	1.742	1.030
0900	1	2.7	-	0.539	-
1100	2	7.9	4.3	0.776	0.027
1300	24	16.6	14.5	1.346	1.310
1500	7	20.5	9.9	1.863	1.010
1700	4	11.4	7.3	1.176	1.030
1900	8	18.5	10.5	1.596	0.695
2100	22	20.2	14.7	1.723	1.210
2300	31	18.8	15.6	1.772	1.380
Overall	150	17.9	13.5	1.630	1.240

Table 6. Diel feeding chronology from August 1982, for juvenile king crab (≤ 90 mm CL). Mean carapace length 63.8 (± 8.3) mm. Time of day is midpoint of 2-h period. Duration of trawling was 70 h.

Time of day	N	Volume of solids as % maximum stomach volume x ± SD		mg dry weight stomach contents per g crab wet weight x ± SD	
0100	25	12.5	10.5	3.32	1.93
0300	25	9.9	6.5	3.25	1.41
0500	25	11.2	7.8	2.95	1.30
0700	25	11.4	7.3	2.68	1.21
0900	25	10.1	6.6	9.82	1.47
1100	25	10.4	7.0	3.01	1.23
1300	23	11.4	6.9	2.87	1.27
1500	25	11.2	8.8	3.85	1.95
1700	25	12.6	9.5	2.83	1.42
1900	25	7.1	3.4	2.36	0.83
2100	25	5.6	3.6	2.04	0.77
2300	24	10.8	7.0	2.71	1.19
Overall	297	10.3	7.5	2.89	1.42

These results are comparable to those of Tarverdieva (1978) for red king crab in Bristol Bay during September. The two peaks in feeding found by Tarverdieva (op. cit.) also occurred at 0300 and 1300 h but in contrast to the findings here the nocturnal peak was higher than the diurnal one. During the long photoperiods of June, a nocturnal feeding rhythm present at other seasons may break down.

The dry weight of stomach contents standardized by crab wet weight was a clearer indicator of diel changes than the volume of solid contents as a percentage of maximum stomach volume. The percentage of stomachs with soft tissue followed the diel trends in dry weight of stomach contents (Figure 11).

DAILY RATION

Using the diel feeding chronologies and the clearance rate equation from Table 2, daily rations in June and August were calculated. Juvenile king crabs in August consumed slightly less than twice the dry weight of material consumed in June (Tables 5 and 6). The June daily ration for juvenile king crab was 6.30 mg dry weight per g crab wet weight per day; the August daily ration, 11.92 mg dry weight per g crab wet weight per day.

The daily ration determined by Tarverdieva (1978) for adult king crab was 3.1 mg/g crab wet weight, about 1/4 to 1/2 of the daily rations. The difference between the calculations here and Tarverdieva's could be a reflection of seasonal differences. More likely it is due to correction for clearance rate in the calculations.

From the daily rations, dietary composition data and caloric equivalents from the literature, a schedule of the energy derived from various prey items was calculated and appears in a following section.

DIETARY COMPOSITION

The Frequency of Newly Discovered Prey as a Function of the Number of Stomachs Examined

Following Vesin et al. (1981), the frequency of newly-discovered prey

as a function of the number of stomachs examined was determined. In 25 stomachs of juvenile king crab from a single station a total of 25 prey items was observed. Examination of 19 stomachs gave 95% of the total number of identified prey items (Figure 12). Thus, 19 is the optimal number of stomachs to examine per sampling unit. Vesin et al. (1981) found that for capelin, Mallotus villosus, examining beyond 10 to 15 stomachs added no new information that influenced overall estimates of dietary composition.

Dietary Composition by Visual Examination of Stomach Contents

The frequency of occurrence, i.e., the percentage of stomachs in which a prey item occurs, gives a crude qualitative view of the extent to which an animal population feeds on a particular item but does not indicate the relative amount or bulk of that item in the stomach or the diet (Hyslop, 1980). In the overall diet of juvenile king crab (CL = 53 to 80 mm), clams, snails, sand dollars, crustaceans and polychaetes rank in that order by frequency of occurrence (Table 7). The major differences in frequency of occurrence between June and August were, first, that sand dollars occurring in 75% of the stomachs in June dropped to 33% in August and, secondly, that Tellina sp in August replaced Cyclocardia cebricostata as the important bivalve.

Dietary composition expressed as the percentage of total number of visually observed occurrences by all items appears in Table 8. For this measure gastropods rank first at 21% in the overall diet followed by pelecypods at 19%, crustaceans at 11%, echinoderms at 10%, polychaetes at 6%, and other taxa at 4.%. Again the major difference between June and August is a decrease in the extent to which sand dollars occur in stomachs.

Frequency of occurrence analyses overestimate the importance of taxa possessing hard tissues that have long residence times in the gut. Dietary composition was corrected for gut residence time following Peterson and Bradley (1978). An example of the calculations appears in Table 9. The uncorrected and corrected dietary compositions appear in Tables 10 and 11. Whereas bivalves, snails and sand dollars dominated the uncorrected dietary composition, polychaetes, a soft bodied prey with short gut residence time, dominated the corrected dietary composition of the larger juvenile king crab.

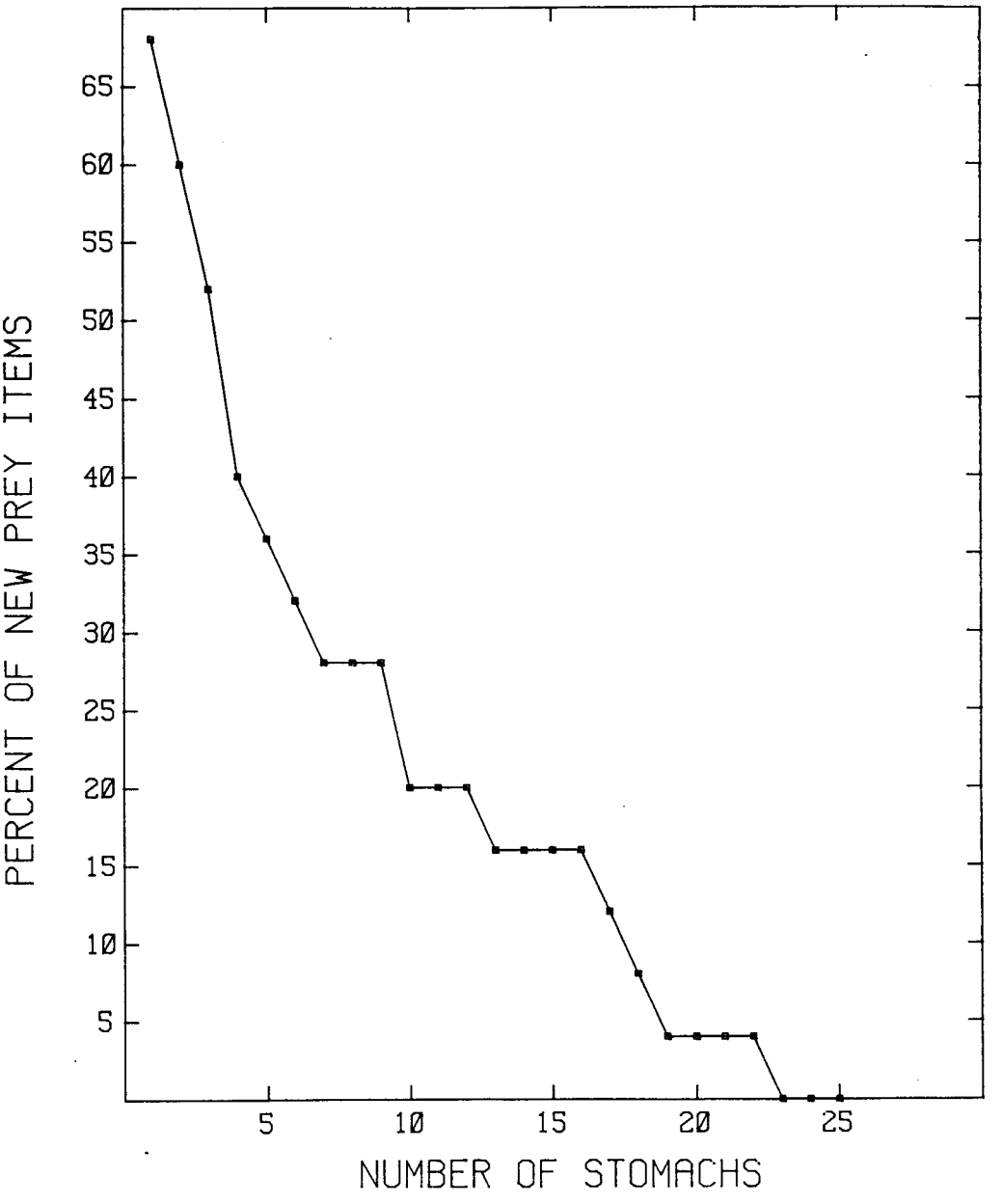


Figure 12. The frequency of newly discovered prey items as a function of the number of stomachs examined. Examination of 25 stomachs of juvenile king crab from one station gave a total of 25 prey items.

Table 7. Percentage frequency of occurrence of prey items visually observed in stomachs of juvenile king crab (CL = 53 to 80 mm). See Figure 15 for locations of stations.

Prey item	% of stomachs with prey item						
	Station C57	Station C91	June Cruise	Station B79	Station B100	August Cruise	Overall
GASTROPODS	100	74	87	82	81	81	86
Neptunea sp	0	0	0	0	6	4	1
Oenopota sp	64	16	43	45	25	33	39
Retusa obtusa	20	0	11	0	6	4	8
Naticidae	0	0	0	18	19	18	7
Neverita nana	16	0	9	36	0	15	11
Trochidae	0	0	0	0	6	4	1
Solariella sp	64	63	64	73	56	63	63
Others	0	10	4	36	12	22	11
PELECYPODS	100	79	91	100	100	100	94
Cyclocardia cebricostata	92	74	84	0	19	11	56
Tellina sp	24	10	18	100	100	100	49
Spisula polynyma	60	5	36	18	12	15	28
Others	0	5	2	0	0	0	1
CRUSTACEANS	44	63	52	82	69	74	60
Balanus sp	8	0	4	18	12	15	8
Amphipods	0	0	0	9	6	7	3
Paguridae	36	5	23	0	0	0	14
Ostracod ??	0	0	0	45	56	52	20
Others	0	58	25	45	31	37	30
POLYCHAETES	32	68	48	54	25	37	44
Pectinaria sp	0	37	16	27	12	18	17
Sabellidae	0	26	11	27	12	18	14
Others	32	5	20	0	0	0	13

Table 7. Continued

Prey item	% of stomachs with prey item						
	Station C57	Station C91	June Cruise	Station B79	Station B100	August Cruise	Overall
ECHINODERMS							
Echinarachuics parma	92	100	95	54	19	33	72
MISCELLANEOUS							
Hydroid	0	5	2	27	25	26	11
Bryozoan	0	5	2	18	19	18	8
Plant matter	0	5	2	9	6	7	4
Fish	8	0	4	0	6	4	4
Floc	100	100	100	100	100	100	100
Sand	100	100	100	100	100	100	100
Number of stomachs	25	19	44	11	16	27	71

Table 8. Uncorrected species composition of the diet of juvenile king crab. (Frequency of occurrence as % of total number of visually observed occurrences by all items.) Totals for calculation include floc and sand.

Prey item	Diet composition as % of all observed occurrences		
	June	August	Overall
GASTROPODS	*	*	*
Neptunea sp	0.0	0.5	0.2
Oenopota sp	6.4	4.6	5.6
Retusa obtusa	1.7	0.5	1.2
Naticidae	0.0	2.6	1.0
Neverita nana	1.3	2.0	1.6
Trochidae	0.0	0.5	0.2
Solariella sp	9.4	8.7	9.1
Others	0.7	3.1	1.6
PELECYPODS	*	*	*
Cyclocardia cebricostata	12.4	1.5	8.1
Tellina sp	2.7	13.8	7.1
Spisula polynyma	5.4	2.0	4.0
Others	0.3	0.0	0.2
CRUSTACEANS	*	*	*
Balanus sp	0.7	2.0	1.2
Amphipods	0.0	1.0	0.4
Paguridae	3.3	0.0	2.0
Ostracod ??	0.0	7.1	2.8
Others	3.7	5.1	4.2
POLYCHAETES	*	*	*
Pectinaria sp	2.3	2.6	2.4
Sabellidae	1.7	2.6	2.0
Others	3.0	0.0	1.8
ECHINODERMS			
Echinarachnius parma	14.0	4.6	10.3
MISCELLANEOUS			
Hydroid	0.3	3.6	1.6
Bryozoan	0.3	2.6	1.2
Plant matter	0.3	1.0	0.6
Fish	0.7	0.5	0.6
Floc	14.7	13.8	14.3
Sand	14.7	13.8	14.3

Table 9. Dietary composition (% frequency of all visually observed occurrences) from visual examination of stomach contents of juvenile king crab corrected for gut residence times and including floc and sand - June cruise.

Taxa	A Uncorrected diet. comp. %	B Residence time h	C Relative comp. (A/B)	D Corrected diet. comp. %
GASTROPODS	*	*	*	*
Neptunea sp	0.0000	259	0.000000	0.0000
Oenopota sp	6.3545	259	0.024535	2.1967
Retusa obtusa	1.6722	259	0.006457	0.5781
Naticidae	0.0000	259	0.000000	0.0000
Neverita nana	1.3378	259	0.005165	0.4625
Trochidae	0.0000	259	0.000000	0.0000
Solariella sp	9.3645	259	0.036157	3.2372
Others	0.6689	259	0.002583	0.2312
PELECYPODS	*	*	*	*
Cyclocardia cebricostata	12.3746	259	0.047778	4.2778
Tellina sp	2.6756	259	0.010330	0.9249
Spisula polynyma	5.3512	259	0.020661	1.8498
Others	0.3344	259	0.001291	0.1156
CRUSTACEANS	*	*	*	*
Balanus sp	0.6689	259	0.002583	0.2312
Amphipods	0.0000	68	0.000000	0.0000
Paguridae	3.3445	68	0.049184	4.4036
Ostracod ??	0.0000	68	0.000000	0.0000
Others	3.6789	68	0.054102	4.8439
POLYCHAETES	*	*	*	*
Pectinaria sp	2.3411	14	0.167224	14.9722
Sabellidae	1.6722	14	0.119446	10.6944
Others	3.0100	14	0.215002	19.2499
ECHINODERMS				
Echinarachnius parma	14.0468	259	0.054235	4.8558
MISCELLANEOUS				
Hydroid	0.3344	11	0.030404	2.7222
Bryozoan	0.3344	11	0.030404	2.7222
Plant matter	0.3344	24	0.013935	1.2477
Fish	0.6689	130	0.005145	0.4607
Floc	14.7157	90	0.163508	14.6394
Sand	14.7157	259	0.056817	5.0871
TOTAL	100.00	--	1.6765	100.00

Table 10. Dietary composition of juvenile king crab (% frequency of all visually observed occurrences). Floc and sand are included in the calculations. Corrections for gut residence times as illustrated in Table 9.

Prey Item	% of Diet					
	June		August		Overall	
	Uncorrected	Corrected	Uncorrected	Corrected	Uncorrected	Corrected
GASTROPODS	*	*	*	*	*	*
Neptunea sp	0.0000	0.0000	0.5102	0.1273	0.2020	0.0606
Oenopota sp	6.3545	2.1967	4.5918	1.1453	5.6566	1.6962
Retusa obtusa	1.6722	0.5781	0.5102	0.1273	1.2121	0.3635
Naticidae	0.0000	0.0000	2.5510	0.6363	1.0101	0.3029
Neverita nana	1.3378	0.4625	2.0408	0.5090	1.6162	0.4846
Trochidae	0.0000	0.0000	0.5102	0.1273	0.2020	0.0606
Solariella sp	9.3645	3.2372	8.6735	2.1633	9.0909	2.7260
Others	0.6689	0.2312	3.0612	0.7635	1.6162	0.4846
PELECYPODS	*	*	*	*	*	*
Cyclocardia cebricostata	12.3746	4.2778	1.5306	0.3818	8.0808	2.4231
Tellina sp	2.6756	0.9249	13.7755	3.4359	7.0707	1.1201
Spisula polynyma	5.3512	1.8498	2.0408	0.5090	4.0404	1.2116
Others	0.3344	0.1156	0.0000	0.0000	0.2020	0.0606
CRUSTACEANS	*	*	*	*	*	*
Balanus sp	0.6689	0.2312	2.0408	0.5090	1.2121	0.3635
Amphipods	0.0000	0.0000	1.0204	0.9694	0.4040	0.4615
Paguridae	3.3445	4.4036	0.0000	0.0000	2.0202	2.3073
Ostracod??	0.0000	0.0000	7.1429	6.7857	2.8283	3.2302
Others	3.6789	4.8439	5.1020	4.8469	4.2424	4.8453
POLYCHAETES	*	*	*	*	*	*
Pectinaria sp	2.3411	14.9722	2.5510	11.7710	2.4242	13.4483
Sabellidae	1.6722	10.6944	2.5510	11.7710	2.0202	11.1069
Others	3.0100	19.2499	0.0000	0.0000	1.8182	10.0862
ECHINODERMS	*	*	*	*	*	*
Echinarachnius parma	14.0468	4.8558	4.5918	1.1453	10.3030	3.0895
MISCELLANEOUS						
Hydroid	0.3344	2.7222	3.5714	20.9739	1.6162	11.4107
Bryozoan	0.3344	2.7222	2.5510	14.9813	1.2121	8.5580
Plant matter	0.3344	1.2477	1.0204	2.7466	0.6061	1.9612
Fish	0.6689	0.4607	0.5102	0.2535	0.6061	0.3621
Floc	14.7157	14.6394	13.7755	9.8877	14.3434	12.3774
Sand	14.7157	5.0871	13.7755	3.4359	14.3434	4.3010

Table 11. Dietary composition of juvenile king crab (% frequency of all visually observed occurrences). Floc and sand are excluded from the calculations.

Prey Item	% of Diet					
	June		August		Overall	
	Uncorrected	Corrected	Uncorrected	Corrected	Uncorrected	Corrected
GASTROPODS	*	*	*	*	*	*
Neptunea sp	0.0000	0.0000	0.7042	0.1468	0.2833	0.0727
Oenopota sp	9.0047	2.7363	6.3380	1.3213	7.9320	2.0356
Retusa obtusa	2.3697	0.7201	0.7042	0.1468	1.6997	0.4362
Naticidae	0.0000	0.0000	3.5211	0.7340	1.4164	0.3635
Neverita nana	1.8957	0.5761	2.8169	0.5872	2.2663	0.5816
Trochidae	0.0000	0.0000	0.7042	0.1468	0.2833	0.0727
Solariella sp	13.2701	4.0324	11.9718	2.4957	12.7479	3.2715
Others	0.9479	0.2880	4.2254	0.8808	2.2663	0.5816
PELECYPODS	*	*	*	*	*	*
Cyclocardia cebricostata	17.5355	5.3286	2.1127	0.4404	11.3314	2.9080
Tellina sp	3.7915	1.1521	19.0141	3.9638	9.9150	2.5445
Spisula polynyma	7.5829	2.3042	2.8169	0.5872	5.6657	1.4540
Others	0.4739	0.1440	0.0000	0.0000	0.2833	0.0727
CRUSTACEANS	*	*	*	*	*	*
Balanus sp	0.9479	0.2880	2.8169	0.5872	1.6997	0.4362
Amphipods	0.0000	0.0000	1.4085	1.1183	0.5666	0.5538
Paguridae	4.7393	5.4853	0.0000	0.0000	2.8329	2.7690
Ostracod??	0.0000	0.0000	9.8592	7.8283	3.9660	3.8766
Others	5.2133	6.0338	7.0423	5.5916	5.9490	5.8149
POLYCHAETES	*	*	*	*	*	*
Pectinaria sp	3.3175	18.6500	3.5211	13.5797	3.3994	16.1394
Sabellidae	2.3697	13.3214	3.5211	13.5797	2.8329	13.4495
Others	4.2654	23.9786	0.0000	0.0000	2.5496	12.1045
ECHINODERMS	*	*	*	*	*	*
Echinarachnius parma	19.9052	6.0486	6.3380	1.3213	14.4476	3.7077
MISCELLANEOUS						
Hydroid	0.4739	3.3909	4.9296	24.1965	2.2663	13.6940
Bryozoan	0.4739	3.3909	3.5211	17.2832	1.6997	10.2705
Plant matter	0.4739	1.5542	1.4085	3.1686	0.8499	2.3537
Fish	0.9479	0.5738	0.7042	0.2925	0.8499	0.4345
Flocculent	*	*	*	*	*	*
Sand	*	*	*	*	*	*

The frequency of occurrence and dietary composition from visual examination for yearling juvenile king crab (CL = 9-25 mm) appear in Table 12. The relative rankings of the major taxa, pelecypods, gastropods, echinoderms and crustaceans, are essentially the same as for the larger juvenile crabs, except that polychaetes and other soft bodied prey were not visually observed in the smallest juveniles. Most yearling king crab had stomachs full of floc and sand with little or nothing else discernible.

Dietary Composition from Dry Weights of Prey Items

Dietary composition based on dry weights of prey items in pooled stomach samples of juvenile king crab (CL = 53-80 mm) appears in Table 13. Floc constituted a substantial proportion of the dry weight of the stomach contents (36% in June, 64% in August, 54% overall). Excluding the floc, sand dollars dominated the dry weight of stomach contents in June followed in rank by clams, gastropods, polychaetes and crustaceans. In August bivalves replaced sand dollars as the dominant class in the stomach contents by dry weight (excluding floc). Overall the dry weight of stomach contents excluding floc was dominated by sand dollars followed by clams, gastropods, polychaetes, and crustaceans.

The above dry weights were measured almost exclusively on hard parts such as bivalve shells, sand dollar tests, and barnacle plates. To estimate the dry weight of soft tissue ingested the soft tissue/hard tissue ratios and dry weights in Tables 14 and 15 were used. Among the bivalves thick shelled species, such as Cyclocardia sp, had soft/hard ratios on the order of 0.05 whereas thin shelled species had ratios between 0.15 and 0.20. Among the gastropods the thick shelled species also had ratios distinctly different from the thin shelled species. For the polychaetes, little soft tissue was found and polychaete dry weights were determined by weighing the sand tubes and large cephalic spines of the Pectinaria sp and the parchment tubes of the Sabellidae. Therefore, the soft tissue dry weights for these soft bodied prey were estimated using the soft tissue to hard part ratios determined in the laboratory.

Dietary composition based on soft tissue dry weights in stomachs of juvenile king crab appears in Tables 16 and 17. Floc, which is predominantly unrecognizable organic matter, constitutes over 80% of the dry weight in the June, August and overall diets whether uncorrected or corrected for gut residence time. Excluding the floc and correcting for gut residence times yields an estimated dietary composition dominated by

Table 12. Dietary composition (% frequency of occurrence as % of stomachs with item and as % of total occurrences by all items) from visual examination of yearling juvenile king crab (CL = 9-25 mm, N = 24).

Prey item	% of stomachs with item	% of all observed occurrences	
		Including floc + sand	Excluding floc & sand
FORAMINIFERA	4.2	1.4	3.2
GASTROPODS			
Naticidae	8.3	2.8	6.4
Trochidae	8.3	2.8	6.4
Other	12.5	4.2	9.7
PELECYPODS	41.7	13.9	32.2
CRUSTACEANS			
Barnacles	8.3	2.8	6.4
Copepods	4.1	1.4	3.2
Amphipods	8.3	2.8	6.4
Other	12.5	4.2	9.7
ECHINODERMS			
Echinarachnius parma	20.8	6.9	16.1
FLOC	91.7	30.6	--
SAND	79.2	26.4	--

Table 13. Dietary composition (% of total dry weight of all prey items in pooled stomach samples) of juvenile king crab (CL = 53-80 mm). These percentages are not corrected for gut residence time.

Prey item	% of total dry weight of prey items					
	June		August		Overall	
	With floc + sand	Without floc + sand	With floc + sand	Without floc + sand	With floc + sand	Without floc + sand
GASTROPODS	*	*	*	*	*	*
Neptunea sp	0.0000	0.0000	0.0094	0.041	0.0058	0.017
Oenopota sp	0.2452	0.4560	0.1320	0.588	0.1769	0.509
Retusa obtusa	0.0000	0.0000	0.0008	0.003	0.0005	0.001
Naticidae	0.0000	0.0000	0.0312	0.137	0.0192	0.055
Neverita nana	0.0000	0.0000	0.1528	0.670	0.0939	0.270
Trochidae	0.0000	0.0000	0.2930	1.285	0.1802	0.519
Solariella sp	1.0755	2.0000	0.9719	4.261	1.0118	2.913
Others	0.0075	0.0139	0.3749	1.644	0.2334	0.672
PELECYPODS	*	*	*	*	*	*
Cyclocardia cebricostata	3.4930	6.4955	0.2058	0.902	1.4714	4.237
Tellina sp	0.0871	0.1620	13.9505	61.163	8.6128	24.798
Spisula polynyma	0.2216	0.4120	0.4910	2.153	0.3873	1.115
Others	0.1220	0.2269	0.0000	0.000	0.0470	0.135
CRUSTACEANS	*	*	*	*	*	*
Balanus sp	0.0000	0.0000	1.2002	5.262	0.7381	2.125
Amphipods	0.0000	0.0000	0.0148	0.065	0.0091	0.026
Paguridae	0.0274	0.0509	0.0000	0.000	0.0105	0.030
Ostracod ??	0.0000	0.0000	0.0546	0.239	0.0336	0.097
Others	0.2241	0.4167	0.1107	0.485	0.1543	0.444
POLYCHAETES	*	*	*	*	*	*
Pectinaria sp	0.5042	0.9375	1.0880	4.770	0.8632	2.485
Sabellidae	0.5689	1.0579	0.3437	1.507	0.4304	1.239
Others	0.0012	0.0023	0.0000	0.000	0.0005	0.001
ECHINODERMS						
Echinarachnius parma	47.1400	87.6594	2.7784	12.181	19.8584	57.177
MISCELLANEOUS						
Hydroid	0.0025	0.0046	0.0242	0.106	0.0158	0.046
Bryozoan	0.0012	0.0023	0.0132	0.058	0.0086	0.025
Plant matter	0.0336	0.0625	0.0132	0.058	0.0211	0.061
Fish	0.0212	0.0394	0.5526	2.423	0.3480	1.002
Floc	36.2475	*	64.5868	*	53.6757	*
Sand	9.9762	*	12.6045	*	11.5926	*

Table 14. Soft tissue to hard tissue ratios for possible prey items from laboratory determinations.

Organism	Size mm	No. of Pooled Samples	$\bar{X} \pm SD$ % shell or hard part wet weight	$\bar{X} \pm SD$ % shell or hard part dry weight	$\bar{X} \pm SD$ Soft/hard ratio dry weight
GASTROPODS					
Solariella sp	5-7	8	68.7 ± 3.0	88.2 ± 1.5	0.1341 ± 0.0195
Oenopota sp	8-29	3	84.6 ± 3.2	95.8 ± 0.6	0.0439 ± 0.0067
Propebella sp	9-18	1	81.7	95.4	0.0487
Boreotrophon sp	12-24	3	80.1 ± 1.2	94.8 ± 0.5	0.0548 ± 0.0053
Natica clausa	5-32	3	55.8 ± 14.1	76.8 ± 10.7	0.3196 ± 0.1956
PELECYPODS					
Cyclocardia sp	5-13	8	81.8 ± 1.2	95.0 ± 0.6	0.0528 ± 0.0068
Laevicardium sp	5-6	2	54.1	81.2	0.1737
Nucula tenuis	~2	1	79.7	94.2	0.0617
Astarte sp	32-39	1	77.4	94.4	0.0594
Spisula polynyma	4-8	1	53.7	87.2	0.1473
CRUSTACEANS					
Barnacles	8-15	2	81.8	95.9	0.0428
Amphipods	3-5	1	ND	75.2	0.3301
Paguridae	~30	1	ND	69.0	0.4498
POLYCHAETES					
Pectinaria sp[a/]	5-8	2	ND	74.6	0.3592
Sabellidae[b/]	~10	2	ND	78.6	0.2882
ECHINODERMS					
Echinarachnius parma[c/]	30-50	1	ND	95.5	0.0473

[a/] Soft worm vs. cephalic spines and sand tube.

[b/] Soft worm vs. parchment tube with minimal adhering sand.

[c/] Viscera vs. test.

Table 15. Dry weights of prey items in pooled stomachs of juvenile king crab (CL = 53-80 mm).

	Dry weight (g) in stomachs			Soft/hard ratio
	June	August	Overall	
GASTROPODS	*	*	*	*
Neptunea sp	0.0000	0.0012	0.0012	0.0439
Oenopota sp	0.0197	0.0172	0.0369	0.0439
Retusa obtusa	0.0000	0.0001	0.0001	0.3196
Naticidae	0.0000	0.0040	0.0040	0.3196
Neverita nana	0.0000	0.0196	0.0196	0.3196
Trochidae	0.0000	0.0376	0.0376	0.1341
Solariella sp	0.0864	0.1247	0.2111	0.1341
Others	0.0006	0.0481	0.0487	0.1202
PELECYPODS	*	*	*	*
Cyclocardia cebricostata	0.2806	0.0264	0.3070	0.0528
Tellina sp	0.0070	1.7900	1.7970	0.1737
Spisula polynyma	0.0178	0.0630	0.0808	0.1473
Others	0.0098	0.0000	0.0098	0.0981
CRUSTACEANS	*	*	*	*
Balanus sp	0.0000	0.1540	0.1540	0.0428
Amphipods	0.0000	0.0019	0.0019	0.3301
Paguridae	0.0022	0.0000	0.0022	0.4498
Ostracod ??	0.0000	0.0070	0.0070	0.3900
Others	0.0180	0.0142	0.0322	0.3900
POLYCHAETES	*	*	*	*
Pectinaria sp	0.0405	0.1396	0.1801	0.3592
Sabellidae	0.0457	0.0441	0.0898	0.2882
Others	0.0001	0.0000	0.0001	0.3237
ECHINODERMS				
Echinarachnius parma	3.7868	0.3565	4.1433	0.1432
MISCELLANEOUS				
Hydroid	0.0002	0.0031	0.0033	0.1000
Bryozoan	0.0001	0.0017	0.0018	0.1000
Plant matter	0.0027	0.0017	0.0044	1.0000
Fish	0.0017	0.0709	0.0726	0.1000
Floc	2.9118	8.2872	11.1990	1.0000
Sand	0.8014	1.6173	2.4187	0.0000

Table 16. Dietary composition (% of total soft tissue dry weight of prey items in pooled stomachs) of juvenile king crab (CL = 53-80 mm). Data for this table were calculated with soft tissue/hard tissue ratios from Tables 14 and 15. Percentages were calculated including floc and sand. Correction is for gut residence times.

	% of Diet					
	June		August		Overall	
Prey Item	Uncorrected	Corrected	Uncorrected	Corrected	Uncorrected	Corrected
GASTROPODS	*	*	*	*	*	*
Neptunea sp	0.0000	0.0000	0.0006	0.0002	0.0004	0.0002
Oenopota sp	0.0245	0.0091	0.0086	0.0030	0.0132	0.0046
Retusa obtusa	0.0000	0.0000	0.0004	0.0001	0.0003	0.0001
Naticidae	0.0000	0.0000	0.0146	0.0050	0.0104	0.0036
Neverita nana	0.0000	0.0000	0.0713	0.0246	0.0509	0.0179
Trochidae	0.0000	0.0000	0.0574	0.0198	0.0410	0.0144
Solariella sp	0.3287	0.1216	0.1904	0.0656	0.2300	0.0808
Others	0.0020	0.0008	0.0658	0.0227	0.0476	0.0167
PELECYPODS	*	*	*	*	*	*
Cyclocardia cebricostata	0.4203	0.1555	0.0159	0.0055	0.1317	0.0463
Tellina sp	0.0345	0.0128	3.5399	1.2191	2.5361	0.8910
Spisula polynyma	0.0744	0.0275	0.1057	0.0364	0.0967	0.0340
Others	0.0273	0.0101	0.0000	0.0000	0.0078	0.0027
CRUSTACEANS	*	*	*	*	*	*
Balanus sp	0.0000	0.0000	0.0750	0.0258	0.0536	0.0188
Amphipods	0.0000	0.0000	0.0071	0.0094	0.0051	0.0068
Paguridae	0.0281	0.0396	0.0000	0.0000	0.0080	0.0108
Ostracod??	0.0000	0.0000	0.0311	0.0408	0.0222	0.0297
Others	0.1992	0.2806	0.0631	0.0827	0.1020	0.1365
POLYCHAETES	*	*	*	*	*	*
Pectinaria sp	0.4127	2.8245	0.5709	3.6374	0.5256	3.4161
Sabellidae	0.3736	2.5572	0.1447	0.9219	0.2103	1.3666
Others	0.0009	0.0063	0.0000	0.0000	0.0003	0.0017
ECHINODERMS	*	*	*	*	*	*
Echinarachnius parma	15.3840	5.6911	0.5812	0.2002	4.8206	1.6936
MISCELLANEOUS						
Hydroid	0.0006	0.0049	0.0035	0.0286	0.0027	0.0222
Bryozoan	0.0003	0.0025	0.0019	0.0157	0.0015	0.0121
Plant matter	0.0766	0.3058	0.0194	0.0719	0.0357	0.1355
Fish	0.0048	0.0036	0.0807	0.0554	0.0590	0.0413
Floc	82.6066	87.9420	94.3507	93.5101	90.9896	91.9923
Sand	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000

Table 17. Dietary composition (% of total soft tissue dry weight of prey items in pooled stomachs) of juvenile king crab (CL= 53-80 mm). Data for this table were calculated with soft tissue/hard tissue ratios from Tables 14 and 15. Percentages were calculated excluding floc and sand. Correction is for gut residence times.

	June		August		Overall	
Prey item	Uncorrected	Corrected	Uncorrected	Corrected	Uncorrected	Corrected
GASTROPODS	*	*	*	*	*	*
Neptunea sp	0.0000	0.0000	0.0106	0.0032	0.0047	0.0019
Oenopota sp	0.1411	0.0753	0.1522	0.0456	0.1460	0.0578
Retusa obtusa	0.0000	0.0000	0.0064	0.0019	0.0029	0.0011
Naticidae	0.0000	0.0000	0.2576	0.0772	0.1152	0.0456
Neverita nana	0.0000	0.0000	1.2625	0.3784	0.5647	0.2234
Trochidae	0.0000	0.0000	1.0162	0.3045	0.4545	0.1798
Solariella sp	1.8899	1.0088	3.3701	1.0100	2.5519	1.0095
Others	0.0118	0.0063	1.1652	0.3492	0.5277	0.2088
PELECYPODS	*	*	*	*	*	*
Cyclocardia cebricostata	2.4166	1.2900	0.2809	0.0842	1.4612	0.5781
Tellina sp	0.1983	0.1059	62.6621	18.7797	28.2384	11.1315
Spisula polynyma	0.4277	0.2283	1.8702	0.5605	1.0729	0.4244
Others	0.1568	0.0837	0.0000	0.0000	0.0867	0.0343
CRUSTACEANS	*	*	*	*	*	*
Balanus sp	0.0000	0.0000	1.3284	0.3981	0.5942	0.2351
Amphipods	0.0000	0.0000	0.1264	0.1443	0.0565	0.0852
Paguridae	0.1614	0.3282	0.0000	0.0000	0.0892	0.1344
Ostracod ??	0.0000	0.0000	0.5502	0.6280	0.2461	0.3708
Others	1.1451	2.3281	1.1161	1.2740	1.1321	1.7058
POLYCHAETES	*	*	*	*	*	*
Pectinaria sp	2.3729	23.4334	10.1059	56.0310	5.8318	42.6803
Sabellidae	2.1483	21.2155	2.5614	14.2017	2.3330	17.0745
Others	0.0053	0.0521	0.0000	0.0000	0.0029	0.0214
ECHINODERMS						
Echinarachnius parma	88.4515	47.2158	10.2886	3.0835	53.4860	21.1590
MISCELLANEOUS						
Hydroid	0.0033	0.0410	0.0625	0.4409	0.0297	0.2771
Bryozoan	0.0016	0.0205	0.0343	0.2418	0.0162	0.1511
Plant matter	0.4404	2.5370	0.3426	1.1081	0.3966	1.6934
Fish	0.0277	0.0295	1.4289	0.8532	0.6545	0.5158
Floc	*	*	*	*	*	*
Sand	*	*	*	*	*	*

polychaetes in both June and August and overall. In the corrected overall diet, four taxa, Pectinaria sp (a polychaete), sand dollars, sabellid polychaete worms, and the clam, Tellina sp, account for 92% of the soft tissue dry weight. Comparing June and August shows the June diet dominated by polychaetes (45%) and sand dollars (47%) and the August diet dominated by polychaetes (70%) and clams (19%).

CALORIC INTAKE

Caloric intake was calculated with values from the literature (Table 18) and from laboratory determinations (Table 19). Attempts to determine the caloric values for whole sand dollars both before and after digestion with 0.01 M HCL failed because of incomplete combustion of the sample even after mixing with benzoic acid. The caloric value for sand dollars used in the calculations was from bomb calorimetry of viscera after dissection from the test (Table 19).

Using the June and August daily rations, 6.30 and 11.92 mg dry weight per gram crab wet weight per day, and the corrected dietary composition based on soft tissue dry weights (Table 16 and 17) the daily rations were converted to calories. Floc dominated the dry weight of stomach contents and, being organic matter, has caloric value. Clearly, floc must be considered in estimating the daily intake of calories, but how floc should be considered in such estimation was not obvious.

One can consider the source of the floc to be one of two extremes. At one end floc is taken to derive entirely from unidentified prey items different from those already identified and for which soft tissue dry weights were calculated. At this extreme the caloric value of the floc is in addition to that of the identified prey items and must be included in any calculations of total caloric intake. At the other extreme floc is taken to derive entirely from the soft tissue of the prey items already identified and for which soft tissue dry weights have been taken into account. At this extreme the caloric value of the floc is equal to that calculated from the soft tissue dry weights of the identified prey and should not be included in any calculations of total caloric intake.

To encompass these extremes total caloric intake was estimated under three assumptions: first, that floc could not be attributed to any of the other items already identified and had a caloric value equal to the mean of all the invertebrates identified as prey items; secondly, that floc was diluted by inorganic matter or derived equally from known and unknown prey

Table 18. Caloric values of marine organisms selected from the literature.

Organism	Caloric Value CAL/g dry weight Spring	Summer	Reference
Annelida			
Lumbringereis fragilis	4857	-	Brawn et al. 1968
Terebellids	4141	-	Brawn et al. 1968
Nepthys ciliata	4061	-	Brawn et al. 1968
Aphrodita hastata	3438	-	Brawn et al. 1968
Maldanid	3276	3549	Brawn et al. 1968
Pectinaria hypoborea	3242	3620	Brawn et al. 1968
Pherusa plumosa	2660	-	Brawn et al. 1968
Sternapsis fosser	2127	-	Brawn et al. 1968
Nichamache sp	-	3561	Brawn et al. 1968
	Annual Mean		
Lumbrinereis fragilis	4565 (4359-4810)		Tyler 1973
Nephtys incisa	3984 (3773-4156)		Tyler 1973
Praxillella praetermissa	2365		
Aphrodita hastata	2638 (1914-3407)		
Mollusca			
Bivalves (no shell)	Summer	Spring	
Yoldia thraciaeformis	4783	4452	Brawn et al. 1968
Yoldia sapotilla	4778		Brawn et al. 1968
Clinocardium ciliatum	4453		Brawn et al. 1968
Yoldia sapotilla	4216 (3880-4555)		Tyler 1973
Nuclulana sp	4184		Tyler 1973
Venericardia borealis	3678 (3400-4202)		Tyler 1973
Artica islandica	4031 (3684-4276)		Tyler 1973
Astarte undata	4234 (3734-4521)		
Modiolus sp	4600 ± 7		Cummins & Wuycheck 1971
Dentalidae			
Dentalium entale (tooth shell)	4560		Tyler 1973
Gastropods			
Thais lapilus (Dog Whelk)	4595		Brawn et al. 1968
Natica clausa (Little Moon Snail)	4392		Brawn et al. 1968
Thais lamellosa (Dog Whelk)	5377		**Paine 1964**
Scaphander punctostrians (Striated canoe shell)	3336		Brawn et al. 1968
Colus stimpsoni (Neptune Shell)	4587		Tyler 1973.

Table 18. Continued

Organism	Caloric Value CAL/g dry weight Spring	Summer	Reference
Hydroids			
Hydra littoralis (freshwater)	6034 ± 146 ash free		Slobodkin & Richman 1961
Chlorohydra viridissima	5729 ± 247 ash free		Slobodkin & Richman 1961
Echinoderms (corrected for $CaCo_3$	Summer	Spring	
Asterias vulgaris	2551	2014	Brawn et al. 1968
Strongylocentrotus droehbachiensis		883	Brawn et al. 1968
Crustaceans			
Barnacles			
Balanus cariosus (no plates)	4596		Paine 1974
Eliminius modestus	5423 ± 212		Cummins & Wuycheck 1971
Amphipods	3761		Brawn et al. 1968
Unicola levcopis	2147 (1845-2512)		Tyler 1973
Leptocheirus pinguis	2740 (2319-3348)		Tyler 1973
Shrimp			
Spirontocaris sp	4423	4065	Tyler 1973
Pandalus montagui	4610 (4390-4345)		Tyler 1973
Pandalus montagui	4740		Brawn et al. 1968
	4958		Tyler 1973
Crab			
Hyas araneus	2610		Brawn et al. 1968
Uca pugnax			
small whole animal	2791.7		Cummins & Wuycheck 1971
medium whole animal	2841.8		Cummins & Wuycheck 1971
large whole animal	1909.6		Cummins & Wuycheck 1971
Mixed algae species	4477		Moshiri & Cummins 1969
Diatoms			
Navicula minima	3218		Cummins & Wuycheck 1971
Navicula sp	4918		Cummins & Wuycheck 1971
Nitzschia paradora	3280		Cummina & Wuycheck 1971

Table 19. Caloric values of tissue from laboratory determinations.

Organism	Calories/g dry wt	Calories/g ash free dry wt
Cyclocardia sp small	4340	4790
Cyclocardia sp large	3810	4650
Sabellid tube worms	3170	4420
Natica clausa	4620	4970
Astarte sp	4710	4930
Oenopota sp	4510	4900
Solariella sp	3730	4430
Sand dollar viscera	2110	4590
Sand dollar*		
dried	230	1560
	360	2310
dried + digested	56	970

*Not enough material to support complete combustion of sample even after mixing with benzoic acid.

and, therefore, had a caloric value one half that used under the first assumption; thirdly, that floc derived totally from the prey items already identified and could be ignored in the calculations. Under the first two assumptions, the corrected dietary composition calculated with floc included (Table 16) was used. Under the third assumption the corrected dietary composition calculated without floc (Table 17) was used. Under the three assumptions, the June daily ration equaled 29.6, 15.9, and 17.5 calories per g crab wet weight per day, respectively (Tables 20, 21, and 22). Similarily, the August daily ration equaled 58.1, 30.4, and 42.2 calories per g crab wet weight per day (Tables 23,24, and 25).

The energetic contribution of each prey item to the total caloric intake appears in the last column in Tables 20-25. Even after halving the caloric value of the floc, between 87 and 91% of the total caloric intake of juvenile king crabs still resides in floc. If one considers floc to derive from the identified prey, then polychaetes and sand dollars constitute 52% and 36%, respectively, of the total caloric intake in June (Table 22) whereas polychaetes and the clam, Tellina sp, constitute 64% and 24% of the caloric intake in August.

IMMUNOASSAY

Antisera from 29 species of potential prey items collected during the August and October cruises were produced. After an initial visual examination of juvenile king crab stomach contents, an additional 8 antisera were produced from prey items collected from Sequim Bay and from a subsequent NOAA/OCSEAP cruise during May of 1983. In the table of self and cross reactions (Table 26) numbers of self reaction lines ranged from 4 lines for several species of polychaetes and nematodes to 11 lines for the king crab. Cross reactions were also evident as expected, particularly among species closely related phylogenetically.

Before analysis of the smallest juvenile king crab, the immunoassay method and microscopic examination were compared in examining gut contents from larger juvenile king crab (CL >50 mm). Twenty stomachs of larger juvenile king crab collected in June 1982 were examined and a species list and frequency of occurrence table developed (Table 27). Extracts of the stomach contents without solid material were saved for the immunoassay. Immunological tests were then conducted on the stomach contents of the same 20 crabs examined visually.

Prey item	Corrected % of diet	Dry wt (mg)	Calories per mg dry wt	Calories per prey item	% of total calories
GASTROPODS	*	*	*	*	*
Neptunea sp	0.0000	0.00000	4.494	0.0000	0.0000
Oenopota sp	0.0091	0.00057	4.510	0.0026	0.0087
Retusa obtusa	0.0000	0.00000	4.494	0.0000	0.0000
Naticidae	0.0000	0.00000	4.620	0.0000	0.0000
Neverita nana	0.0000	0.00000	4.620	0.0000	0.0000
Trochidae	0.0000	0.00000	3.730	0.0000	0.0000
Solariella sp	0.1216	0.00766	3.730	0.0286	0.0964
Others	0.0008	0.00005	4.494	0.0002	0.0007
PELECYPODS	*	*	*	*	*
Cyclocardia cebricostata	0.1555	0.00980	4.340	0.0425	0.1434
Tellina sp	0.0128	0.00080	4.530	0.0036	0.0123
Spisula polynyma	0.0275	0.00173	4.530	0.0079	0.0265
Others	0.0101	0.00064	4.530	0.0029	0.0097
CRUSTACEANS	*	*	*	*	*
Balanus sp	0.0000	0.00000	4.596	0.0000	0.0000
Amphipods	0.0000	0.00000	4.002	0.0000	0.0000
Paguridae	0.0396	0.00249	3.944	0.0098	0.0331
Ostracod ??	0.0000	0.00000	4.510	0.0000	0.0000
Others	0.2806	0.01768	4.510	0.0797	0.2689
POLYCHAETES	*	*	*	*	*
Pectinaria sp	2.8245	0.17794	3.242	0.5769	1.9457
Sabellidae	2.5572	0.16110	3.170	0.5107	1.7225
Others	0.0063	0.00040	3.503	0.0014	0.0047
ECHINODERMS					
Echinarachnius parma	5.6911	0.35854	2.110	0.7565	2.5516
MISCELLANEOUS					
Hydroid	0.0049	0.00031	5.724	0.0018	0.0060
Bryozoan	0.0025	0.00016	5.724	0.0009	0.0030
Plant matter	0.3058	0.01927	4.477	0.0862	0.2909
Fish	0.0036	0.00022	5.086	0.0011	0.0038
Floc	87.9420	5.54035	4.970	27.5355	92.8717
Sand	0.0000	0.00000	0.000	0.0000	0.0000
TOTALS	100.0	6.30	--	29.649	100.0

Table 20. Caloric intake from various prey items based on June daily ration of juvenile king crab. Calculations include floc with an estimated caloric value of 4.970 calories/mg dry weight.

Table 21. Caloric intake from various prey items based on June daily ration of juvenile king crab. Calculations include floc with an estimated caloric value of 2.485 calories/mg dry weight.

Prey item	Corrected % of diet	Dry wt (mg)	Calories per mg dry wt	Calories per prey item	% of total calories
GASTROPODS	*	*	*	*	*
Neptunea sp	0.0000	0.00000	4.494	0.0000	0.0000
Oenopota sp	0.0091	0.00057	4.510	0.0026	0.0162
Retusa obtusa	0.0000	0.00000	4.494	0.0000	0.0000
Naticidae	0.0000	0.00000	4.620	0.0000	0.0000
Neverita nana	0.0000	0.00000	4.620	0.0000	0.0000
Trochidae	0.0000	0.00000	3.730	0.0000	0.0000
Solariella sp	0.1216	0.00766	3.730	0.0286	0.1799
Others	0.0008	0.00005	4.494	0.0002	0.0013
PELECYPODS	*	*	*	*	*
Cyclocardia cebricostata	0.1555	0.00980	4.340	0.0425	0.2677
Tellina sp	0.0128	0.00080	4.530	0.0036	0.0229
Spisula polynyma	0.0275	0.00173	4.530	0.0079	0.0494
Others	0.0101	0.00064	4.530	0.0029	0.0181
CRUSTACEANS	*	*	*	*	*
Balanus sp	0.0000	0.00000	4.596	0.0000	0.0000
Amphipods	0.0000	0.00000	4.002	0.0000	0.0000
Paguridae	0.0396	0.00249	3.944	0.0098	0.0619
Ostracod ??	0.0000	0.00000	4.510	0.0000	0.0000
Others	0.2806	0.01768	4.510	0.0797	0.5020
POLYCHAETES	*	*	*	*	*
Pectinaria sp	2.8245	0.17794	3.242	0.5769	3.6326
Sabellidae	2.5572	0.16110	3.170	0.5107	3.2157
Others	0.0063	0.00040	3.503	0.0014	0.0087
ECHINODERMS					
Echinarachnius parma	5.6911	0.35854	2.110	0.7565	4.7636
MISCELLANEOUS					
Hydroid	0.0049	0.00031	5.724	0.0018	0.0112
Bryozoan	0.0025	0.00016	5.724	0.0009	0.0056
Plant matter	0.3058	0.01927	4.477	0.0862	0.5431
Fish	0.0036	0.00022	5.086	0.0011	0.0072
Floc	87.9420	5.54035	2.485	13.7678	86.6933
Sand	0.0000	0.00000	0.000	0.0000	0.0000
TOTALS	100.0	6.300	--	15.881	100.0

Table 22. Caloric intake from various prey items based on June daily ration of juvenile king crab. Calculations exclude floc.

Prey item	Corrected % of diet	Dry wt (mg)	Calories per mg dry wt	Calories per prey item	% of total calories
GASTROPODS	*	*	*	*	*
Neptunea sp	0.0000	0.00000	4.494	0.00000	0.0000
Oenopota sp	0.0753	0.00474	4.510	0.02140	0.1220
Retusa obtusa	0.0000	0.00000	4.494	0.00000	0.0000
Naticidae	0.0000	0.00000	4.620	0.00000	0.0000
Neverita nana	0.0000	0.00000	4.620	0.00000	0.0000
Trochidae	0.0000	0.00000	3.730	0.00000	0.0000
Solariella sp	1.0088	0.06356	3.730	0.23706	1.3521
Others	0.0063	0.00040	4.494	0.00178	0.0102
PELECYPODS	*	*	*	*	*
Cyclocardia cebricostata	1.2900	0.08127	4.340	0.35271	2.0117
Tellina sp	0.1059	0.00667	4.530	0.03021	0.1723
Spisula polynyma	0.2283	0.01438	4.530	0.06515	0.3716
Others	0.0837	0.00527	4.530	0.02389	0.1362
CRUSTACEANS	*	*	*	*	*
Balanus sp	0.0000	0.00000	4.596	0.00000	0.0000
Amphipods	0.0000	0.00000	4.002	0.00000	0.0000
Paguridae	0.3282	0.02067	3.944	0.08154	0.4651
Ostracod ??	0.0000	0.00000	4.510	0.00000	0.0000
Others	2.3281	0.14667	4.510	0.66148	3.7728
POLYCHAETES	*	*	*	*	*
Pectinaria sp	23.4334	1.47630	3.242	4.78617	27.2981
Sabellidae	21.2155	1.33658	3.170	4.23695	24.1656
Others	0.0521	0.00328	3.503	0.01151	0.0656
ECHINODERMS					
Echinarachnius parma	47.2158	2.97459	2.110	6.27639	35.7976
MISCELLANEOUS					
Hydroid	0.0410	0.00258	5.724	0.01479	0.0844
Bryozoan	0.0205	0.00129	5.724	0.00739	0.0421
Plant matter	2.5370	0.15983	4.477	0.71557	4.0813
Fish	0.0295	0.00186	5.086	0.00945	0.0539
Floc	*	*	4.970	*	*
Sand	*	*	0.000	*	*
TOTAL	100.0	6.30	--	17.533	100.0

Table 23. Caloric intake from various prey items based on August daily ration of juvenile king crab. Calculations include floc with an estimated caloric value of 4.970 calories/mg dry weight.

Prey item	Corrected % of diet	Dry wt (mg)	Calories per mg dry wt	Calories per prey item	% of total calories
GASTROPODS	*	*	*	*	
Neptunea sp	0.0002	0.0000	4.494	0.0001	0.0002
Oenopota sp	0.0030	0.0004	4.510	0.0016	0.0027
Retusa obtusa	0.0001	0.0000	4.494	0.0001	0.0001
Naticidae	0.0050	0.0006	4.620	0.0028	0.0047
Neverita nana	0.0246	0.0029	4.620	0.0135	0.0233
Trochidae	0.0198	0.0024	3.730	0.0088	0.0151
Solariella sp	0.0656	0.0078	3.730	0.0292	0.0501
Others	0.0227	0.0027	4.494	0.0121	0.0209
PELECYPODS	*	*	*	*	*
Cyclocardia cebricostata	0.0055	0.0007	4.340	0.0028	0.0049
Tellina sp	1.2191	0.1453	4.530	0.6583	1.1323
Spisula polynyma	0.0364	0.0043	4.530	0.0196	0.0338
Others	0.0000	0.0000	4.530	0.0000	0.0000
CRUSTACEANS	*	*	*	*	*
Balanus sp	0.0258	0.0031	4.596	0.0142	0.0244
Amphipods	0.0094	0.0011	4.002	0.0045	0.0077
Paguridae	0.0000	0.0000	3.944	0.0000	0.0000
Ostracod ??	0.0408	0.0049	4.510	0.0219	0.0377
Others	0.0827	0.0099	4.510	0.0445	0.0765
POLYCHAETES	*	*	*	*	*
Pectinaria sp	3.6374	0.4336	3.242	1.4056	2.4178
Sabellidae	0.9219	0.1099	3.170	0.3484	0.5992
Others	0.0000	0.0000	3.503	0.0000	0.0000
ECHINODERMS					
Echinarachnius parma	0.2002	0.0239	2.110	0.0503	0.0866
MISCELLANEOUS					
Hydroid	0.0286	0.0034	5.724	0.0195	0.0336
Bryozoan	0.0157	0.0019	5.724	0.0107	0.0184
Plant matter	0.0719	0.0086	4.477	0.0384	0.0660
Fish	0.0554	0.0066	5.086	0.0336	0.0578
Floc	93.5101	11.1464	4.970	55.3976	95.2864
Sand	0.0000	0.0000	0.000	0.0000	0.0000
TOTAL	100.0	11.920	--	58.138	100.0

Table 24. Caloric intake from various prey items based on August daily ration of juvenile king crab, calculations include floc with an estimated caloric value of **2.485 calories/mg dry weight.**

Prey item	Corrected % of diet	Dry wt (mg)	Calories per mg dry wt	Calories per prey item	% of total calories
GASTROPODS	*	*	*	*	*
Neptunea sp	0.0002	0.0000	4.494	0.0001	0.0003
Oenopota sp	0.0030	0.0004	4.510	0.0016	0.0052
Retusa obtusa	0.0001	0.0000	4.494	0.0001	0.0003
Naticidae	0.0050	0.0006	4.620	0.0028	0.0092
Neverita nana	0.0246	0.0029	4.620	0.0135	0.0444
Trochidae	0.0198	0.0024	3.730	0.0088	0.0289
Solariella sp	0.0656	0.0078	3.730	0.0292	0.0959
Others	0.0227	0.0027	4.494	0.0121	0.0398
PELECYPODS	*	*	*	*	*
Cyclocardia cebricostata	0.0055	0.0007	4.340	0.0028	0.0092
Tellina sp	1.2191	0.1453	4.530	0.6583	2.1627
Spisula polynyma	0.0364	0.0043	4.530	0.0196	0.0644
Others	0.0000	0.0000	4.530	0.0000	0.0000
CRUSTACEANS	*	*	*	*	*
Balanus sp	0.0258	0.0031	4.596	0.0142	0.0466
Amphipods	0.0094	0.0011	4.002	0.0045	0.0148
Paguridae	0.0000	0.0000	3.944	0.0000	0.0000
Ostracod ??	0.0408	0.0049	4.510	0.0219	0.0719
Others	0.0827	0.0099	4.510	0.0445	0.1462
POLYCHAETES	*	*	*	*	*
Pectinaria sp	3.6374	0.4336	3.242	1.4056	4.6178
Sabellidae	0.9219	0.1099	3.170	0.3484	1.1446
Others	0.0000	0.0000	3.503	0.0000	0.0000
ECHINODERMS					
Echinarachnius parma	0.2002	0.0239	2.110	0.0503	0.1652
MISCELLANEOUS					
Hydroid	0.0286	0.0034	5.724	0.0195	0.0641
Bryozoan	0.0157	0.0019	5.724	0.0107	0.0352
Plant matter	0.0719	0.0086	4.477	0.0384	0.1262
Fish	0.0554	0.0066	5.086	0.0336	0.1104
Floc	93.5101	11.1464	2.485	27.6988	90.9977
Sand	0.0000	0.0000	0.000	0.0000	0.0000
TOTAL	100.0	11.920	--	30.439	100.0

Table 25. Caloric intake from various prey items based on August daily ration of juvenile king crab. Calculations exclude floc.

Prey item	Corrected % of diet	Dry wt (mg)	Calories per mg dry wt	Calories per prey item	% of total calories
GASTROPODS	*	*	*	*	*
Neptunea sp	0.0032	0.00038	4.494	0.0017	0.0040
Oenopota sp	0.0456	0.00544	4.510	0.0245	0.0581
Retusa obtusa	0.0019	0.00023	4.494	0.0010	0.0024
Naticidae	0.0772	0.00920	4.620	0.0425	0.1007
Neverita nana	0.3784	0.04510	4.620	0.2084	0.4936
Trochidae	0.3045	0.03630	3.730	0.1354	0.3208
Solariella sp	1.0100	0.12039	3.730	0.4491	1.0638
Others	0.3492	0.04163	4.494	0.1871	0.4431
PELECYPODS	*	*	*	*	*
Cyclocardia cebricostata	0.0842	0.01004	4.340	0.0436	0.1032
Tellina sp	18.7797	2.23854	4.530	10.1406	24.0213
Spisula polynyma	0.5605	0.06681	4.530	0.3027	0.7169
Others	0.0000	0.00000	4.530	0.0000	0.0000
CRUSTACEANS	*	*	*	*	*
Balanus sp	0.3981	0.04745	4.596	0.2181	0.5166
Amphipods	0.1443	0.01720	4.002	0.0688	0.1630
Paguridae	0.0000	0.00000	3.944	0.0000	0.0000
Ostracod ??	0.6280	0.07486	4.510	0.3376	0.7998
Others	1.2740	0.15186	4.510	0.6849	1.6224
POLYCHAETES	*	*	*	*	*
Pectinaria sp	56.0310	6.67890	3.242	21.6530	51.2922
Sabellidae	14.2017	1.69284	3.170	5.3663	12.7118
Others	0.0000	0.00000	3.503	0.0000	0.0000
ECHINODERMS					
Echinarachnius parma	3.0835	0.36755	2.110	0.7755	1.8371
MISCELLANEOUS					
Hydroid	0.4409	0.05255	5.724	0.3008	0.7125
Bryozoan	0.2418	0.02882	5.724	0.1650	0.3908
Plant matter	1.1081	0.13208	4.477	0.5913	1.4008
Fish	0.8532	0.10170	5.086	0.5172	1.2252
Floc	*	*	4.970	*	*
Sand	*	*	0.000	*	*
TOTAL	100.0	11.920	--	42.215	100.0

Table 26. Matrix of self and cross reactions between prey items from immunological testing with micro-ouchterlony-double-diffusion-in-agar technique.

		Extract																					
		1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22
1.	Axiothella rubrocincta	9	1	1	0	1	2	1	1	0	1	1	2	2	0	1	0	0	0	1	0	1	1
2.	Pista elongata	0	4	0	1	1	1	0	1	0	0	0	0	0	0	0	0	0	0	0	0	1	0
3.	Harmothoe imbricata	1	2	4	0	1	2	0	2	0	1	1	1	1	0	0	0	0	0	0	0	1	0
4.	U/K sabellidae polychaete	1	1	2	5	2	2	2	2	0	1	1	1	0	0	0	0	0	0	0	0	0	0
5.	Ophelia limacina	1	1	1	2	5	1	1	2	0	1	1	1	1	0	0	0	0	0	0	0	0	0
6.	U/K glyceridae polychaete	2	3	2	4	4	8	3	3	1	3	2	3	1	3	3	3	2	3	0	0	2	1
7.	Pectinaria sp	1	2	0	1	1	1	9	1	0	1	0	1	1	0	0	0	0	0	0	0	0	0
8.	U/K oligochaetes	2	2	2	4	4	5	1	8	2	3	4	3	4	3	3	1	1	2	0	0	0	0
9.	U/K nematodes	0	0	0	0	0	0	1	1	4	0	0	0	0	1	1	0	1	1	0	0	0	0
10.	Spisula polynyma	3	2	3	3	1	2	2	1	0	7	6	6	4	2	2	2	3	1	2	0	1	1
11.	Tellina lutea	1	1	1	2	1	1	1	2	0	1	7	2	2	1	0	0	0	0	0	0	0	0
12.	Cyclocardia cebricostata	1	1	1	2	2	1	2	1	1	2	1	5	3	0	1	3	0	0	0	0	1	0
13.	Solariella sp	2	2	1	1	1	2	0	3	0	2	2	3	6	1	1	1	1	1	0	1	0	0
14.	U/K hermit crab	2	2	2	2	1	1	0	2	0	2	2	1	1	7	2	3	8	4	4	0	0	0
15.	Balanus sp.	2	1	1	2	1	2	0	1	0	1	2	1	0	3	9	2	5	2	0	0	1	0
16.	U/K cumacean	1	0	0	0	0	1	1	1	1	0	0	0	1	1	1	9	2	2	0	0	0	0
17.	Paralithoides camtschatica	5	1	1	1	1	0	0	2	0	3	2	2	2	2	3	2	11	4	1	0	1	0
18.	Chionoecetes bairdi	1	1	1	3	1	1	1	0	0	3	2	3	2	2	2	2	7	7	0	0	1	0
19.	U/K bryozoans	0	0	0	0	0	0	0	0	0	0	2	0	0	0	0	0	0	0	5	0	0	0
20.	U/K diatoms	0	0	0	0	0	0	0	0	0	1	1	0	0	0	0	0	0	0	0	6	0	0
21.	Dendraster exentricus	1	1	0	1	0	0	2	0	0	2	1	1	0	0	3	1	1	1	1	0	11	0
22.	U/K gadidae fish	1	0	0	0	0	0	0	0	0	1	2	0	1	0	2	0	2	1	0	1	0	5

Table 27. Results of visual examination of stomach contents of king crab >50 mm C.L. Station C-57, June 1982. X = item detected visually.

	Crab #																		
Prey item	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21
Pectinaria sp	X						X			X		X	X					X		
Spisula polynyma	X				X			X			X	X				X				
Tellina sp		X				X	X						X				X			
Cyclocardia sp	X			X	X	X	X	X	X	X		X	X		X	X	X	X	X	X
Solariella sp					X		X	X			X	X				X		X	X	X
Oenopota sp	X			X	X		X	X		X		X			X					
Retusa sp										X										
U/K Trochidae fam.				X		X			X	X					X					X
U/K Naticidae fam.				X				X												
U/K gastropod																			X	
Hermit crab												X								
King crab														X						
U/K crustacean															X					
Balanus sp			X	X																
U/K hydroid										X				X						

There was an average of four prey antisera per crab stomach showing precipitin lines. However, these lines were not always strong and distinct. Moreover, there were only 2 lines at the most showing for these reactions. More precipitin lines were expected (Feller, personal communication) and more needed to confirm a positive predator-prey interaction using Feller's algorithm.

There were several possible explanations for the number of precipitin lines being lower than expected. First, during handling and long-term storage in a freezer, the antigenic protein may have broken down causing the loss of specificity needed to confirm the predator-prey interaction. Immunoassays were performed on several stomachs collected during May and June cruises of 1983. These stomachs had not been stored long prior to the immunoassay. The results were similar. There were few precipitin lines showing and those not very distinct. The problem was not due to handling and storage.

Secondly, the titre (antibody concentration) of the antisera may have been too low. Prey extracts and homologous antisera had produced many precipitin lines, as shown in Table 26; however, the stomach contents may readily have been diluted by digestive secretions in the foregut. Serial dilutions and analysis of antisera indicated the titre was sufficiently high. Similarly, dilution of antigenic material to a probable level found in the gut showed positive precipitin results when tested with its respective antisera. Also, the total protein concentrations of crab stomachs examined was as high as the original antigenic material.

Thirdly, the antigenic determinants (the separate combining sites on the surface of the protein) could have been rapidly denatured due to digestive processes. Two pieces of evidence support this explanation. The first came from one king crab observed feeding on sabellid polychaetes during a shipboard experiment in June of 1983 and flash frozen at that time. When the gut was dissected, the tissue and worm tube could readily be seen. Immunological tests were run on the stomach contents. Two precipitin lines were observed between the stomach contents and the sabellid polychaete antisera. Reaction lines were not very distinct, and 5 lines (the self reaction number for sabellid polychaetes) were expected because the tissue ingested was fresh and still obviously present in the gut.

The other evidence came from a supplemental feeding experiment performed to address the question of how long particular antigenic determinants remain viable in the digestive tract of a crustacean predator. Live red rock crab, Cancer productus, were collected in Sequim Bay and held in the laboratory for 3-4 days to clear their gut contents.

They were then fed thawed juvenile gadid fish which had been collected previously from Bristol Bay during the August 1982 cruise. The time of feeding was noted for each crab. The crabs were frozen whole at preset time intervals of 1.5, 4, 8, and 24 hours after being fed. Also frozen were other red rock crabs that had not been fed and, therefore, had empty guts (T = 0). Visual examination of the stomach contents of the experimental crab showed that at T = 1.5 hours, fish in the gut were still recognizable as such. Fish were still present at T = 4 and 8 hours, but the contents were ground to a fine paste. At 24 hours the gut was empty in some crabs, others still had a small amount of finely ground paste. At T = 0 the crabs, indeed, had empty stomachs. Ouchterlony tests were performed using these stomach contents to demonstrate whether or not antigenic determinants within the gut declined over time due to digestion processes. The fish antisera (Ab) was placed in the center well of the slide. The fish antigen (Ag) was placed in an outer well. The time series stomach contents were also placed in surrounding outer wells in a manner that would easily show disappearance or retention of the precipitin lines.

As shown in Figure 13A, the fish antisera - antigen reaction had 5 self reaction lines as expected. The two inner precipitin lines continue through the T = 1.5 hour stomach contents and T = 4 well. One precipitin line continues through to T = 8. There were no lines at T = 24 hours and as expected none at T = 0. The three outer precipitin lines between the fish Ag and Ab were absent from stomachs throughout the time series. The antigenic determinants for these 3 lines no longer existed after 1.5 hours of digestion. There were 2 determinants that survived longer; however, all antigenic material was gone at 24 hours. The information obtained from this experiment correlated with the visual examination of the gut contents. There was little, if any fish remaining in the gut at 24 hours and no precipitin lines to indicate otherwise.

This feeding experiment was conducted with red rock crab because live king crab were not available at Sequim. Hence any conclusions made should be tentative until feeding experiments can be carried out with king crab and other prey items in addition to fish. With this caveat, the indications are still strong that the antigenic material necessary for detection in the gut degrades with time. Moreover, some antigenic determinants break down after a very short time in the foregut of crabs. The loss of antigenicity correlates with the visually observed residence time of the fish in the gut. This may be true for other soft bodied prey species as well.

Feller et al (1979) designed an algorithm to assure that precipitin lines observed were correctly attributed to the presence of the prey

13a

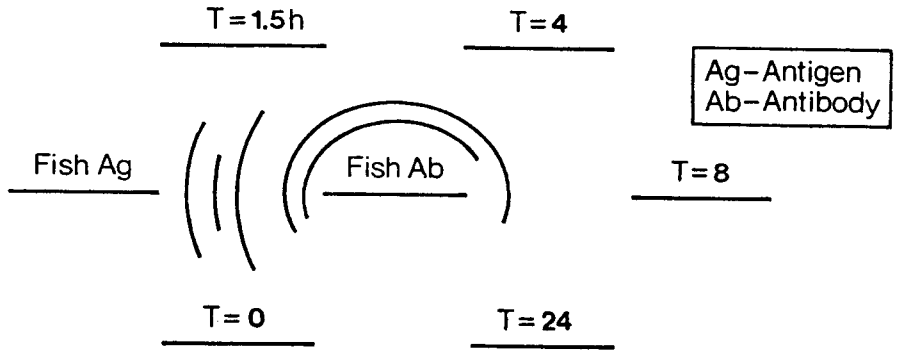
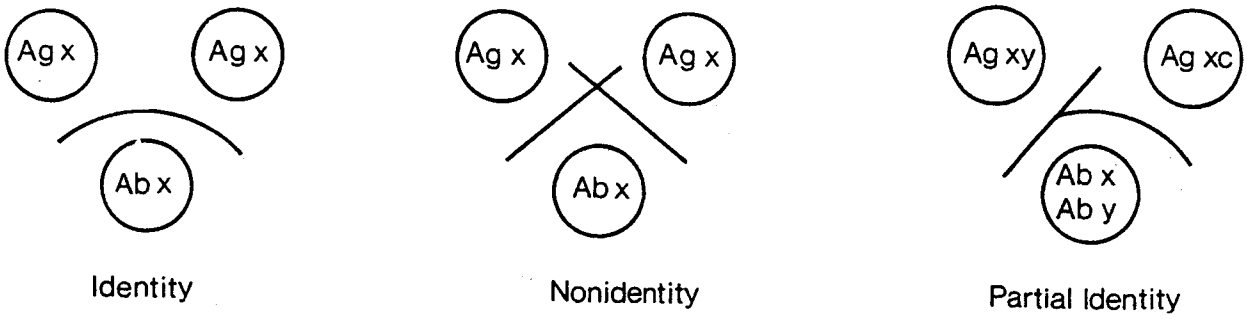


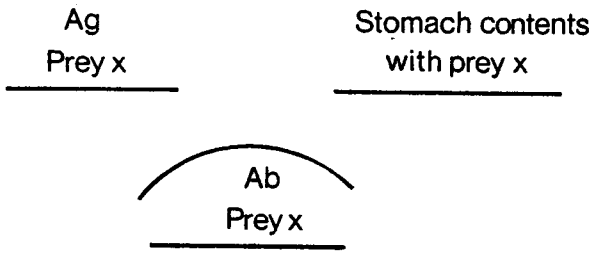
Figure 13a. Loss of precipitin reaction lines for fish antigens with time spent in crab foreguts.

13b



13b. Precipitin reaction lines of identity, nonidentity, and partial identity.

13c



13c. Example of positive reaction between stomach contents and prey item. A line of identity is formed.

being tested rather than to cross reactions. The algorithm is by design relatively conservative. Because only one or two reaction lines were occurring, any antisera that had a cross reaction of 2 or more with king crab (see Table 26, column 17) would automatically be eliminated from consideration as a prey item. Such antisera included Spisula sp, hermit crab, Balanus, and gadid fish - food items which visual examination of gut contents had demonstrated as present in the gut. An example of the application of Feller's algorithm is given in Figure 14.

In any given antigen there may be antigenic determinants that will survive longer when subjected to digestive processes as evidenced by the 2 out of 5 remaining precipitin lines from the king crab that fed on the sabellid polychaete. The few precipitin lines that did occur in king crab stomachs were related to strong antigenic determinants. How long they remain is determined by the digestive processes of a particular organism and the composition of the antigenic determinant.

Because of rapid digestion in the guts of crab, it was apparent that Feller's algorithm of counting the number of precipitin lines and subtracting cross reactions was not going to suffice for this study. Because there was information to be obtained from the precipitin reactions, Feller's algorithm was replaced with a different approach that experimentally determined the type of precipitin reaction. According to Roitt (1971), there are three basic patterns (Figure 13b) of precipitation that can be obtained in Ouchterlony tests:

(a) The REACTION OF IDENTITY - this occurs between identical antigenic determinants, causing the precipitin lines to fuse giving a continuous arc.

(b) The REACTION OF NONIDENTITY - this occurs where two antigens do not contain any common antigenic determinants, causing the precipitin lines to form independently and cross without any interaction.

(c) The REACTION OF PARTIAL IDENTITY - this occurs where partially related antigens have one common determinant giving a continuous line of identity. An extra determinant in one of the antigens gives a line of nonidentity causing a spur to form.

To separate positive predator-prey interactions from potential cross reactions Feller's algorithm was replaced with more immunoassay tests using lines of identity and nonidentity. The procedure for all the crab stomachs was first to test the stomach contents against all the antisera. Any antisera that showed a positive reaction with contents was retested

Algorithm Example

Number of reaction lines observed in stomach contents of king crab

hermit crab	-	2
Spisula sp	-	2

Step 1 Rank the potential prey taxa based on a ratio of:

$$\frac{\text{\# of lines observed in the gut of sample crab}}{\text{\# of lines observed in self reaction (See Table 3)}}$$

hermit crab	2/7	.29	1
Spisula sp	1/7	.14	2

Step 2 Eliminate cross reactions that may have been due to cross reactions with the predator (king crab)

Antiserum by rank	# reaction lines observed between king crab and antisera		# of lines due to cross reactions with king crab		
HERMIT CRAB	2	-	8	=	NEG
SPISULA SP	1	-	3	=	NEG

Step 3 Eliminate cross reactions that may have been due to cross reactions with other prey in the gut.

Figure 14. An example of the algorithm for eliminating false detections due to immunological cross reactions.

against its respective antigen and stomach contents, and the reaction examined for lines of identity (see Figure 13c).

Tables 28 and 30 give the results of these tests. X's indicate that precipitin lines were present on the first test. Underlined X's indicate that the second test showed a positive line of identity, confirming that prey item existed in the stomach. X's not underlined may or may not be prey items. Present immunological evidence can neither confirm nor deny their being prey items. Only those items showing a positive reaction after retesting are considered to have been detected for this report.

For the larger juvenile king crabs (CL >50 mm) (Tables 27 and 28), the immunoassay detected a maldanid polychaete, the clam, Spisula polynyma, pagurid crab, and a tunicate in stomachs where these items were undetected by visual examination. For Spisula polynyma, the immunoassay detected this clam in 4 cases where it was not detected visually. Visual examination detected S. polynyma in 5 cases where the immunoassay did not detect the clam or failed to give a positive detection when retested for lines of identity.

For yearling juvenile king crab (CL <30 mm) (Tables 29 and 30), the immunoassay added 5 prey items not detected visually: three polychaetes, an oligochaete, and a nematode. These new items are all soft bodied prey; two are meiofaunal. A total of 8 prey were detected visually and 10 immunologically. Five items were detected immunologically but not visually and three visually but not immunologically. For items detected both immunologically and visually, the frequency of occurrence increased by using the immunoassay. For yearling king crab collected on the North Aleutian Shelf cruise in September 1983, nothing could be visually distinguished in the stomachs except floc and sand. Among these crabs the immunoassay detected a maldanid polychaete, a glycerid polychaete, oligochaetes, the clam, Cylcocardia cebricostata, a pagurid crab, and sand dollars.

Table 28. Immunoassay precipitin reactions from stomachs of juvenile king crab 50-90 mm C.L., station C-57, June 1982. Crab numbers match those in Table 27.

Antisera	Crab # 1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21
Arctomdia brevis																					
Axiothella rubrocineta	X	X		X		X	X	X			X	X	X	X	X		X		X	X	
Pista elongata																					
Harmothoe imbricata														X							
U/K sabellid polychaete		X										X									
Nereis vexillosa																					
Naineris dendritica							X														
Lumbrineris tetrauna																					
U/K polychaetes			X									X									
Spisula polynyma	X		X	X	X	X	X			X	X	X	X			X		X	X	X	
Tellina lutea															X	X	X			X	
Solariella sp					X		X									X				X	
Fusitriton sp							X									X					
Corophium amphipod																					
Crangon shrimp																					
U/K hermit crab	X	X	X	X	X		X	X	X	X	X	X		X			X		X	X	X
Balanus sp												X									
Leptochelia savignyi																					
King crab	X		X		X		X	X	X		X	X	X	X	X	X	X	X	X	X	
Tanner crab																X					

Antisera	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20
U/K brittle star																				
U/K sea urchin												X								
U/K tunicate						X								X	X					
U/K hydroid												X			X					
U/K bryozoan																				
U/K diatoms															X					
U/K gadidae fish															X					

X - indicates at least one precipitin line between stomach contents and antisera.

_ - indicates "line of identity" between antigen and stomach contents and the probable presence of the prey item.

Table 29. Results of visual examination of stomach contents of juvenile king crab < 40 mm C.L.

Prey item	Crab # 100	101	104	106	108	109	112	114	116	132(a)	134(a)	136(a)	138(a)
U/K bivalve	X												
U/K gastropod				X									
Trochidae fam.			X										
Naticidae fam.					X	X	X						
U/K crustacean		X	X					X					
U/K copepod													
U/K barnacle					X		X						
Caprellid amphipod					X		X						
U/K echinoid		X											
Foraminifera													
Sand	X	X	X	X	X	X	X	X	X	X	X		X
Floc	X	X	X	X	X	X	X	X		X	X	X	X

(a) These crab were collected during September of 1983.

Table 30. Immunoassay precipitin reactions from stomachs of juvenile king crab <40 mm C.L.

Antisera	Crab # 102	103	105	107	110	111	113	115	133(a)	135(a)	137(a)	139(a)
Axiothella rubrocincta			X	X		X				X		
Pista elongata												
Harmothoe imbricata				X	X	X				X		
Fam. Sabellidae					X							
Ophelia limacina			X		X		X					
Fam. Glyceridae		X	X	X	X	X	X		X	X	X	X
Pectinaria sp		X			X	X	X			X		
U/K oligochaetes		X	X	X	X	X	X			X	X	
U/K nematodes					X							
Spisula polynyma	X	X	X									
Tellina lutea												
Cyclocardia cebricostata		X	X	X	X	X				X		
Solariella sp			X	X		X				X		
U/K hermit crab	X	X	X	X	X	X	X			X	X	
Balanus sp			X	X	X	X					X	
U/K cumacean		X	X		X	X					X	
Red king crab	X	X	X	X	X	X	X		X	X	X	X
Tanner crab	X	X	X		X	X	X		X	X	X	
U/K bryozoans			X									
U/K diatoms					X							
Sand dollar	X	X	X	X	X	X		X		X	X	
Gadidae fish										X	X	

X - Indicates at least one precipitin line between stomach contents and antisera.

_ - "Line of identity" between antigen and stomach contents indicating probable presence of prey item.

(a) - These crab were collected during September of 1983.

DISCUSSION

IMMUNOASSAY

The immunological examination of stomach contents as applied here provided evidence that juvenile king crab consume prey items overlooked by conventional visual examination of gut contents and that these overlooked prey were soft-bodied, readily-digested organisms. As expected, the value of the immunoassay was greatest for the smallest juvenile king crab.

The immunoassay suffered some lack of sensitivity apparently due to low gut residence times of antigenic determinants. Because of the rapid breakdown of antigenic determinants in crab stomachs, the extent to which the smallest juvenile crabs depend on soft bodied macro and meiofaunal prey could well be underestimated here.

Further use of this immunoassay for king crabs and other crustaceans should be enhanced by experimental determination of gut residence times of the antigenic determinants. Particularly important would be the determination whether there is substantial enough variation in gut residence times of antigenic determinants with prey type to be a significant source of bias. If prey types do vary substantially in the gut residence times of their antigenic determinants, then correction of dietary composition determined by immunoassay would follow the procedures used here for correction of dietary composition determined by visual examination.

Replacing the algorithm for eliminating reactions that may be cross-reactions with the retesting for lines of identity after initial screenings proved to be a better method for juvenile king crab although more time consuming. Retesting for lines of identity reduces potential loss of information due to the conservative nature of the algorithm. More study is needed to develop an improved experimental approach to the elimination of cross reactions.

Other experimental studies to refine the immunoassay would include the following: time studies of the decay of mixtures of antigenic determinants using prey with no cross reactions; feeding experiments to determine the effects of digestive processes on changes in the antigenic determinants;

development of unique antigens to decrease cross reactions; and investigation of other immunological approaches.

Any immunoassay suffers two problems in a diverse prey community. Because antisera were not prepared for all possible prey species, it is still possible that even with the retesting for lines of identity that some positive reactions are due to another immunologically related but untested prey. Also, because antisera were prepared only for the probable, not all possible, prey, some prey may remain undetected. The import of these considerations is that the immunoassay like visual examination may be overlooking prey items.

The immunoassay provided evidence that juvenile king crab, especially, the smallest juveniles (CL <30 mm), consume soft-bodied prey types overlooked by conventional visual examination. In so doing, however, it proved more time consuming, more expensive, and more complicated in its application and interpretation than expected. The results here indicate that immunological examination of stomach contents needs to be thoughtfully applied and in specific situations will require supplemental experimental work to support and refine its application. Immunological examination proved valuable in this study and in future should be seriously considered, especially, for small-sized predators, as a supplement to conventional visual examination of stomach contents. Further development of immunological approaches to stomach contents analysis is necessary to increase their effectiveness and value.

POTENTIAL BIAS IN DETERMINATIONS OF DIET

The greatest difficulty in this study was in obtaining unbiased estimates of dietary composition, and correction of bias was the driving force behind the technique development and supplemental laboratory determinations. Determining the number of a given prey type in crab stomachs proved impossible because shells and tests were often ground too finely to distinguish individuals. Indeed, during the clearance rate determinations, particle size of stomach contents fell rapidly with time and is, therefore, a potential indicator of when the animal fed. Dry weights proved more meaningful than volume in the diel feeding chronology and were, of course, more appropriate for conversion to caloric content (Hyslop, 1980) after estimating the amount of soft tissue ingested from dry weight of hard parts in the gut.

A presently uncorrectable source of bias with king crab is the loss of prey hard parts during ingestion. Three lines of evidence suggest that

juvenile king crabs may depend on clams, especially Spisula polynyma, to a greater extent than data here indicate. First, juvenile king crabs were directly observed scraping the flesh from bivalve shells rather than ingesting shell along with the flesh. Secondly, whereas most of the shell of small clams, such as, Cyclocardia cebricostata were observed in the gut, only bits of the shell margin of Spisula polynyma were found. Thirdly, the immunoassay detected Spisula sp in the stomachs of the larger juveniles where visual examination did not. Given the rapid clearance rate for clam soft tissue determined in shipboard experiments and the three considerations above, the contribution of Spisula to the crab's diet is probably underestimated here.

COMPARISON OF VARIOUS METHODS FOR DETERMINING DIETARY COMPOSITION

For the June, August, and overall diets of juvenile king crab (CL = 53 to 80 mm) comparisons of dietary composition determined by visual examination, dry weights and caloric intake appear in Tables 31, 32, and 33. The major problem in all estimates of dietary composition from stomach analysis is that what is found in the stomach is not directly representative of what occurs in the diet. Corrections done here were designed to estimate the relative contribution of prey items to the diet rather than just to the contents of stomachs.

The findings here agreed with Hyslop (1980) that the frequency of occurrence method gives only a crude qualitative view of dietary composition, suffers greatly when food items are not readily identifiable, and is not an indicator of the amount or bulk of food consumed. Perhaps the most fruitful way to view the frequency of occurrence data is to see it as indicating whether a given prey is consumed by most, some, or only a few of the juvenile crab population.

In contrast to the frequency of occurrence method, the gravimetric approach using dry weights, although more tedious and time consuming, gives the best indication of the amount of food consumed and is necessary for determination of caloric intake (Hyslop, 1980). In interpreting the relative importance of prey items in the diet, more credence was given to rankings of dietary importance based on dry weights and calories than those based on frequency of occurrence.

Perception of what prey were most important changed after correction for gut residence times, estimation of soft tissue dry weights and conversion to caloric equivalents. The major effect of such corrections was to show that, excluding floc, molluscs and echinoderms dominate

Table 31. Comparison of June dietary composition of juvenile king crab estimated by various methods.

	By visual examination			By dry weight			By calories
	% of stomachs	% of all occurrences		% of dry wt	% of tissue dry wt		% of calories
		Uncorrected	Corrected*		Uncorrected	Corrected*	
Gastropods	87	19.5 (27.5)	6.7 (8.4)	1.3 (2.5)**	0.4 (2.0)**	0.13 (1.1)**	0.10 (1.5)**
Pelecypods	91	20.8 (29.4)	7.2 (8.9)	3.9 (7.3)	0.6 (3.2)	0.20 (1.7)	0.19 (2.7)
Crustaceans	52	7.7 (10.9)	9.5 (11.8)	0.2 (0.5)	0.2 (1.3)	0.32 (2.6)	0.30 (4.2)
Polychaetes	48	7.0 (10.0)	44.9 (56.0)	1.1 (2.0)	0.8 (4.5)	5.39 (44.7)	3.67 (51.5)
Echinoderms	95	14.0 (19.9)	4.8 (6.0)	47.1 (87.6)	15.4 (88.4)	5.69 (47.2)	2.55 (35.8)
Other	32	1.6 (2.4)	7.2 (8.9)	0.1 (0.1)	0.1 (0.5)	0.32 (2.6)	0.30 (4.3)
Floc	100	14.7	14.6	36.2	82.6	87.9	92.9
Sand	100	14.7	5.1	10.0	ø	ø	ø

*Corrected for gut residence times.
**Calculated using totals without floc and sand.

Table 32. Comparison of August dietary composition of juvenile king crab estimated by various methods.

	By visual examination			By dry weight			By calories
	% of stomachs	% of all occurrences		% of dry wt	% of tissue dry wt		% of calories
		Uncorrected	Corrected*		Uncorrected	Corrected*	
Gastropods	81	22.5 (31.0)	5.6 (6.4)	2.0 (8.6)**	0.4 (7.2)**	0.14 (2.2)**	0.11 (2.5)**
Pelecypods	100	17.3 (23.9)	4.3 (5.0)	14.6 (64.2)	3.7 (64.8)	1.26 (19.4)	1.17 (24.8)
Crustaceans	74	15.3 (21.1)	13.1 (15.1)	1.4 (6.0)	0.2 (3.1)	0.16 (2.4)	0.15 (3.1)
Polychaetes	37	5.2 (7.0)	23.5 (27.2)	1.4 (6.3)	0.7 (12.7)	4.56 (70.2)	3.02 (64.0)
Echinoderms	33	4.6 (6.3)	1.1 (1.3)	2.8 (12.2)	0.6 (10.3)	0.20 (3.1)	0.09 (1.8)
Other	48	7.7 (10.6)	39.0 (44.9)	0.6 (2.6)	0.1 (1.9)	0.17 (2.6)	0.18 (3.7)
Floc	100	13.8	9.9	64.6	94.4	93.5	95.3
Sand	100	13.8	3.4	12.6	Ø	Ø	Ø

*Corrected for gut residence times.
**Calculated using totals without floc and sand.

Table 33. Comparison of overall dietary composition of juvenile king crab estimated by various methods.

	By visual examination			By dry weight		
	% of stomachs	% of all occurrences		% of dry wt	% of tissue dry wt	
		Uncorrected	Corrected*		Uncorrected	Corrected*
Gastropods	86	20.8 (28.9)**	6.2 (7.4)**	1.7 (5.0)**	0.4 (4.4)**	0.14 (1.7)
Pelecypods	94	19.4 (27.2)	5.8 (7.0)	10.5 (30.3)	2.8 (30.8)	0.97 (12.2)
Crustaceans	60	10.7 (15.0)	11.2 (13.4)	0.9 (2.7)	0.2 (2.1)	0.20 (2.5)
Polychaetes	44	6.3 (8.8)	34.7 (41.7)	1.3 (3.7)	0.7 (8.2)	4.78 (59.8)
Echinoderms	72	10.3 (14.4)	3.1 (3.7)	19.8 (57.2)	4.8 (53.5)	1.69 (21.2)
Other	11	4.0 (5.7)	22.3 (26.8)	0.4 (1.1)	0.1 (1.1)	0.21 (2.6)
Floc	100	14.3	12.4	53.7	91.0	92.0
Sand	100	14.3	4.3	11.6	Ø	Ø

*Corrected for gut residence times.
**Calculated using totals without floc and sand.

stomach contents but soft-bodied polychaete worms are the major food of juvenile king crab.

The results of correction for differential gut residence were sensitive to the values determined for gut residence time. Note the rise in the dietary importance of the miscellaneous category of food items in August (Table 32). An increase in their frequency of occurrence in August coupled with low gut residence times means a high corrected percentage of all occurrences. Whereas frequency of occurrence after correction was high, dietary importance by dry weight was quite low. These results suggest two alternative explanations. In August a greater number of crabs could have been consuming a greater number of miscellaneous items but only in small amounts. Alternatively, the gut residence times for these miscellaneous items could have been underestimated. More experimental effort in determining stomach clearance rates for a larger set of potential prey items would have been desirable.

Less dramatic than changes brought through correction for gut residence time were changes in relative ranking in the diet after estimation of soft tissue dry weights from the dry weights of hard parts in stomachs and soft tissue/hard tissue ratios. Floc increases in the overall diet from 54% of the dry weight of stomach contents to 91% of the estimated dry weight of soft tissue (Table 33). Correction for gut residence time increases floc contribution to 92% of the total corrected dry weight of soft tissue. Excluding floc, only polychaetes increase in relative ranking after estimation of soft tissue dry weight but not dramatically so. It is after correction for gut residence times that polychaetes come to dominate the dietary composition based on tissue dry weight.

Comparing the corrected dietary compositions determined by frequency of occurrence, soft tissue dry weight and caloric intake (columns 3, 6, and 7 in Tables 31 and 32) clearly indicates two things: First, a substantial proportion of the bulk of the food ingested resides in the floc and, secondly, soft-bodied polychaete worms are a substantially more important dietary component than previously supposed. Every stomach examined contained floc, which constituted 54% of the overall dry weight of stomach contents. In terms of corrected soft tissue dry weight and caloric intake, over 90% of the diet of juvenile king crab derives from whatever prey items contribute to the floc found in the stomachs.

Polychaetes are the dominant prey taxa in the crab diet by frequency of occurrence, soft tissue dry weight and caloric intake. Except for echinoderms, dietary composition by soft tissue dry weight parallels dietary composition by caloric intake. The caloric values of the prey

items generally fall between 4000 and 5000 calories per g dry weight. This similiarity of caloric values produced the parallel rankings between soft tissue dry weight and caloric intake. Echinoderms were the exception to the parallel ranking because their caloric value was about half the average of the other prey items.

Whereas the dietary composition by soft tissue dry weight and that by caloric intake are similiar, dietary composition by frequency of occurrence differs from both of the former. In August the prey taxa rank by caloric intake in the following order: polychaetes >> clams >> other > crustaceans > gastropods > echinoderms. In contrast in August prey taxa rank by corrected frequency of occurrence in this order: other > polychaetes > crustaceans > gastropods > clams > echinoderms. In June the rankings by caloric intake are as follows: polychaetes >> echinoderms >> other = crustaceans > clams > gastropods; and by frequency of occurrence: polychaetes >> crustaceans > other = clams = gastropods > echinoderms. The different results from the frequency of occurrence and gravimetric-caloric methods reinforce Hyslop's (1980) statement that **frequency of occurrence data suffer when prey is not readily identifiable** and that frequency of occurrence data is a poor indicator of the bulk of food consumed.

THE FOOD OF JUVENILE KING CRAB

What are the most important items in the diet of juvenile king crab? The answer depends upon the meaning one assigns to the large proportion of floc found in the stomach contents. If one regards the floc as soft tissue from largely unknown organisms that are a different set from those visually identified and whose hard parts were weighed, then one must conclude that the prey items comprising over 80% of the diet by dry weight and over 90% by caloric intake are unknown. If one regards the floc as organic matter derived from prey items identified visually and in rough proportion to the weights determined, then one may conclude that four items dominate the diet of the larger juvenile king crab (CL = 53-80 mm). In order these dominant items are (1) the polychaete, Pectinaria sp, (2) a **sabellid polychaete, (3) the sand dollar, Echinarachnius parma, and (4)** the clam, Tellina sp. The polychaetes constituted more than 50% of the diet by weight and calories in both June and August. The sand dollar was energetically important in June but not in August whereas Tellina sp was important in August. Juvenile king crab appear to be a predator on small, lowly motile benthic organisms that reside at or just below the surface of the sediment.

The assumption that, at least for the larger juvenile king crab, the floc is composed mainly of the soft tissues of prey items identified visually is more reasonable than the assumption that floc derives mainly from a different and unknown set of prey items. The main evidence for the position comes from the immunoassay. For the larger juvenile crab the immunoassay detected the same polychaetes and clams detected visually but often did so in stomachs where the items were, in fact, not detected visually. This result indicates the presence of soft tissue from the prey items amid the visually unrecognizable organic matter. Also, for the larger juvenile crabs, of the two items that the immunoassay detected beyond those detected visually one was a polychaete. Furthermore, as discussed above concerning the clam, Spisula polynyma, the crabs may be ingesting the meat of clams in greater amounts than the presence of hard parts in the stomach indicates. For the larger juvenile king crab (CL = 53-80 mm) the floc comes mainly from polychaetes and clam tissue and not from some totally different, unknown set of prey items. This position **implies that the most reasonable estimates of daily caloric intake were** those calculated without floc, 17.5 and 42.2 calories/g crab wet weight/day in June and August.

The situation for the yearling king crab (CL <30 mm) appears somewhat different from that of the larger juveniles. Floc and sand were often the only visually discernible items in stomachs of yearling king crab. The immunoassay results indicate that the diet of yearling king crab includes a greater proportion of prey items that may not be detected visually and includes items not observed in the larger juveniles. Bivalves, gastropods, sand dollars, barnacles, and small crustaceans were detected both visually and immunologically in yearling king crab and also occur in the diet of the larger juveniles. In addition to these items, the immunoassay detected three polychaetes, (Pectinaria sp, a maldanid, and a glycerid), oligochaetes, and nematodes not detected visually. The immunological evidence suggests that yearling king crab depend more than the larger juveniles on small soft bodied prey including meiofaunal groups not evident in the diet of the larger juveniles.

The dietary differences between June and August have been considered in this study to be seasonal or temporal changes. However, the possibility that the observed differences were due to differences in geographical location or depth may be equally a factor because precisely the same stations were not repeated in August as in June. All stations contributing to the data considered here occurred off Port Moller and were more than one but less than 20 nautical miles apart (Figure 15). Depths in June were 58-65 m and in August, 64-71 m. Examination of Table 7

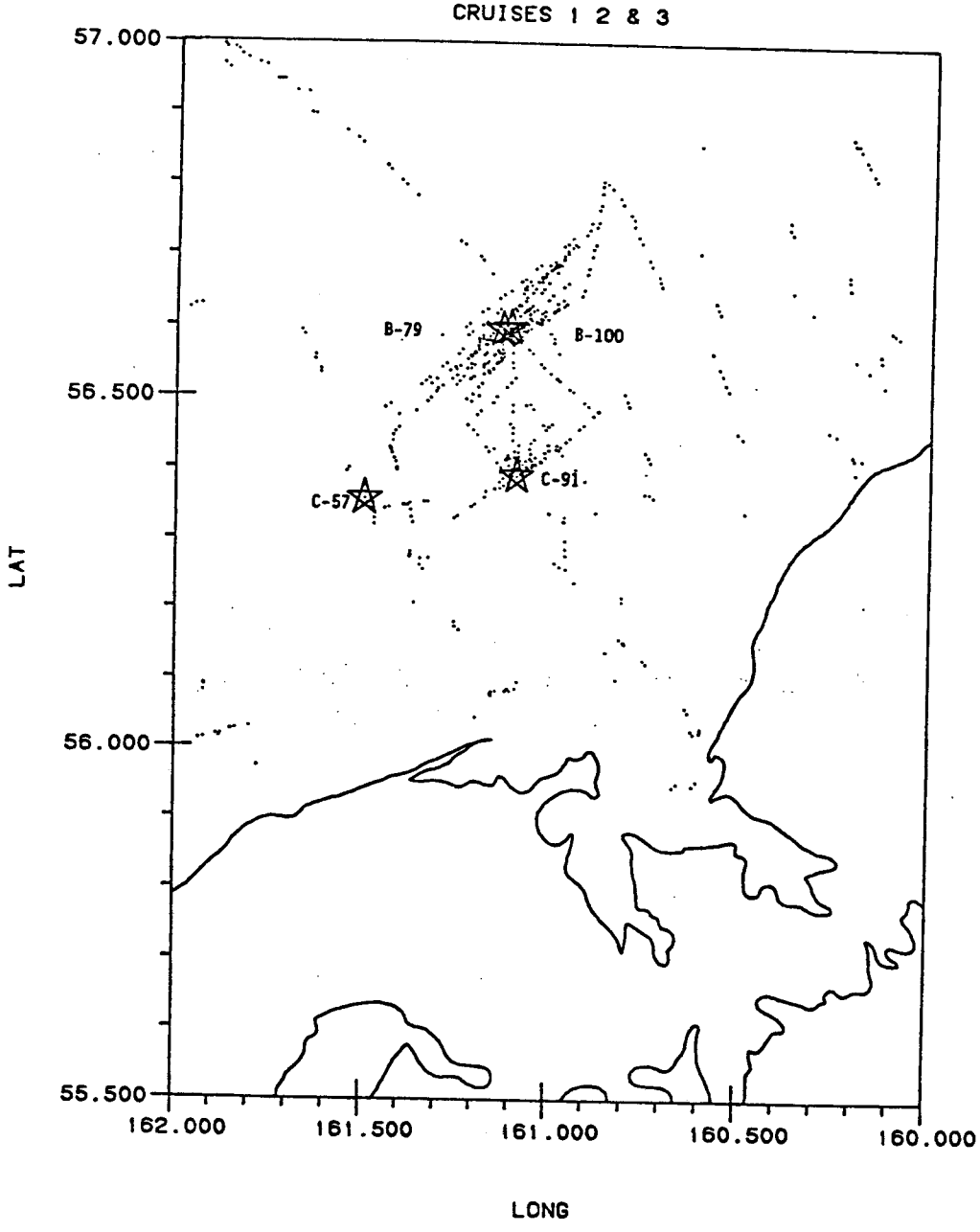


Figure 15. Station locations near Port Moller during June, August, and October, 1982.

shows high similiarity between the stations from August and less similiarity between the stations from June.

The results confirm the hypothesis that juvenile king crab depend upon soft-bodied readily digested prey items to a greater extent than previously thought and indicate that polychaete worms are a consistent and substantial proportion of the crab's diet by bulk and by energy. The diet of the smallest juveniles contains soft-bodied meiofaunal groups detected immunologically but not observed in the diet of larger juveniles.

POTENTIAL IMPACTS FROM OIL AND GAS DEVELOPMENT ON JUVENILE CRABS

Potential impacts from oil and gas development could derive from habitat disturbance, exposure to contaminants from platform discharges, and oil spills. The assessment of risk from these potential impacts **requires judgments concerning, first, the manner and extent to which** disturbance and contaminant exposure is likely to occur and, secondly, the direct and indirect consequences likely given the anticipated extent of disturbance and exposure. The potential impacts differ with life stage. This study was concerned with evaluating possible impacts on juvenile king crab. Because of their different habitats and diets, impacts are assessed separately for the smallest juveniles (CL <30 mm) and the larger juveniles (CL >40 mm).

Assessment of impacts requires consideration of the highly aggregated or clumped distribution of juvenile king crab. The larger juveniles (CL >40 mm) were essentially exclusively concentrated off Port Moller in water depths of 45 to 75 m. In this region larger juvenile king crab appear to aggregate along the seaward side of an oceanographic structural front now being studied by other NOAA/OCSEAP investigators. The temporal changes in the distribution of the larger juveniles may be related to movements in the front's position. The thought that the shallow nearshore zone north of the Alaska Peninsula held abundant juvenile king crab was not confirmed by this survey for the larger juveniles. The smallest juvenile king crab do occur in the nearshore zone amid patches of cobble and rock with abundant epifauna. These patches provide food and shelter from predation in an area of open, high-energy sandy bottoms. More detailed information on the distribution of juvenile crabs along the North Aleutian Shelf will come from another NOAA/OCSEAP study now in progress. The current perception of juvenile crab distribution indicates that for the smallest juveniles impacts from disturbance and platform discharges are unlikely whereas impacts from oil spills need consideration. For the larger juveniles (CL >40 mm) potential effects from disturbance, discharges and

spills need consideration.

The effects of oil spills in the nearshore zone are well documented (see Clark, 1982). Incorporation of oil into the subtidal sediment and its subsequent loss are functions of the circumstances of the particular spill and the energy of the nearshore zone. Because of its high energy the nearshore zone of the North Aleutian Shelf appears likely to have oil incorporated into and readily lost from subtidal sand following a spill. Whereas prediction of the probable occurrence, magnitude and extent of an oil spill reaching the nearshore subtidal habitats of the smallest juvenile king crab is beyond the scope of this study, there is little doubt that should a significant spill reach the nearshore zone there could be substantial acute, lethal and sublethal effects. Substantial immediate effects including the oiling and mortality of intertidal crabs occurred during the AMOCO CADIZ spill (See review by Conan et al, 1981). Substantial mortality of juvenile king crab would require water column concentrations of 4.2 ppm total hydrocarbons by IR, the 96-h LC_{50} for moribundity found by Brodersen et al (1977) for juvenile king crab exposed to WSF of Cook Inlet crude oil. The concentrations of oil in the sediment that would produce mortality in the juvenile king crab are not known. If a spill should produce acute mortality in the smallest juvenile king crab, any substantial loss of yearling crab could be felt as decrease in year class strength in the commercial fisheries 8 years later when the crabs would have reached harvestable size.

Chronic indirect effects persisting beyond a spill could derive from loss or reduction in the macro or meiofaunal food of the smallest juveniles. Meiofaunal groups vary considerably in their resistance to oil contamination and can recover quickly (Giere, 1979). In studying a refinery effluent Dicks and Hartley (1982) report that oligochaetes had decreased density at stations near the refinery and showed a gradient in density paralleling that of sediment concentrations of aliphatic hydrocarbon. The immunoassay identified oligochaetes as a dietary item for the smallest juvenile crab. In subtidal recruitment studies Vanderhorst (Unpublished data; see Vanderhorst, 1984) found significant reductions in the numbers of species of polychaetes, mollusks and crustaceans recruiting into sand contaminated with crude oil at total oil levels initially at 2000 ppm and falling to below 1000 ppm in 3 months. Densities of a crustacean and a polychaete selected a priori for detailed analysis were reduced to 1/4 and 1/3, respectively, of the densities in control sand. From intertidal recruitment studies Vanderhorst et al. (1981) predicted full recovery of the infauna to take 31 months following an initial contamination of the sand at 1800 ppm. An oil spill in the shallow nearshore zone can reasonably be expected to reduce the density of food important to juvenile crabs, but prediction of the extent of such restriction in the crab's food supply requires prediction of the salient features of such a spill.

supply requires prediction of the salient features of such a spill.

Restricted food supply can stop growth in marine organisms (Edwards and Huebner, 1977), and retarded growth rates in rock lobster, Jasus lalandii, correlate with the biomass of its principal prey (Newman and Pollock, 1974). Because juvenile lobsters prey upon a restricted size range of small prey, their growth rates are more heavily influenced by the availability of smaller prey than are the growth rates of the adults (Pollock, 1979; Griffiths and Seiderer, 1980). Juvenile king crab are probably also more heavily influenced by the availability of small prey. For juvenile king crab a restriction in food supply can be reasonably expected to retard growth if alternative food is not available or taken. Following the AMOCO CADIZ spill retarded growth was reported for flatfish in one of the heavily contaminated estuaries and edible crab catches were depressed for a year (Maurin, 1981). The expectation that an oil spill in the nearshore zone would retard growth of juvneile king crab through depression of its infaunal prey appears reasonable.

The larger juvenile crab (CL >40 mm) occur on soft bottoms at 45 to 70 m in a relatively small area off Port Moller and could potentially be impacted by physical disturbance, platform discharges, and oil spills. Physical disturbance of the bottom occurs around platforms and is localized. In the vicinity of platforms the effects of disturbance on benthic infauna are usually not clearly separable from effects due to sediment burdens of contaminants (Addy et al., 1978; Dicks and Hartley, 1982). Near platforms in the North Sea oil field in 70 m, Addy et al. (1978) did observe decreased densities of polychaete worms so that the reduction of a food item important to the diet of juvenile crabs could make the vicinity of platforms energetically unrewarding. On the other hand, Wolfson et al (1979) report increases in the density of tube-dwelling polychaetes in the vicinity of an oil platform in California. In a shallow Texas bay in which high turbidity appeared to enhance sedimentation of hydrocarbons, Armstrong et al (1979) found the density of benthic infauna depressed in the vicinity of the outfall of an oil separator platform. Depression of infaunal density appeared to occur where the sedimentary concentration of naphthalenes exceeded 2 ppm. The magnitude of exploration, development and production in the relatively small area off Port Moller in which the juvenile crabs concentrate needs to be predicted before one can assess whether disturbance and production discharges constitute a significant potential impact.

A potential benefit that king crab could derive from oil platforms is an increase in habitat. The smallest juvenile blue king crab (CL <30 mm) near the Pribilof Islands have been found predominantly in shell hash (Armstrong and Pearson, unpublished data). Juvenile red king crab (CL <30

mm) also occur in similiar habitat as well as others offering shelter (Fishman and Armstrong, personal communication). Under an oil platform off California, Wolfson et al (1979) found shell hash from mussels with a mean depth of 3 m. If such shell piles develop under platforms in the Bering Sea, they could offer increased habitat for the recruitment of the smallest juvenile king crab in an otherwise predominantly sandy area.

If an oil spill reaches the area of juvenile crab abundance off Port Moller, potential indirect effects from spilled oil even to the 40-70 m depths where the larger juveniles occur cannot be dismissed although direct lethal effects seem unlikely. Studies after the TSESIS oil spill in the Baltic Sea demonstrate that hydrocarbons from spilled oil can reach deep soft bottoms to produce observable effects on the benthic infauna (Kineman et al., 1980). Following the TSESIS spill hydrocarbons were sedimented to the 30-40 m bottom after attachment to particulates and through incorporation into copepod fecal pellets (Boehm et al., 1980). The contaminated particulates and fecal pellets were not apparently incorporated immediately into bottom sediments because elevated burdens were not found in surface sediment grabs. Rather the depositing matter accumulated in the nepheloid layer at the water/sediment interface. Hydrocarbon concentrations in material recovered from sediment traps ranged up to 3.276 mg/g for aliphatics and 3.624 mg/g for aromatics. The main effect of the contaminated sediment was the disappearance of the amphipods perhaps through emigration and depression of meiofaunal densities (Elmgren et al., 1980). Densities of other infauna appeared unaffected. Small crustaceans were 2 to 3% of the diet of the larger juvenile king crab so that the crab does not appear to be highly vulnerable to their loss.

Other events following the TSESIS spill have implications for juvenile king crab. Whereas the densities of the clam, Macoma balthica, were not reduced, the clam did accumulate high burdens of hydrocarbons even at stations with little or no hydrocarbon burden in the surface sediment (Boehm et al., 1980). The clams were apparently accumulating hydrocarbons from the contaminated floc in the nepheloid layer. The burdens rose, fell and rose again 10 months after the spill. The surprising rise in the course of apparent depuration was attributed to the reintroduction of contaminated floc by bottom currents.

Juvenile king crab in August gained 25% of their caloric intake from clams so that potential accumulation of hydrocarbons in clam tissue raises the question of hydrocarbon accumulation in the crabs. Whereas mollusks can accumulate hydrocarbons from contaminated sediment, sediment-dwelling polychaetes, the major food of the juvenile king crab, do not accumulate hydrocarbons from food or sediment (Neff and Anderson, 1981). Two crabs

have been shown to readily and rapidly metabolize hydrocarbons gained from contaminated food (Corner et al,1973; Lee et al., 1976,1977). Other crabs have been found to have enzyme systems capable of metabolizing hydrocarbons (Lee et al, 1976,1977; Varanasi and Malins, 1977). The fiddler crab, Uca pugnax, has been reported to lack the ready ability to metabolize hydrocarbons and field populations burrowing into sediment heavily contaminated with oil maintained body burdens of hydrocarbons between 180 and 280 ppm over 4 years (Burns, 1978). Based on the general ability of crabs to metabolize hydrocarbons, the king crab can also be expected to metabolize hydrocarbons, but its ability to do so has not been experimentally demonstrated and needs study before definitive assessment of the likelihood of hydrocarbon accumulation can be made.

Potential accumulation of hydrocarbon body burdens also raises the spectre of taste tainting of the commercially valuable adult king crab. After 48-h exposure to two crude oils layered on the water surface, thresholds at which taste panels detected tainting of cooked meat ranged from 49 to 160 ppm for penaeid shrimp and from 620 to 1250 ppm for blue crab, Callinectes sapidus (Knieper and Culley, 1975). Lobsters accidently exposed to diesel oil for 24 h showed taste tainting with 12-16 ppm total hydrocarbons in the cooked and canned meat (Paradis and Ackman, 1975). These findings suggest that taste tainting in crustaceans may require a high exposure level.

In assessing the likelihood of taste tainting in king crab two questions need to be addressed. First, what levels of hydrocarbon accumulation are likely? Secondly, do such levels produce taste tainting. The findings of Lee et al (1976,1977) that crabs rapidly metabolize and excrete hydrocarbons and those of Neff and Anderson (1981) that crustacean muscle tissue accumulates low levels of hydrocarbons that are rapidly released suggest that accumulation and any attendant tainting may be transient in the king crab. There are no accumulation and taste tainting data specifically for the king crab so that definite statements on the likelihood of taste tainting in king crab can not presently be made. Taste tainting is not readily predictable from hydrocarbon concentrations in the cooked meat (Mac Intyre, 1982) so that taste panel testing is necessary if king crab prove capable of accumulating hydrocarbons.

CONCLUSIONS AND RECOMMENDATIONS

Juvenile red king crab, Paralithodes camtschatica (CL >40 mm), were concentrated off Port Moller whereas juvenile tanner crab, Chionoecetes bairdi (CW <20 mm) were concentrated in the Amak Island Black Hill Region. Juvenile tanner crab, C. opilio, were not found in the study area. Both the juvenile king and tanner crab, C. bairdi, were in deeper water in August 1982 than in June 1982. The smallest juvenile king crab (CL <30 mm) were found in shallow nearshore areas amongst cobble and rock with abundant epifauna. The apparent concentration of the larger juvenile king crab along an oceanographic front and their movement with changes in the front's position and the habitat needs of the smallest juvenile king crab warrant more study.

Power laws describe the relationships between carapace size and maximum stomach volume in both king and tanner crab. Sex and shell condition did not affect the relationship. Our model differs substantially from that currently used by other workers.

Shipboard experiments showed that the clearance of contents from the stomachs of juvenile king crab was best described by multi-compartmental exponential decay models. Stomach residence time calculated from these models showed considerable variation with prey type. Soft tissue, such as, shucked clam, falls to 5% of its initial dry weight in the gut in 11 h whereas hard tissue, such as barnacle plate, remains in the stomach almost indefinitely (10^4 h) unless regurgitated.

For juvenile king crab (CL = 53-80 mm) collected in June the volume of solid material in the stomach averaged 18% of the maximum stomach volume and the dry weight of the stomach contents, 1.63 mg dry weight per g crab wet weight. In August the volume of solids averaged 10% of the maximum stomach volume, and the dry weight of the stomach contents 2.89 mg dry weight per g crab weight. In August, the volume and dry weight of stomach contents varied significantly with time of day. In June and August there were two feeding periods. During the period between 1300 h and 1800 h crabs showed greater stomach contents than those collected between 0000h and 0800h.

Using the diel feeding chronologies and the multi-compartmental exponential decay function for the evacuation of stomach contents, the daily rations of juvenile king crab were calculated to be 6.30 and 11.92 mg dry weight per g crab wet weight per day in June and August, respectively.

Using several methods to determine dietary composition gave a more complete picture of the crab's diet than reliance on one method alone. Visual examination of stomach contents gave dietary composition by frequency of occurrence. Measuring dry weights of the hard parts of prey items and estimating soft tissue intake with appropriate ratios gave a measure of dietary composition by bulk that was converted to dietary composition in terms of caloric intake. The immunoassay determined the extent to which readily digested prey items detectable immunologically went undetected by visual examination.

Examination of stomach contents alone does not indicate relative importance in the diet because such examinations are biased in favor of prey items with long stomach residence times. For the juvenile king crab correction of dietary composition for gut residence times profoundly changes the perceived dietary importance of certain prey types. After correction for gut residence times molluscs and echinoderms, whose hard parts dominate stomach contents, become of lesser dietary importance whereas soft bodied polychaete worms become the first-ranking dietary item. The results indicate that future dietary studies involving crabs will be obligated to consider and correct for gut residence times. More experimental effort to determine gut residence times for more prey types would have been desirable in this study.

For juvenile king crab (CL = 53-80 mm), floc, i.e., unidentifiable amorphous organic matter, constitutes the major bulk of the stomach contents. Assuming that this floc derived mainly from prey items whose hard parts were weighed, and after correcting for gut residence times, four taxa (two polychaetes, a sand dollar, and a clam) accounted for 92% of the soft tissue dry weight in the diet. The immunoassay results supported the reasonableness of the above assumption. Under this assumption the caloric intakes were 17.5 and 42.2 calories per g crab wet weight per day in June and August, respectively. Energetically two polychaetes, Pectinaria sp. and a sabellid, constituted over 50% of the caloric intake in June and August. The sand dollar, Echinarachnius parma, constituted 36% of the caloric intake in June but only 2% in August. Bivalves constituted 3% of the caloric intake in June but 25% in August. The major bivalve in the August diet was a small, thin-shelled clam, Tellina sp. Juvenile king crab appear to be predators of small, poorly motile benthic organisms living at or just beneath the sedimentary

surface.

The smallest juvenile king crab consume meiofaunal taxa not observed in the larger juveniles. For the yearling king crab (CL <30 mm) visual examination of the stomach contents was not as revealing as hoped. The immunoassay did detect polychaetes, oligochaetes and nematodes not detected visually and not seen visually or immunologically in the stomachs of the larger juvenile crabs.

The immunoassay indicated that juvenile king crab, especially the smallest juveniles (CL <30 mm) consume soft-bodied prey types overlooked by conventional analyses of stomach contents. To separate positive detections from those due to cross reactions the mathematical algorithm used by Feller et al. (1979) proved inadequate and was replaced by successive retesting to examine lines of identity, nonidentity, and partial identity. Also, the antigenic determinants responsible for the immunological reaction between prey item proteins and the antisera proved to be rapidly digested in crab stomachs. Because of this loss of antigenicity and other factors, the immunoassay may be overlooking prey items. The immunoassay can be considered a potentially valuable and, for small predators, a possibly necessary supplement to conventional analyses of stomach contents. However, it is not a substitute for these latter analyses and needs thoughtful application. The immunological examination of stomach contents definitely needs further technical refinement, and its future application in specific situations will require supplemental experimental support.

The main perceptions from this study are that the problems inherent in stomach analysis require the integration of several methods to determine dietary composition and that failure to correct for biases can give substantially misleading results.

Potential impacts from oil and gas development could derive from habitat disturbance and exposure to contaminants from platform discharges and oil spills. The assessment of risk from these potential impacts **requires judgments concerning, first, the manner and extent to which disturbance and contaminant exposure are likely to occur and, secondly, the** direct and indirect consequences likely given the anticipated extent of disturbance and exposure. The current perception of juvenile crab distribution suggests that there are differences between the smallest juvenile (CL <30 mm) and the larger juvenile king crab (CL >40 mm) in the likely impacts. Because of the shallow nearshore distribution of the smallest juveniles, impacts from disturbance and platform discharges are unlikely whereas impacts from oil spills need consideration. Because of the concentration of the larger juveniles off Port Moller in depths of 40

to 70 m, potential effects from disturbance and platform discharges need consideration whereas direct effects from oil spills seem unlikely.

Chronic indirect effects persisting beyond an oil spill could derive from loss or reduction in the macro or meiofaunal food of the smallest juvenile king crab. An oil spill in the shallow nearshore zone can reasonably be expected to reduce the density of food important to juvenile crabs, but prediction of the extent of such restriction in the crab's food supply requires prediction of the salient features of such a spill. Based on findings with other crustaceans a restriction in food supply can be reasonably expected to retard growth in juvenile king crab if alternative food is not available or taken.

The magnitude of exploration, development and production in the relatively small area off Port Moller in which the larger juvenile king crab concentrate needs to be predicted before one can assess whether disturbance and production discharges constitute a significant potential impact for the larger juveniles. Whereas the major food items of the juvenile king crab, polychaete worms, have been shown to accumulate little hydrocarbon burdens from contaminated food or sediment, bivalves, a lesser but still significant food of the crabs, do accumulate hydrocarbons. Whereas crabs in general appear readily capable of metabolizing hydrocarbons, the present lack of specific information on accumulation and metabolism of hydrocarbons by king crab precludes definitive assessment of hydrocarbon accumulation in king crab.

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DISTRIBUTION OF LARVAL AND JUVENILE RED KING CRABS (PARALITHODES CAMTSCHATICA) IN BRISTOL BAY

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CLARIFICATION

All references to "sea onion" in this volume refer to the sea squirt (an ascidian). References to asteroids refer to sea stars.

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ABSTRACT

The goal of this study was to better define the relationship between larval distribution and juvenile recruitment of red king crab (Paralithodes camtschatica) in the Bristol Bay region. Cruises during April-May, June and September 1983 collected larvae with bongo net tows, and juveniles and adults with trynet trawls and rock dredge hauls. Ancillary physical and biological measurements were made and tested for correlations with the observed larval and juvenile distributions.

The results of the larval sampling demonstrated a very weak 1983 cohort. Hatch apparently occurred during the last week of April and the first week of May, later than recorded in most years. The distribution of larval red king crab in Bristol Bay was characterized by a density maximum near the middle of the bay, and generally low density along the North Aleutian Shelf (NAS) as compared to earlier years. Larvae were not found in Togiak or Kvichak Bays. Vertically stratified samples gave strong evidence of diel vertical migration by red king crab larvae. The distribution of larval red king crab observed during 1983 is generally consistent with the concept of transport northeast along the North Aleutian Shelf and northwest in the upper part of Bristol Bay. It is not known whether longshore NAS currents may persist all the way into Kvichak Bay, but the occurrence of 1983 young-of-the-year crabs suggest this since no larvae were observed there. It is not clear whether the location of the larval density maximum was a result of offshore transport from the NAS or release by ovigerous females observed in the middle of Bristol Bay.

The results of juvenile sampling demonstrated the presence of crabs younger than three years generally inshore of the 50 m isobath. Age 0+ crabs (1982 cohort) were found off Ports Moller and Heiden and in Togiak and Kvichak Bays, both during April-May and June. Young-of-the-year crabs (1983 cohort) were found off Ports Moller and Heiden and in

Kvichak Bay during September. The distribution of juvenile crabs supports the hypothesis of "refuge" habitat. The results of statistical analyses indicate that biological parameters correlated better with the apparent juvenile crab distributions than did physical parameters. Strong, positive correlations were found between age 0+ to 2 juvenile crabs and sea urchin (Strongylocentrotus droehbachiensis) biomass and between young-of-the-year crabs and tube-building polychaete worm biomass. Older juvenile crab distributions correlated positively with sea onion (Boltenia ovifera) biomass.

The physiological and ecological characteristics of red king crab larvae make this life history stage the most susceptible to oil and gas pollution. The natural variability being documented in red king crab stocks indicates that vulnerability of the fishery to oil and gas could be greatly increased during years of extremely low recruitment such as 1983.

SECTION 1.0

INTRODUCTION

The red king crab fisheries of the southeastern Bering Sea (SEBS) have, in recent history, been the richest fished by U.S. fleets with an ex-vessel value of $169 million in 1980 (Eaton 1980; NOAA 1981; Otto, et al. 1980a; Otto 1981). Populations in 1978 to 1980 were the highest estimated by the National Marine Fisheries Service (NMFS) in over 10 years (Otto 1981; Otto, et al. 1982) and caused an expansion in fishing effort and the fleet working the SEBS. However, the commercial fishery suffered depressed landings of red king crab in 1981 and 1982. Landings declined from 131 x 10^6 lb in 1980 to about 35 x 10^6 lb in 1981 (INPFC 1982), and the fishery was closed at about 3.5 x 10^6 lb in 1982 (M. Hayes, NMFS, Seattle, pers. communication). Such severe reductions in landings are in accord with NMFS predictions of decreased abundance (a five-fold decrease from 1979 to 1982; Otto, et al. 1982), and reflect substantial, but unexplained, variation in success of year classes. Further depression of fishable stocks and mature females and subadults have been so severe that NMFS and the Alaska Department of Fish and Game (ADF&G) recommended that the 1983 season for Bristol Bay not be opened so that the population might recover (M. Hayes, NMFS, Seattle, pers. communication). Exact causes underlying such pronounced fluctuations in abundance of this and other crab species are not known, but numerous hypotheses have been advanced that advocate both biotic and abiotic factors (see reviews by Hayes 1983, Armstrong 1983).

Oil and gas development on the outer continental shelf of Alaska is scheduled to begin in the near future and proceed over the next decade. The Minerals Management Service (MMS) has charged the Outer Continental Shelf Environmental Assessment Program (OCSEAP) with initiation of research contracts designed to elucidate biological and physical/chemical processes in the areas of proposed oil and gas development. The

results of many research projects have been summarized in workshops sponsored by OCSEAP at which oil impact scenarios were considered and the vulnerability of species gauged. Crab biology was reviewed for the St. George Basin by Curl and Manen (1982), and for the North Aleutian Shelf (NAS) by Armstrong, et al. (1983a).

A notable example of research initiated to better understand the life history and general biology of a species is that recently and presently focused on red king crab along the NAS and throughout Bristol Bay. Despite extensive literature on the species (e.g., Armstrong, et al. 1983b; Reeves and Marasco 1980) much is unknown regarding early life history in the SEBS. Armstrong (1983) listed research needs that included studies of temporal and spatial larval population dynamics, the relationship of larval hatch and transport to female stocks, and location of megalopae at metamorphosis and substrate types on which survival of 0+ to 1+ juveniles is greatest. Armstrong et al. (1983b) advanced hypotheses on hatching success and larval survival and metamorphosis that stated: 1) much of the female population of the SEBS may be superfluous to year class success because it occurred over the central shelf where either larval and/or 0+ juvenile survival is very low; 2) the nearshore area of the NAS is critical for larval growth and survival; 3) larvae can be transported great, but variable, distances during pelagic growth; 4) survival of young benthic instars is probably very dependent on settlement onto protective "refuge" substrates; and 5) that such substrates (shell, cobble, invertebrate aggregates) are patchy along the nearshore NAS.

Based on recent work by Armstrong, et al. (1981a, 1983b) and research priorities identified at the 1982 North Aleutian Shelf synthesis meeting (Armstrong, et al. 1983a), the program discussed in this report was initiated by OCSEAP in 1983 to provide specific information on early life-history of red king crab in Bristol Bay.

1.1 Study Objectives

The goal of the present study is to provide sufficient information on larval and juvenile red king crab distributions and associated environmental variables to reasonably describe the potential effects of oil and gas development on the crab population and its fishery. Specific objectives of the program are to:

1) collect and measure larval red king crabs, identify them to growth stage and assess their apparent spatial distributions in Bristol Bay;

2) determine the spatial distribution and changes in individual size of juvenile red king crabs (<60 mm carapace width) in the study area;

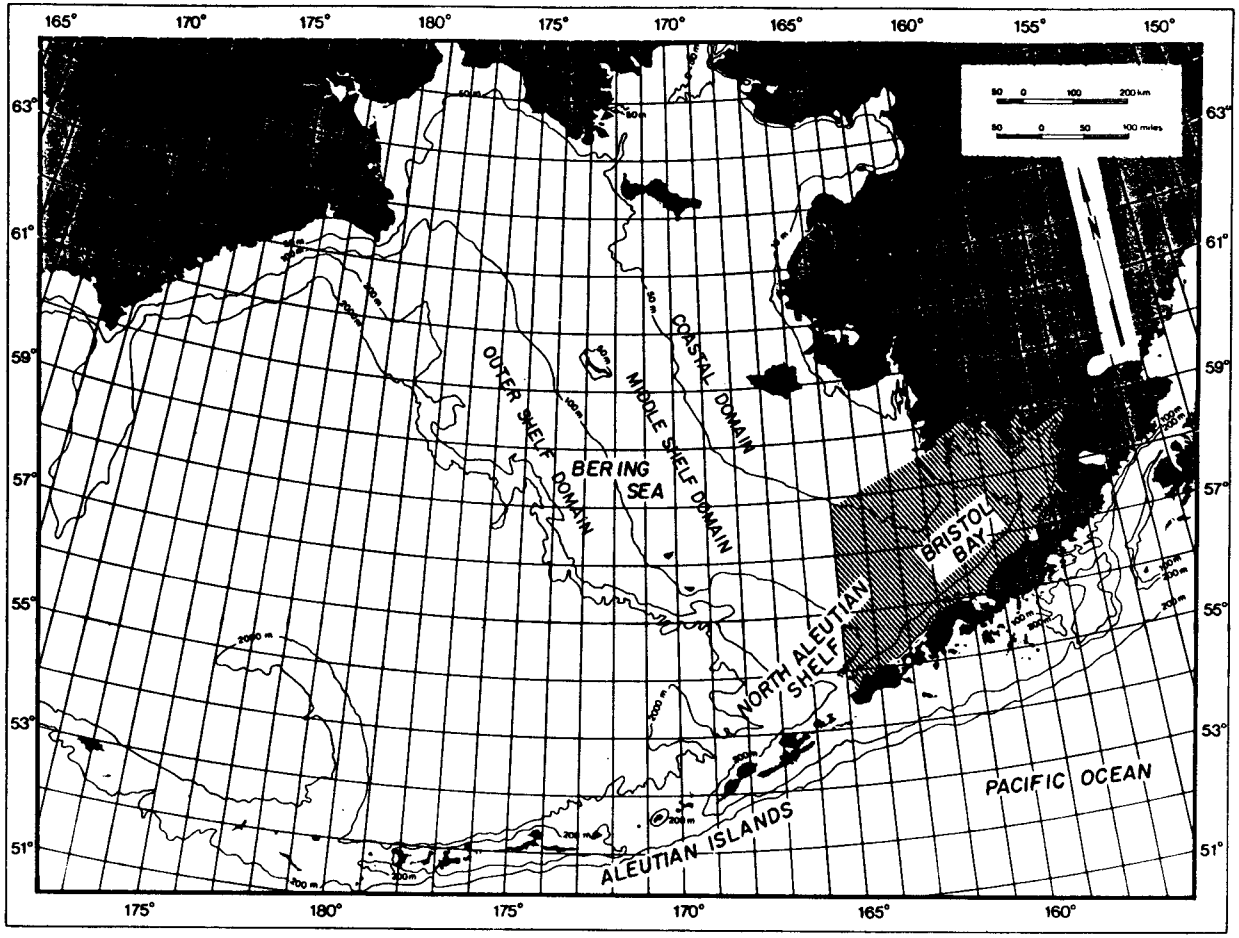
3) identify correlations between the physical and biological environment of the Bristol Bay vicinity and the observed distribution and relative abundance of larval and juvenile red king crabs; and

4) contribute to an overall understanding of OCS oil and gas development effects on red king crab populations and fisheries for this species.

1.2 Description of the Study Area

The study area, which includes Bristol Bay and a portion of the southeastern Bering Sea (SEBS) and the North Aleutian Shelf (NAS), is indicated in Figure 1.2-1. The area covers the area north and west of the Alaska Peninsula and Unimak Island west to 165°W and south and east of a line running from 165°W, 57°45'N to Cape Newenham. This study was originally designated "North Aleutian Basin"; it has been retitled "Bristol Bay" to more accurately indicate the focus of the study.

The Bristol Bay area is shallow with depths of over 100 m limited to a small area in the extreme southwest of the study area, just north of the North Aleutian Shelf. Approximately one half of the area is shallower



▒ = STUDY AREA

BRISTOL BAY
RED KING CRAB

LOCATION OF STUDY AREA

FEBRUARY 1984 | FIGURE 1.2-1

Figure 1.2-1 Location of study area.

than 50 m. The oceanography of the SEBS and NAS vicinities has recently been summarized in Hood and Calder (1981); hydrography and circulation are reviewed by Kinder and Schumacher (1981a, b). The sedimentary environment and substrates in the area have been summarized by Sharma (1979).

1.3 Life History and General Biology of the Red King Crab

1.3.1 Distribution and Abundance: Benthic Juveniles and Adults

Red king crab (Paralithodes camtschatica) are widely distributed from the Sea of Japan in the western Pacific through the Kuril Islands to the Kamchatka Peninsula, across to the southeastern Bering Sea and as far south as British Columbia in the eastern Pacific (Marukawa 1933; Vinogradov 1946; Weber 1967). The species is rather uncommon north of latitude 57°N and is characterized as part of the subarctic-boreal faunistic system (Neyman 1963, 1969). Further, Russian scientists rarely find it in large numbers north of the Anadyr faunistic barrier (a line from the Anadyr River to St. Matthew Island), in marked contrast to the blue king crab which ranges farther north and seems to inhabit colder water (Slizkin 1973).

In the SEBS where a major fishery is centered, information on distribution and abundance of red king crab in these shelf areas is more comprehensive than for any other decapod fished by U.S. fleets. For more than 12 years, the NMFS has conducted broadscale trawl surveys in the southeastern Bering Sea, and Otto (1981) provides a history of information gathered by Japanese and Russian fleets during their participation in the fishery. A series of annual reports by the International North Pacific Fisheries Commission (INPFC) since the late 1950s provides a continuum of detailed data on king and also Tanner crab (Chionoecetes spp.) stocks in the southeastern Bering Sea as well as in other locations fished by member nations.

Data on distribution and abundance of red king crab are essential for predictions of potential oil and gas development impacts, particularly in regards to early life history stages which may be most susceptible to hydrocarbon toxicity (Armstrong, et al. 1983a,b). Distribution seems to be coupled, in part, to physical oceanographic domains which, for the SEBS shelf including Bristol Bay, are the coastal, middle and outer shelf domains that extend to about the 50 m, 100 m and 200 m isobaths, respectively (Kinder and Schumacher 1981a; Figure 1.2-1). Throughout this area red king crab are distributed somewhat in accord with sex and life history stage. In general, female and small male king crabs (<110 mm carapace length) are found closer to shore and somewhat east of large males (Otto, et al. 1980a,b, 1981). Very young juvenile red king crabs of 0+ to 4+ age classes are rarely caught in nets throughout the NMFS survey area, even though the mesh used would retain animals as small as 30 mm. The implication is that juvenile crabs up to 60 mm in carapace length (about 3 years old; Weber 1967) are absent from the survey area and likely occur very nearshore along the North Aleutian Shelf or in eastern Bristol Bay. More precise information on this subject is a major objective of the present study.

Abundance estimates of red king crab have fluctuated between years in the last decade and cycles of high to low abundance may occur in this species' populations as have also been observed for the Dungeness crab, Cancer magister (Armstrong 1983; Botsford and Wickham 1978). Landings from the Kodiak king crab fishery have also fluctuated widely from 94 x 10^6 lb in 1965 to a low of 10 x 10^6 lb in 1981, and have remained around 14 x 10^6 lb to the present (NOAA 1981). Poor recruitment is cited as the cause for this pronounced decline in abundance. In the southeastern Bering Sea, crabs were in moderate abundance in 1953, increased in abundance to 1959, fell between 1964-70, and then increased through 1979 (Otto 1981). However, abundance estimates for total (juvenile plus adult) male king crab in this area have declined from 181 million animals in 1977 to 129 million in 1982 (Otto, et al. 1982). Most importantly, estimates of sublegal males one to two years from

entering the fishery have declined nearly threefold from 64 to 17 million, leading to predictions of several consecutive years of poor fisheries. Abundance estimates of legal male crabs dropped from over 45 million animals in 1979 to about five million in late 1982; (M. Hayes, NMFS, Seattle, pers. communication; Otto, et al. 1982) which has resulted in the severe reductions in commercial landings.

Change in abundance of king crab populations is an important biological factor considered later in discussing oil impacts. Cycles of abundance suggest that year class failure or success may be based on survival of critical life history stages such as larvae or young juveniles, likely in nearshore habitats. Instantaneous mortality rates of juvenile and sublegal, sexually mature crab are estimated to be low, about 0.10 yr^{-1} until entering the fishery (Balsiger 1976; Reeves and Marasco 1980). Consequently the magnitude of a future fisheries cohort is largely determined by the reproductive success and survival of larvae and young-of-the-year (0+ crab) in nursery areas. Vagaries of temperature, food supply and predator populations are factors probably affecting survival, but as yet are poorly studied. In addition, the number and location of spawning females may significantly influence larval survival and location of megalopae relative to optimal substrate at metamorphasis (Armstrong, et al. 1983b). Additional information on these topics are also important objectives of the present study. Female abundance and geographic location have shifted from high numbers nearshore off Unimak Island to Port Heiden in the late 1970s to very low abundance nearshore along the entire NAS, and a redistribution over the central shelf domain (Armstrong, et al. 1983b). Potential oil perturbations could add to natural pressures on larval and juvenile populations and further suppress stocks.

1.3.2 Reproduction

During late winter and early spring in the Gulf of Alaska, adult males apparently migrate from deeper, offshore areas to join females in

shallow water for breeding around Kodiak Island (NOAA 1981; Powell, et al. 1974; Weber 1967) and it is suspected that such migratory behavior occurs in the southeastern Bering Sea as well. Eggs carried from the previous year hatch about April 1-20 (Armstrong, et al. 1983b; Haynes 1974; Weber 1967) and females soon undergo physiological changes leading to molt. By pheromone attraction (NOAA 1981) sexually mature males locate preecdysial females, embrace them for as long as 16 days, and mate just after the female molts (Powell, et al. 1974). The nearshore, shallow water habitat is apparently selected in part for warmer water temperatures and also perhaps greater food supplies. The average temperatures associated with sexually mature males and females are 1.5° and 4°C, respectively (NOAA 1981). Stinson (1975) correlated male and female abundance with temperature and, from NMFS survey data through 1975, located most sexually mature females inside a 4°C isotherm nearshore off Unimak Island and directly in front of Port Moller. Weber (1967) summarized data on temperature-related hatchout time and development, noting both regional and annual differences in larval appearance and rate of development attributable to temperature variations. Larval development time can double with a decrease of temperature from 10° to 5°C (Kurata 1960, 1961), and an average of 460 degree days (= cumulative average daily temperature) is required for development from hatch of egg to metamorphosis of megalops (Kurata 1961).

After molting, a female must be located and mated within five days for viable eggs to be produced. Males are larger than females in 97 percent of all mating pairs (Powell, et al. 1974), and insemination of larger females by smaller males results in reduced clutch size (egg number). Any combination of events through natural and fishery mortality and pollution that substantially reduce numbers of large males at some point in time could threaten the breeding potential of the species. Reeves and Marasco (1980) estimated that a male-female weight ratio of 1.7 is required for 100 percent copulation. This estimate is based, in part, on behavioral observations by Powell, et al. (1974). Below this value, decreasingly lighter males will have less success breeding large mature

females. This relationship supports the observations of the 1982 NMFS survey cruise that found an unusually large number of barren female crabs in a year of very low male abundance. The relationship between spawners and eventual recruits for this species is unclear (Reeves and Marasco 1980).

Females carry eggs for up to 11 months as embryos develop through naupliar stages to prezoea (Marukawa 1933). This protracted developmental time makes eggs (during early cleavage) and later embryos susceptible to long-term benthic oil pollution, and should be considered in scenarios of oil mishaps and possible perturbations to larval populations. Again, gravid king crab females are aggregated nearshore in relatively shallow water along the North Aleutain Shelf, but such distribution is poorly studied to date.

1.3.3 Larval Biology

Time and Area of Hatch. Larvae are hatched nearshore (Armstrong, et al. 1983b; Haynes 1974), molt through four zoeal stages, each about three weeks (Armstrong, et al. 1983b; Marukawa 1933), spend two to four weeks as megalopae, and then metamorphose to first instars about late July to August (Armstrong, et al. 1983b; Kurata 1960; Weber 1967). Eggs normally begin to hatch in early April (Haynes 1974; INPFC 1960; Sato 1958), although female king crab may vary in time of hatch between widely separated populations from Unimak Island to Port Moller. Korolev (1968) summarized data collected by Soviet scientists for June 1959 along the North Aleutian Shelf. Over 95 percent of the female populations between 161°25' to 165°10'W had spawned and carried new egg masses in June, while 90 percent of females east of 161°25'W (Port Moller and east) carried empty egg cases indicative of recent hatch, and only 10 percent carried new purple egg masses. Armstrong, et al. (1983b) have presented evidence that egg hatch is not synchronous along the NAS from Unimak Island to Cape Seniavin, and concluded that larvae emerge earlier in the southwest portion of the NAS range and later to the northeast, probably in accord with differences in water temperature.

Interannual timing of the onset of hatch and seasonal occurrence of pelagic larvae can vary by as much as 1.5 months. Japanese data (INPFC 1963, 1965) show that nearly 100 percent of gravid females sampled during 1960 carried "eyed" eggs (fully developed zoeae, hatch imminent) until May 10 and 50 percent carried empty egg cases by May 20-30. In 1963, eyed eggs were carried until April 20 and 50 percent had hatched by April 30. Larvae hatched late (mid-May) in 1976, but early in 1979 when most were already stage IV (SIV) by mid-June (Armstrong, et al. 1983b).

Horizontal transport of king crab larvae by currents is thought to move them significant distances from the origin of hatch, and implies to some authors that recruitment of juveniles to a given area might depend on larvae hatched elsewhere, including areas south of the Alaska Peninsula (Haynes 1974; Hebard 1959). Hebard (1959) calculated that larvae hatched at Amak Island could be transported over 95 km to the northeast and metamorphose at Port Moller based on a net current speed of 2 cm sec^{-1}. He further discussed possible transport of larvae from south of the Alaska Peninsula through Unimak and False Passes. Haynes (1974) adds credence to this supposition by showing a northerly dispersion of king crab larvae off the southwest tip of Unimak Island, and a northeast shift in areas of larval abundance from Black Hills into Bristol Bay (May-July 1969 and 1970). This pattern may in part be due to inadequate spatial sampling. Armstrong, et al. (1983b) concluded that larvae could be transported over 200 km along the NAS based on the time required for development (3.5-4 months) and current speeds of about 2 cm sec^{-1} (Kinder and Schumacher 1981b).

Growth. Temperature is considered one of the most crucial physical factors affecting survival and growth of larvae. Kurata (1960, 1961) calculated that 460 degree-days were required to progress from hatch to metamorphosis. Lethal temperatures are those greater than 15°C or lower than 0.5-1.8°C (Kurata 1960). He found greatest survival of zoeae between 5-10°C and formulated an equation that relates developmental

time to temperature. Time from egg-hatch to molt of stage I (SI) to stage II (SII) varies from 24 days at 2°C to nine days at 8°C (Kurata 1960). Severe climatological changes could account for large fluctuations in survival of a year-class and later recruitment to the fishery. Niebauer (1981) shows that the limit of ice in the southeastern Bering Sea (as a relative measure of water temperature) was several hundred kilometers farther south in 1976 than 1979 and actually extended to the Alaskan Peninsula near Black Hills. Both 1975 and 1976 were severely cold years and poor survival of larvae and juveniles then could account for low abundance of sublegal males five to six years later in 1981-82.

Growth of larvae is substantial during pelagic development with increases from about 200 mg dry weight as new SI zoeae to over 1,200 mg as megalopae (Armstrong, et al. 1983b). Feeding habits and prey preference of larvae in the wild are unknown, but both zooplankton and centric diatoms have been found in guts of specimens from the NAS (D. Armstrong, unpublished data from June 1983). Paul, et al. (1979) studied the response of red king crab zoeae to food density and found that while several species of copepods were captured, the density required greatly exceeded natural densities as measured by integrative bongo tows. Paul and Paul (1980) studied the effect of temperature and starvation on subsequent ability to capture food, and found that red king crab zoeae held at 2° and 4°C without food for 84 hours were unable to capture prey when later presented. This result suggests that starvation may be caused by relatively short periods of low food abundance and is applicable to considerations of early zoeal ecology along the NAS.

1.3.4 Benthic Biology of Young Juveniles

Little is known of the distribution and abundance of young-of-the-year (0+) crabs and of subsequent instars through two years of age (1+) along the NAS and, in fact, throughout the southeastern Bering Sea; providing information on this life-history stage (stanza) is a major objective of the present project. Weber (1967) described shallow water

ecology of young juveniles in Dutch Harbor that, along with descriptions of habitat occupied around Kodiak Island (Jewett and Powell 1981; Powell and Nickerson 1965) and in Kachemak Bay (Sundberg and Clausen 1979) has led to a hypothesis of strict habitat requirements for survival (Armstrong 1983; Armstrong, et al. 1983b). A working hypothesis in the beginning of the present study was that 0+ juveniles require substrate that affords both refuge from predators and adequate food (e.g. shell, cobble, biological materials such as tube worms). The link between the location of megalops larvae at metamorphosis and appropriate bottom material was viewed as one critical determinant of year class strength.

Location of such refuge substrate and 0+ to 1+ juveniles was found previously to be very difficult along the NAS. During a 1982 OCSEAP project to study feeding habits of small juvenile red king crab, almost no animals in this size range (about 5 to 25 mm carapace length) were found using nets, divers and underwater cameras (W. Pearson, Battelle NW Laboratories, pers. communication). The National Marine Fisheries Service has caught virtually no crab of this size in over a decade of extensive sampling (e.g. Otto, et al. 1982). Armstrong, et al. (1983b) attributed this to inappropriately large gear and little effort nearshore where they assumed this stage must be most common.

Growth rates of 0+ and older juveniles have been studied and animals reach mean carapace lengths of about 11 mm, 35 mm, 60 mm and 80 mm at one, two, three and four years, respectively (Powell and Nickerson 1965; Weber 1967). Growth models for the species have been developed by McCaughran and Powell (1977), Reeves and Marasco (1980) and Weber (1967). Young-of-the-year molt from eight (Powell 1967) to 11 (Weber 1967) times in the first year. Such a high frequency of molting could make them particularly susceptible to nearshore oil pollution since ecdysis is the time of greatest sensitivity to toxicant stress (Armstrong, et al. 1976; Karinen 1981).

Juvenile crab in 2+ to 3+ age classes (entering their third through fourth year) form large aggregates called "pods" in the Gulf of Alaska (Powell and Nickerson 1965). Podding behavior is probably based on chemosensory cues (subject to oil effects) and is thought to serve as protection from predators. It is not known if the same behavior occurs among juveniles of the North Aleutian Shelf.

Red king crab are sexually mature at about 95-100 mm carapace length for males (NOAA 1981; Weber 1967) and 85-90 mm for females in the Bering Sea (Weber 1967) or 93-122 mm in the Gulf of Alaska (Powell and Nickerson 1965). Animals are five to six years old at sexual maturity and males are therefore capable of breeding two to three years prior to entering the fishery at about eight years of age.

SECTION 2.0

METHODS

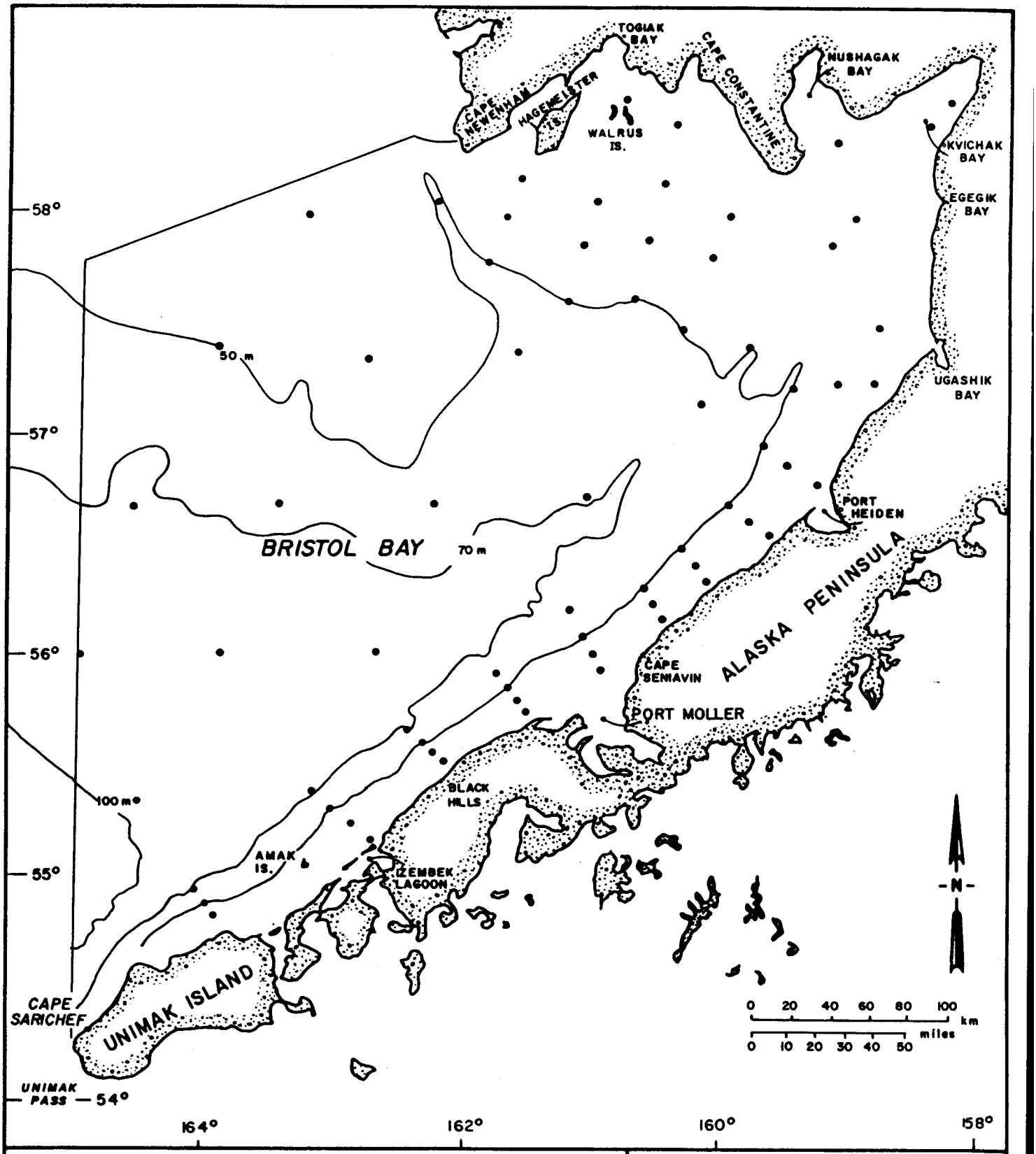
2.1 Field Methodology

2.1.1 Timing and Location of Sampling Effort

Three cruises were scheduled for this project during 1983: 18 April to 7 May (cruise 83-1); 2-17 June (cruise 83-3); and 9-23 September (cruise 83-5). In addition, opportunistic sampling for decapod larvae along the 50 m isobath from Port Moller to Unimak Island was conducted on 27 May 1983 during the Blue King and Korean Hair Crab cruise to the Pribilof Islands (cruise 83-2). The NOAA ship Miller Freeman was used for all cruises. The sampling locations for the three scheduled cruises are shown in Figures 2.1-1 through 2.1-3. The types of data collected and quantities are summarized in Table 2.1-1.

The sampling design originally consisted of 72 permanent stations, each to be sampled at least once during every cruise. Twelve of the stations were offshore at previously established NMFS crab fisheries survey locations (Otto, et al. 1982). The other 60 stations were arranged in 15 transects perpendicular to the shore with station bottom depths of 20, 30 and 50 or 70 m for each station in every transect.

The alpha-numeric station code (Figures 2.1-4 and 2.1-5) indicates the subarea (letters), transect number within the subarea (first digit), and the approximate bottom depth in meters (last two digits). Three of the transects occupied equivalent positions to those sampled by Armstrong during 1982 west of Black Hill to Cape Sarichef on Unimak Island. Two transects were similarly located off Port Moller. Five transects were located along the south side of Bristol Bay between Ports Moller and Heiden. Four more transects were located along the north shore out to Cape Newenham and one was located down the axis of Kvichak Bay.



• = SAMPLING STATION

—— = STUDY AREA BOUNDARY

BRISTOL BAY RED KING CRAB

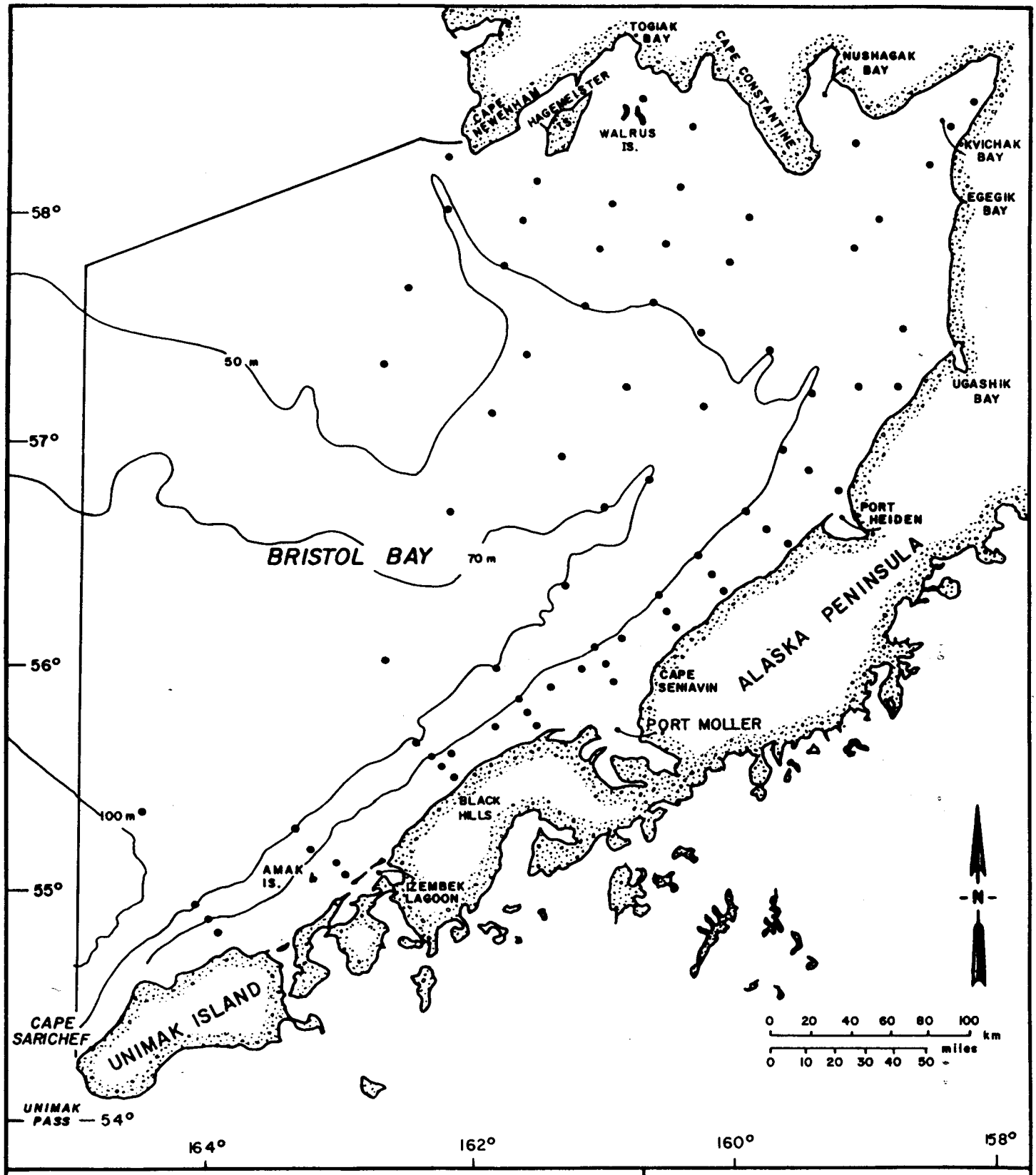
CRUISE 83-1

SAMPLING STATIONS

VTN

FEBRUARY 1984

FIGURE 2.1-1



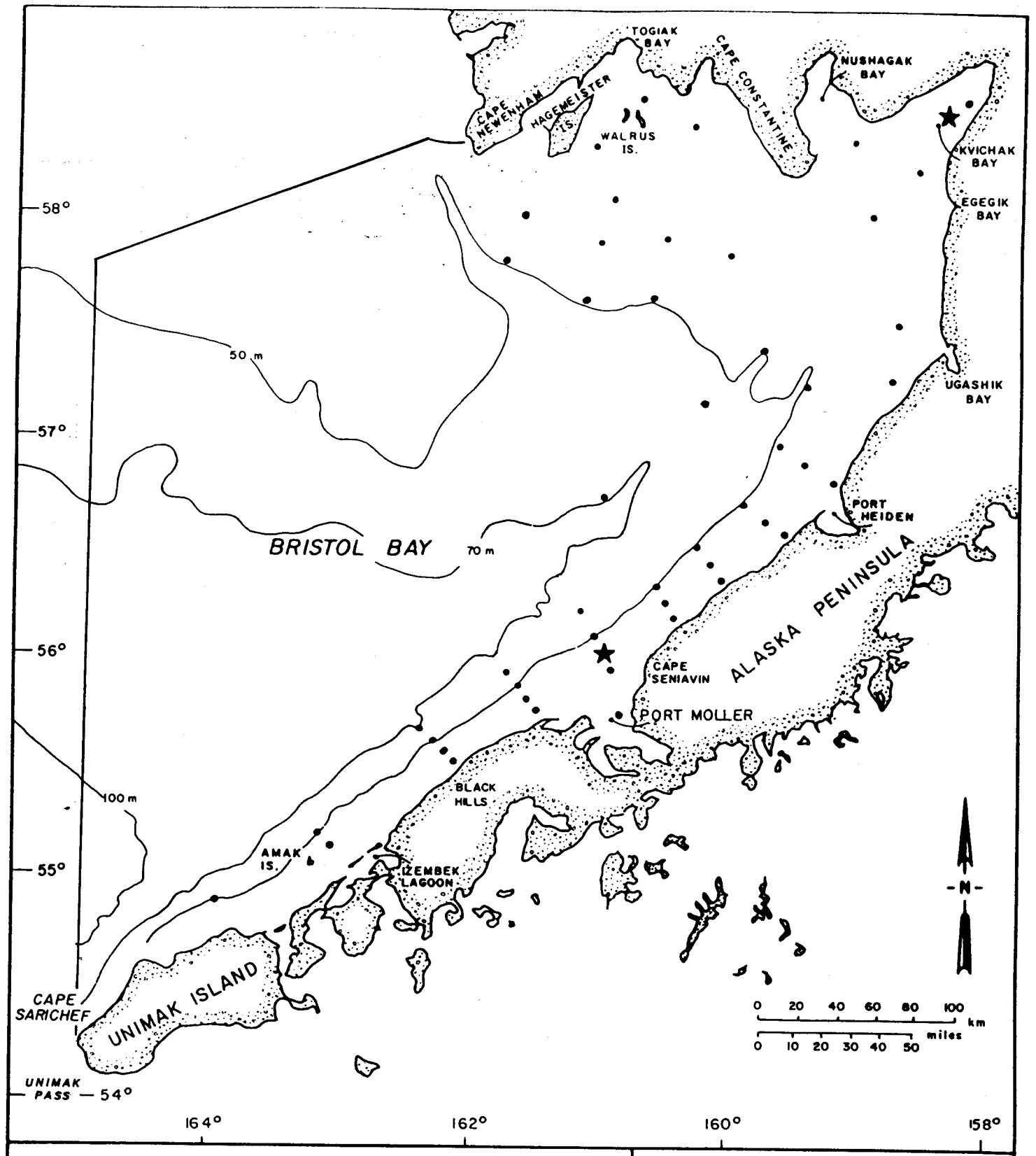
• = SAMPLING STATION

— = STUDY AREA BOUNDARY

BRISTOL BAY
RED KING CRAB

CRUISE 83-3
SAMPLING STATIONS

FEBRUARY 1984 | FIGURE 2.1-2



— = STUDY AREA BOUNDARY

• = SAMPLING STATION

★ = INTENSIVE SIDE SCAN SONAR SURVEY SITE

BRISTOL BAY RED KING CRAB

CRUISE 83-5

SAMPLING STATIONS

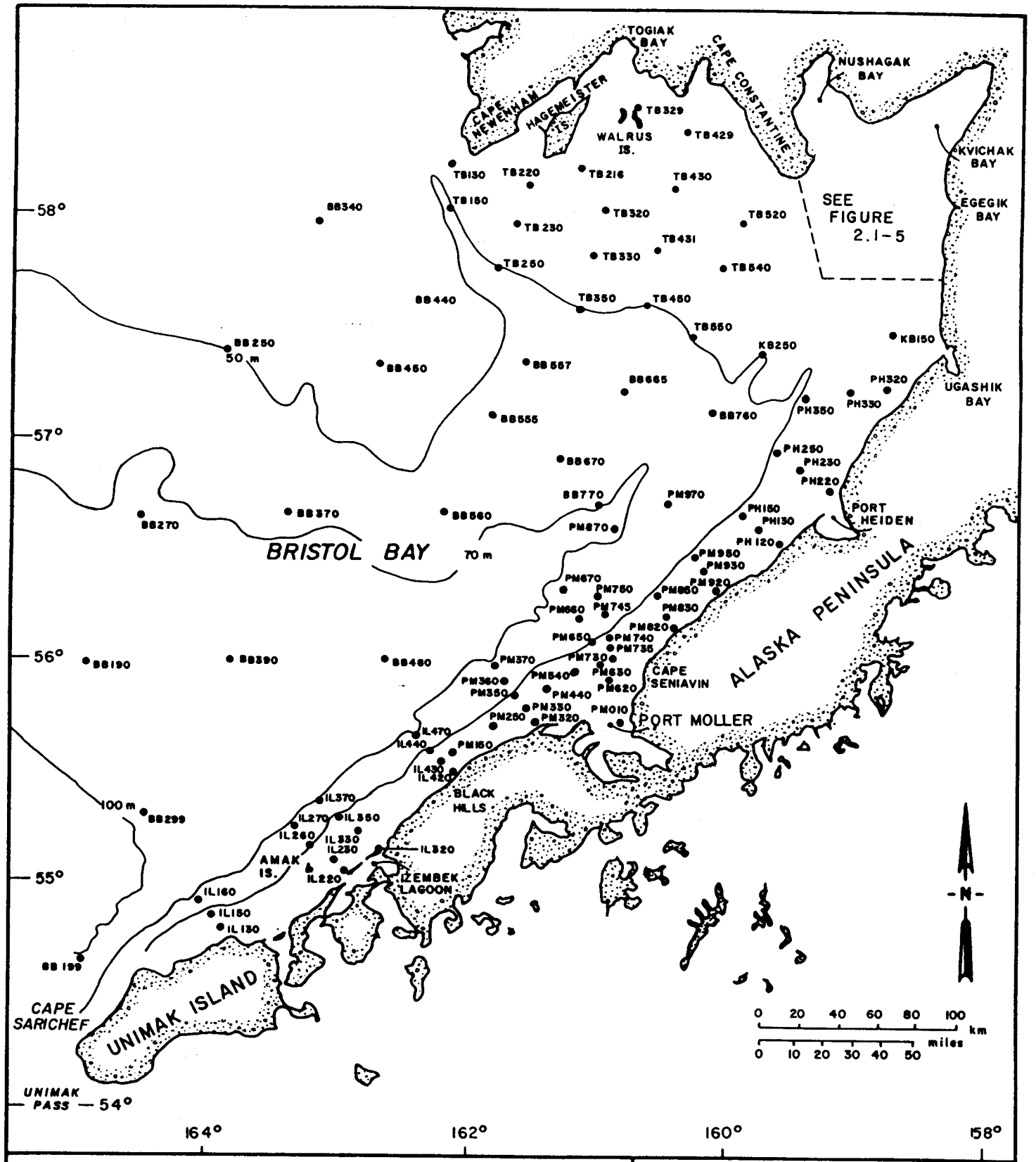
FEBRUARY 1984 | FIGURE 2.1-3

TABLE 2.1-1

SUMMARY OF FIELD SAMPLING EFFORT

Type of Sampling	Cruise 83-1	83-2	83-3	83-5
	69(72)[a]	16(17)	88(64)	47(48)
CTD casts	76	-	76	47
Van Veen bottom grabs	2	-	-	-
Shipek bottom grabs	46	-	20	12
Rock dredges	51	-	42	16
Trynet otter trawls	50	-	78	35
Bongo net tows	77	16	79	24
Tucker trawls	16	-	6	-
Sameoto neuston sampler tows	4	-	-	-
Shrimp pot sets	3	-	12	-
Crab pot sets	-	-	5	-
Fathometer surveys (hrs/nm)	12.3/-[b]	-	16.0/97	22.0/68
Side-scan sonar surveys (hrs/nm)	-	-	-	19.6/52

(a) Survey stations occupied (planned).
(b) Not recorded

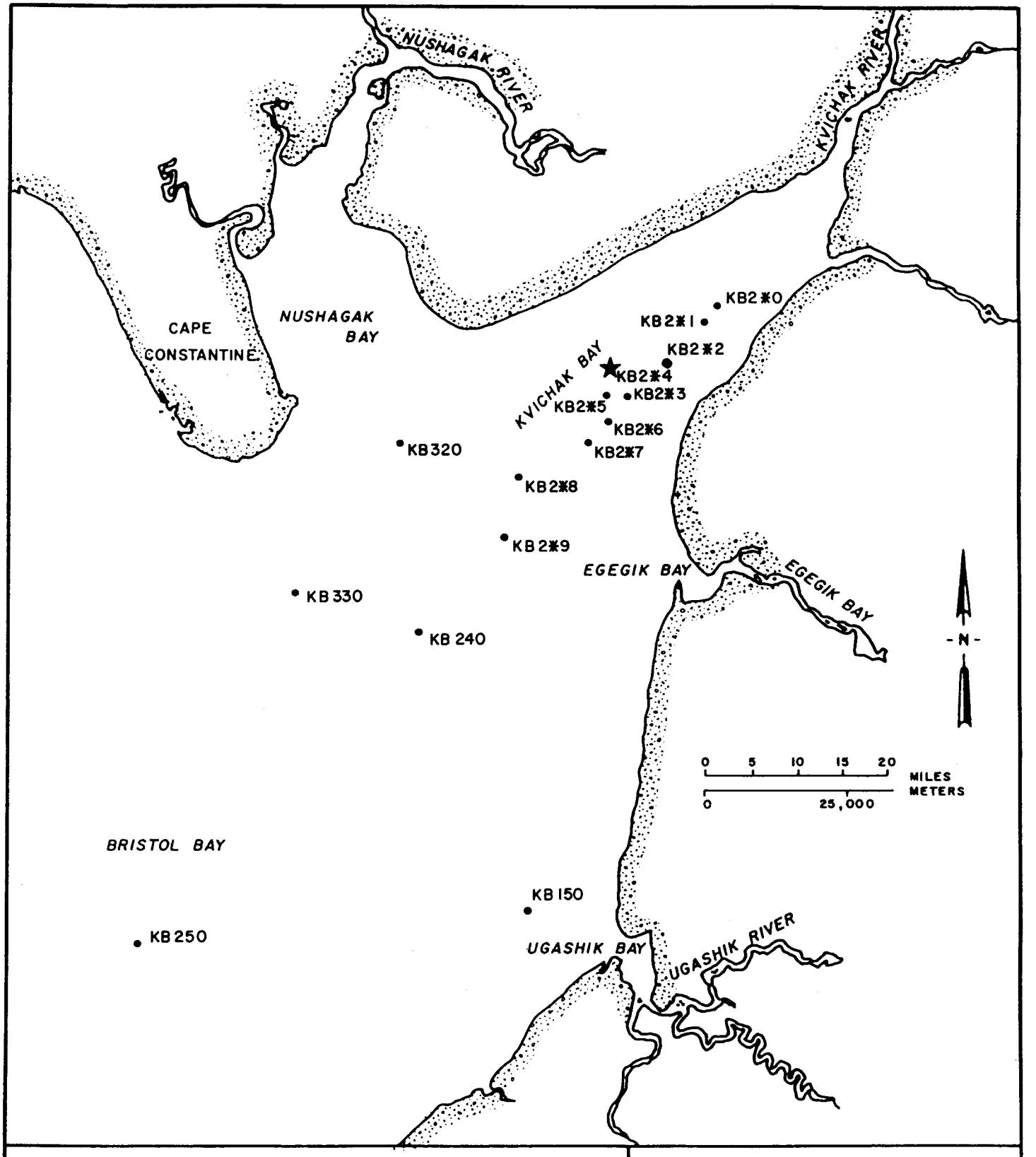


BB - BRISTOL BAY
IL - IZEMBEK LAGOON
PM - PORT MOLLER
PH - PORT HEIDEN
KB - KVICHAK BAY
TB - TOGIAK BAY
(See text for explanation of numbers.)

BRISTOL BAY RED KING CRAB

STATION IDENTIFICATION NUMBERS

FEBRUARY 1984 | FIGURE 2.1-4



• = SAMPLING STATION

★ = INTENSIVE SIDE SCAN SONAR SURVEY SITE

BRISTOL BAY
RED KING CRAB

STATION IDENTIFICATION NUMBERS
IN THE KVICHAK BAY VICINITY

vtn

FEBRUARY 1984 | FIGURE 2.1-5

2.1.2 Field Gear and Sampling Methods

Physical Environment. Temperature and conductivity data were collected with the Miller Freeman's CTD system. Depth-specific conductivity and temperature were later converted to salinity using a NOAA computer algorithm. Near-surface and near-bottom salinity data were selected for correlation with the observed larval and juvenile red king crab distributions. Near-surface, instead of surface, salinity (and temperature) values were selected for two reasons: 1) the shallowest CTD readings varied between 0.2 and 1.5 m; and 2) a subsurface value was thought to be more representative for correlation to organisms collected in oblique plankton tows. The near-bottom values were generally recorded about 5 m off the bottom.

Sediment samples were collected primarily with a Shipek grab during cruises 83-1 and 83-3; a few sediment samples were taken with a Van Veen grab during cruise 83-1. A sample of surface sediment was scooped from the grab sample, placed in a labeled plastic bag and frozen for later analysis. A field description of each sediment sample was recorded in the chief scientists' field notes during cruise 83-1.

During cruise 83-5 (September), a side scan sonar unit was used in an attempt to discern gravel substrates from silt and sand. A 500 kH_z Klein Associates, Inc. fish was towed at approximately 15 m from the bottom. Scope (wire out) and towing speed were varied to achieve distance above bottom, but in general the target speed relative to the substrate was 2 knots. A path width of 150 m was selected. Results were printed with a Klein Associates 521 T continuous recorder. Trynet trawls and Shipek grabs were then collected to ground proof the side scan traces. Two station locations were selected for intensive side scan sonar surveys: PM730 (Figure 2.1-3) and KB2*4 (Figures 2.1-3 and 2.1-5).

Larvae. Larval red king crab distribution and relative abundance were documented with standard net hauls over transects designed to fill existing data gaps and to establish a continuing program. The primary sampling method for collecting larval red king crabs was the standard oblique bongo net tow in order to facilitate comparisons with previous Alaskan plankton and larval decapod collections both in Bristol Bay and off Kodiak Island. The nets were fished in CALCOFI fashion (Smith and Richardson 1977) to a depth of 80 m, or 10 m above the bottom, whichever was less. Eighty meters was selected as the bottom depth to be fished because crab megalopae are known to vertically migrate down to a depth of at least 70 m, but apparently not to 90 m (Ito and Ikehara 1971; Kendall, et al. 1980). The objective of the bongo net collections was to sample all of the larval crabs in the water column independent of time of day when sampled.

The bongo nets used were paired 0.333 mm (333) and 0.505 mm (505) mesh nets 60 cm in diameter with a length:width ratio of 5:1. These mesh sizes have been used in previous Alaskan plankton and larval decapod collections (Armstrong, et al. 1981a; Haynes 1974; Kendall, et al. 1980). A TSK and/or a General Oceanics "bullet" flowmeter was attached at the mouth of one or both of the nets. Collections were preserved in the field with 4 percent formalin and BHT added to preserve color of the larvae.

Two additional sampling devices, a Tucker trawl and a neuston net, were also utilized at two stations to characterize diel vertical stratification, which may be important for potential oil impact assessment. The sampling design utilized followed that of Kendall, et al. (1980) to assure a good comparison. The mesh size of both nets was 0.505 mm and the depths sampled were 0, 10, 20, 30, 40 and 50 m. Sampling was done at dawn, midday, dusk and midnight.

Epibenthos. All of the epibenthic sampling was conducted from either the NOAA Ship Miller Freeman and its MonArk launch. Sampling days

consisted of 24 hours on all cruises with the use of two scientific crews. Each station was surveyed prior to bottom sampling with the ship's 50kH Simrad fathometer in order to assess the trawlability of the bottom and determine the selection of sampling gear.

Samples of epibenthic organisms were obtained with trynet trawls and rock dredges; these gear are described in Table 2.1-2. The trynet was generally the preferred gear for apparent smooth, flat bottoms, whereas the rock dredge was used where the bottom appeared to be rocky or broken. A number of trynets were damaged or lost when sampling was attempted on rough bottoms. Several stations were sampled with both gear types in an attempt to compare their performance. The scope (towing wire to water depth ratio) and the towing speed were adjusted by the Miller Freeman fishing crew to maximize gear efficiency. The trynet was towed with scopes ranging from 3.0:1 to 4.5:1 and ship speeds of 2.5 to 3.5 knots. The rock dredge was towed with a scope of 4:1, and ship speeds in the range of 1.0 to 3.0 knots.

Quantitative try net and rock dredge samples were placed on a sorting table, characterized in field notes, and sorted to the lowest possible taxonomic groups. Voucher specimens of many taxa were preserved for further identification or verification. Samples were carefully searched for small red king crabs. Taxonomic groups were weighed on a large fisheries deck scale (for large organisms or large samples) or a triple-beam dial-type gram scale (for small organisms or samples). All organisms were counted, with the exception of colonial forms or small attached fauna. Very large samples were subsampled, and the total sample weights and counts were extrapolated from the subsample data.

All red king crabs and Tanner crabs were measured for length (king crabs) or width (Tanner crabs), and information on sex, maturity, shell condition, egg condition and external parasites was recorded. Individual weights were obtained for all king crabs except the very small young-of-the-year, which were frozen for later analysis. Lengths

TABLE 2.1-2

EPIBENTHIC SAMPLING GEAR

Gear Type	Gear Description
Trynet trawl	Headrope length: 5.38 m Doors: Cruises 83-1 and 83-3; wood, approximately 0.4 x 0.9 m with extra heavy shoe Cruise 83-5 aluminum Bridles: 18.3 m, 3/16 in. (0.48 cm) stainless steel (Cruise 83-1, part) 3/8 in. (0.95 cm) nylon (Cruise 83-1, part) 1/2 in. (1.3 cm) steel cable (Cruise 83-1, part, Cruises 83-3 and 83-5)
Rock dredge	Mouth: 0.91 m x 0.41 m, steel frame Chafing gear: Large mesh nylon netting with poly-line whiskers

were recorded for subsamples of large catches of yellowfin sole, rock sole, Pacific cod, walleye pollock and several other fish species. Stomachs of these species were examined for content when time allowed.

A number of rock dredge samples were treated qualitatively, primarily in areas of high juvenile abundance. These samples were described in field notes (see Appendix C) and searched carefully for juvenile crabs. Crabs from these samples were measured and data recorded as described above.

Field coding forms were used to record all taxonomic identifications, counts, weights and size information. A separate coding form was used to record location, time, depth and other pertinent information for each sample; this information was taken directly from the Marine Operations Abstract (MOA) kept by the bridge Duty Officer. Observational data, such as sample descriptions and fish stomach contents, were recorded in the Chief Scientist's field notes (see Appendix D).

2.1.3 Limitations

The most serious limitation in sampling juvenile king crab is the lack of suitable fishing gear (Powell and Nickerson 1965). Any surface-deployed device designed to sample early juveniles can at best be considered only as a reconnaissance tool. The rough terrain where early juvenile king crab are found in the coastal waters of the North Aleutian Basin severely limits attempts at quantitative sampling. The epibenthic data collected during this study are therefore considered qualitative; any calculated density and biomass numbers should be viewed as estimates, their greatest value being for within-study comparisons. The data resulting from trynet samples are probably the most accurate due to the generally reliable fishing behavior of this gear, which was used primarily on smooth, small grained bottoms. The rock dredge, used on rough bottoms, has erratic fishing behavior, apparently similar to that of the bottom skimmer described by Sundberg and Clausen (1979).

2.2 Laboratory Methodology

2.2.1 Sediment Analysis

Homogenization was accomplished by kneading the sample bag for several minutes. Following digestion of organics, the samples were wet sieved on a No. 230 sieve. Material passing through the sieve was then transferred to a settling chamber; the remainder was dried at 103°C, cooled, weighed and placed on a nest of sieves of decreasing size (Nos. 5, 7, 10, 14, 18, 25, 35, 45, 60, 80, 120, 170 and 230). The material retained on each sieve was then weighed. Approximately 30 grams of the material which passed through the No. 230 sieve were transferred to a settling chamber; 5 ml of sodium hexametophosphate was added and diluted to 1 liter with deionized water. The samples were allowed to soak for 12 hours. A settling cylinder was then filled, thoroughly mixed, returned to vertical position and 25 ml aliquots withdrawn at specified times and depths. The aliquots were placed in a tared 50 ml beaker which was covered and dried in an oven at 90°C. The beakers were then reweighed after cooling for one hour.

2.2.2 Larval Counts

The preserved samples were first either subsampled using a Folsom plankton splitter or rough sorted for decapod larvae in their entirety. The decision of whether to sort the entire sample or to split it depended on its size and condition. The general, subjective rule governing this decision was that if the sample was "clean" and had a volume greater than 0.15 liter, it was subsampled. Samples were considered "clean" if the volume of gelatinous zooplankton was low and there were no large phytoplankton aggregations, both of which would interfere with splitting.

Most samples were counted in their entirety; however, as needed, samples were sequentially divided with the plankton splitter until 100 to

200 individuals of the most common single larval growth stage of red king crab were left to be enumerated in a single split. Repeated splitting until each common organism has numbers between 100 and 200 in a given subaliquot is a common zooplankton counting method (Jacobs and Grant 1978). The level of confidence for the total number of larval red king crab in every sample usually was in excess of 0.90. This conclusion was obtained through the following reasoning. Since the organisms have been randomly distributed by the plankton splitter (Jacobs and Grant 1978) the counts of each subsample should obey the Poisson distribution (Elliott 1971). Under these conditions the sample variance equals the sample mean (Snedecor and Cochran 1967) and the optimal number to be counted equals the reciprocal of the square of the desired confidence level (Cassie 1971; Watt 1968). For the 0.90 level of confidence, the number is 100 organisms, while 400 organisms will produce a 0.95 level of confidence.

All counted samples and splits were saved separately for any necessary future verification. Counts were recorded on a coding sheet.

2.3 Data Reduction

The raw larval counts were converted into population density data. For the rarer stages the conversion is merely division of the total number counted by the volume (m^3) of the sample. Where aliquots were taken, the density values obtained were multiplied by the reciprocal of the size of the split used. Areal density (per 100 m^2) was obtained by first dividing the volume sampled by the sampling depth, then dividing 100 m^2 by the resulting area and multiplying sample counts by this second value. The second calculated value is necessary to convert the counts from a sample-specific area into standard counts per 100 m^2 (see discussion in Armstrong, et al. 1983b).

The final stage of data reduction was conversion of VTN formats into OCSEAP formats, File Type 124-Zooplankton and 123-Fish and Shellfish

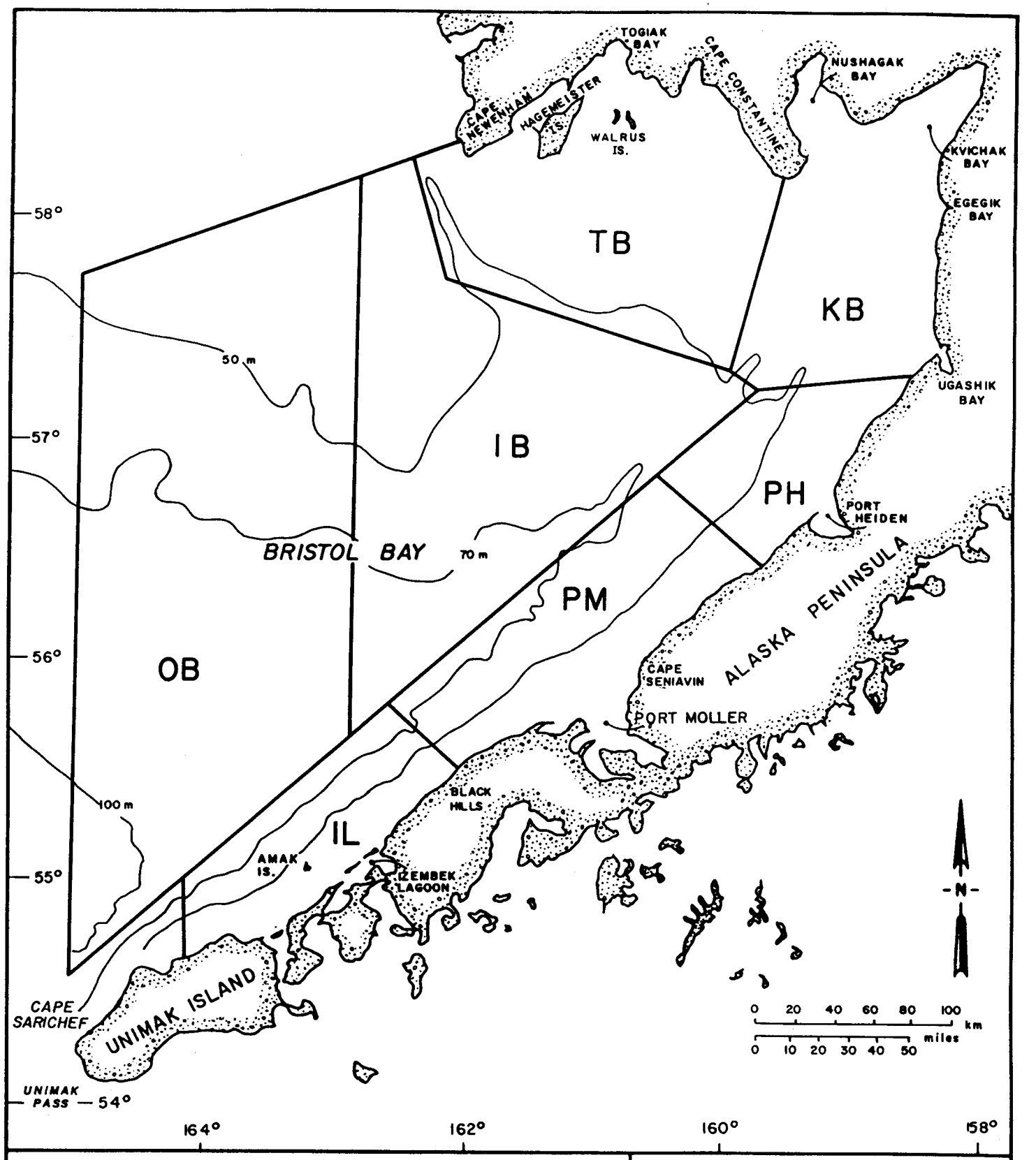
Resource Assessment. The conversion utilized computer programs previously developed for this purpose during OCSEAP RU608 - Kodiak Shelf Holozooplankton Distribution and OCSEAP RU623 - North Aleutian Shelf Sea Otter contracts. The converted data were put onto a magnetic tape at Mellonics Information Center, Canoga Park, California, and the final data product tape was then submitted to the OCSEAP Project Data Manager.

2.4 Data Analysis

Larval Crab. The crab larvae were initially described with a set of summary tables and density maps by stage and cruise. Seven subareas (strata) were selected for statistical comparison of areal results. These areas were shown in Figure 2.4-1, and are a modification of sampling strata defined by Armstrong, et al. (1983b) for analyses of data collected 1976-1982.

The second statistical treatment was a multiple correlation analysis, producing a correlation matrix between all of the included variables, after which multiple linear regression was run on selected variables. Prior to statistical treatment, the data were tested for normality, and as they were not normally distributed, the data were log-transformed in order to obtain valid statistical results. For larvae, the initial list of variables included temperature and salinity at five and 10 meters depth, time of day, time of year, station position, bottom depth and maximum depth of tow. Multiple correlation analysis was selected as the initial statistical treatment because it is a mathematically succinct method of determining the relative magnitude of different interactions within a large set of variables. In addition to the statistical analysis of relative abundance and apparent distribution, a limited analysis was performed on the Tucker trawl and neuston net samples to test for the presence of larval diel vertical stratification.

Post-larval Crab. Biological information collected for post-larval red king crabs included carapace length, weight, sex, shell condition and



OB - OUTER BRISTOL BAY
IB - INNER BRISTOL BAY
PM - PORT MOLLER
PH - PORT HEIDEN
KB - KVICHAK BAY
TB - TOGIAK BAY
IL - IZEMBEK LAGOON

BRISTOL BAY RED KING CRAB

STUDY AREA SUBAREAS FOR DATA ANALYSIS

FEBRUARY 1984

FIGURE 2.4-1

egg condition for females. Analysis of these data was performed without the use of the computerized data management system due to the small sample size. Length data were tabulated to show the distribution of crabs by age class. Geographical plots were produced to show the distribution of post-larval crabs by age within each cruise.

Assignment of relative age at size for the immature king crab was taken from Weber (1967) who examined the growth of immature king crabs from the southeastern Bering Sea. The average and range of the carapace length of crabs at ages 1, 2 and 3 are 11 and 9-14 mm, 35 and 29-41 mm, and 60 and 50-67 mm, respectively. Weber (1967) gave the average size of age 4 crab as 78 mm; however, no size range for this age was presented. After examination of the means and ranges of smaller age classes, a conservative range of $\pm$4 mm (74-82 mm) was assumed for age 4 crabs. The size of 82 mm was chosen as the cut-off for age 4 crabs, in part because the smallest ovigerous female that was found in this survey was 83 mm. All crabs >83 mm were assigned the age of 4++. Since growth for the sexes is similar until the fourth year of life at approximately 80 mm (Weber 1967), size data for males and females to 82 mm were combined.

The emphasis of the post-larval part of this study is on crabs of age 3 years and younger. Accordingly, these individuals (<67 mm) are referenced in this report as "juvenile" crabs, while individuals older than 4 years (>83 mm) are "adults". Crabs age 3+ and 4 (>68 and <83 mm) are included in the sections dealing with adults.

The distribution data were tabulated by station for each cruise. Because certain stations were sampled more than others, these data were standardized by calculating a catch per station value for each of the six sampling subareas (for this purpose, subareas IB and OB were combined as BB). The overall mean catch per station for each cruise was calculated as the sum of the mean catches per station in a subarea divided by the total number of stations sampled in that subarea.

Epibenthic density and biomass data were analyzed in two ways. First, mean biomass values were calculated for each major taxonomic group per cruise; these values were labeled mean catch per unit effort (CPUE) in units of gm-2. These data are presented in tabular form to show the relative importance of major fish and invertebrate groups in the samples. The second major analysis of epifaunal data was cluster analysis. Cluster analysis using EAP (1982) involved a square root transformation of all data and appropriate standardizations. Dissimilarities or distances among the entities (samples or species) were calculated using the Bray-Curtis Index (Bray and Curtis 1957). Formation of the two dendrograms and the two-way matrix of sample and species groups involved flexible sorting with the addition of a step across distances re-estimation for the species groupings and the two-way matrix.

Post-larval king crab densities and related physical and biological environmental variables were examined using correlation and multiple linear regression analyses. For the purpose of these analyses, king crabs were divided into four age groups: 1) young-of-the-year or 0+; 2) ages 1, 1+ and 2; 3) ages 2+ and 3; and 4) ages 3+ and older (3++). The four physical variables were: 1) depth; 2) bottom water temperature; 3) bottom water salinity; and 4) percent gravel in sediment samples. The biological variables used were the mean sample biomass values for nine taxa: 1) flatfishes; 2) roundfishes (all fish except Pleuronectidae); 3) polychaete worms; 4) shrimps (including pandalids and crangonids); 5) the sea star (Asterias amurensis); 6) the sea urchin (Strongylocentrotus droebachiensis); 7) sponge; 8) bryozoans; and 9) the sea onion (Boltenia ovifera). Biomass data were available for all of these taxa with the exception of bryozoan biomass from all quantitative trynet and rock dredge samples. Bryozoan biomass data were not always available due to the difficulty of separating this taxon from its substrate; however, the taxon was included in the analysis because of its apparent use as food by juvenile red king crabs (see Appendix F).

SECTION 3.0

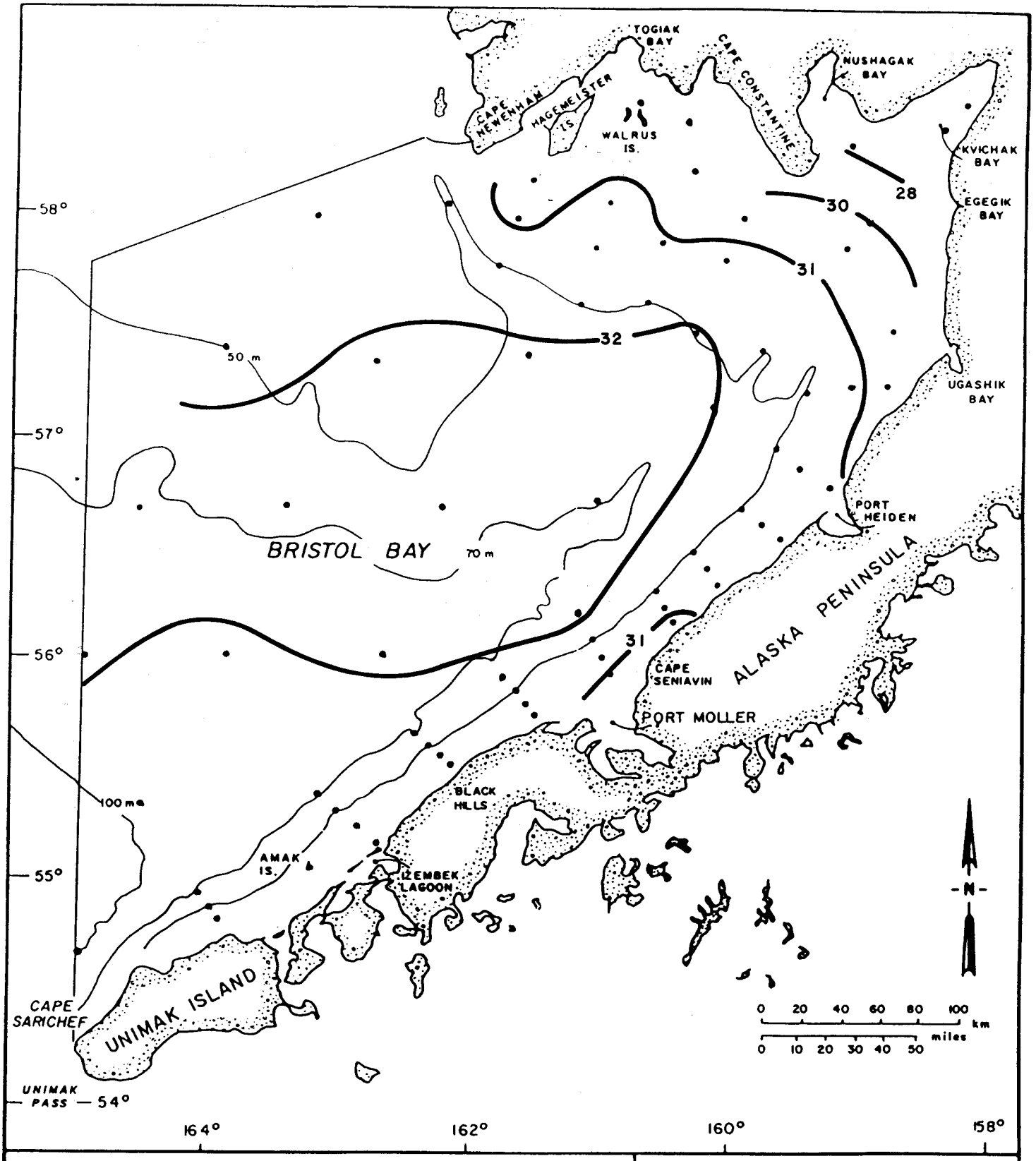
RESULTS

3.1 Physical Environment

3.1.1 Hydrography

Salinity. Near-surface salinity contours for the April, June and September cruises are presented in Figures 3.1-1, 3.1-2 and 3.1-3, respectively; near-bottom salinity contours are shown in Figures 3.1-4, 3.1-5 and 3.1-6. Salinity generally increased offshore. Maximum salinities at all depths were found in the deepest offshore parts of the study area and lower salinities were found onshore, especially near areas of freshwater runoff which included Kvichak and Nushagak Bays, Port Heiden and Port Moller. Very little vertical salinity stratification was observed during the study. Salinity decreased slightly over the study period and the lowest salinities were recorded during September in Kvichak Bay. The freshwater from Kvichak and Nushagak Bays apparently flows largely to the west, along the north side of Bristol Bay.

Temperature. Near-surface temperature contours for the April, June and September cruises are presented in Figures 3.1-7, 3.1-8 and 3.1-9, respectively; near-bottom temperature contours are shown in Figures 3.1-10, 3.1-11 and 3.1-12. Observed temperatures ranged from below 1° in April to over 12°C in September. The lowest temperatures were found at depth during the spring and the highest were associated with onshore areas in summer and fall. The strongest feature shown by the temperature data is the seasonal thermocline, which was most prominent during the June cruise (83-3). The maximum temperature differences between surface and bottom (>4°C) and the coldest bottom water during June, were observed offshore of the Black Hills vicinity (Figure 3.1-11). There was



• = SAMPLING STATION

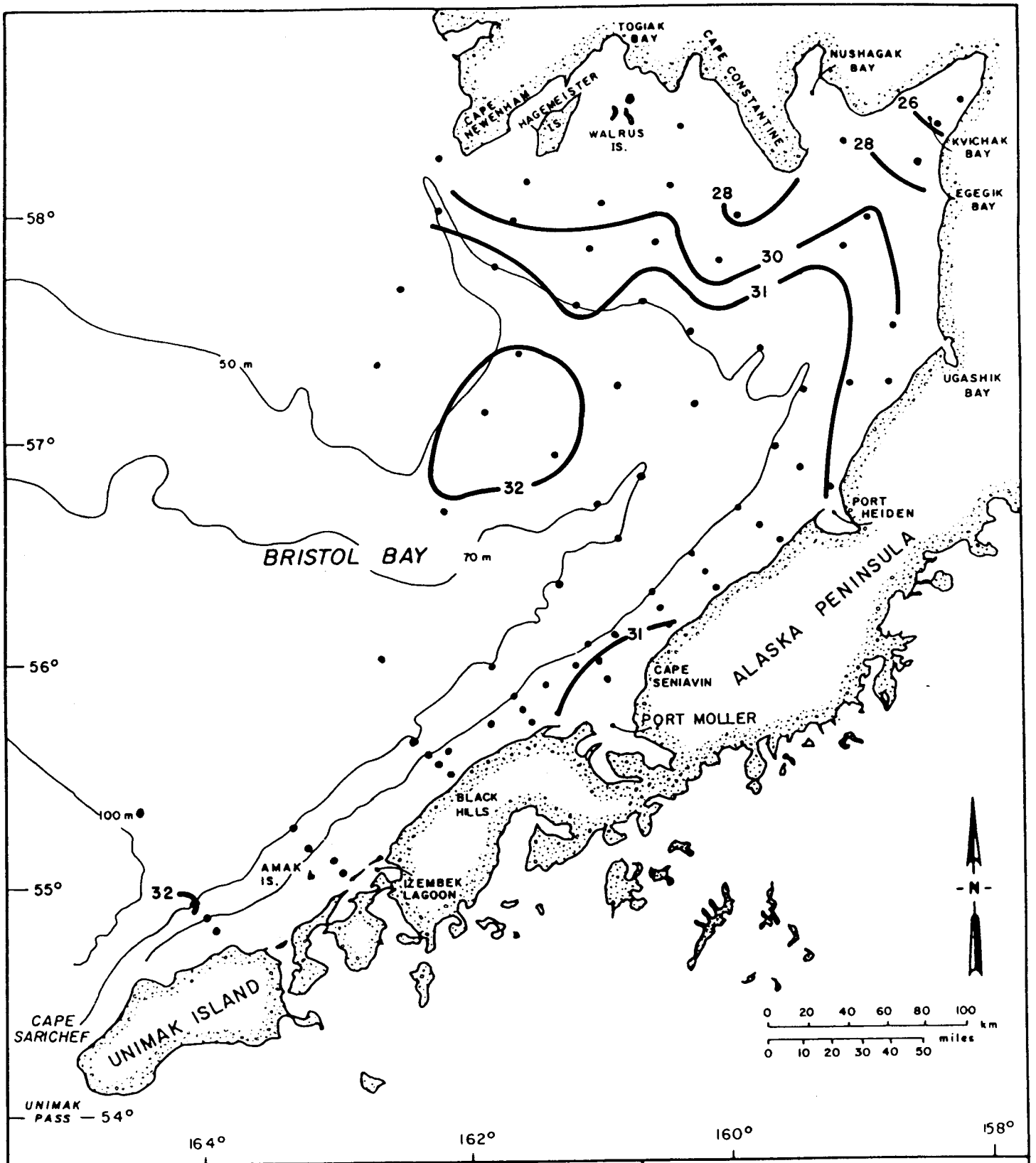
—30— = ISOHALINE (‰)

BRISTOL BAY RED KING CRAB

CRUISE 83-1

10 METER SALINITY CONTOURS

FEBRUARY 1984 | FIGURE 3.1-1



• = SAMPLING STATION

—30— = ISOHALINE (‰)

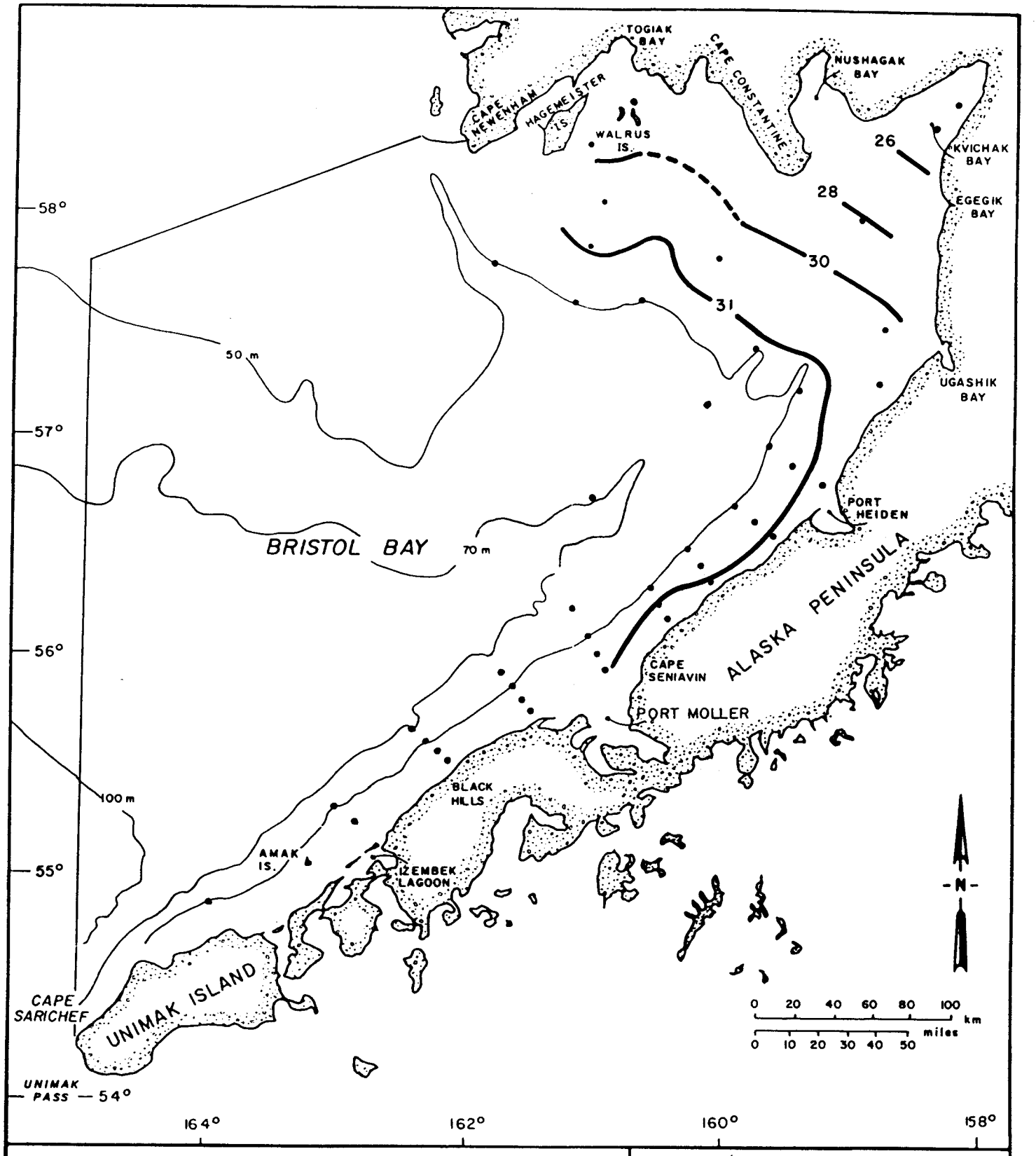
BRISTOL BAY
RED KING CRAB

CRUISE 83-3

10 METER SALINITY CONTOURS

FEBRUARY 1984

FIGURE 3.1-2



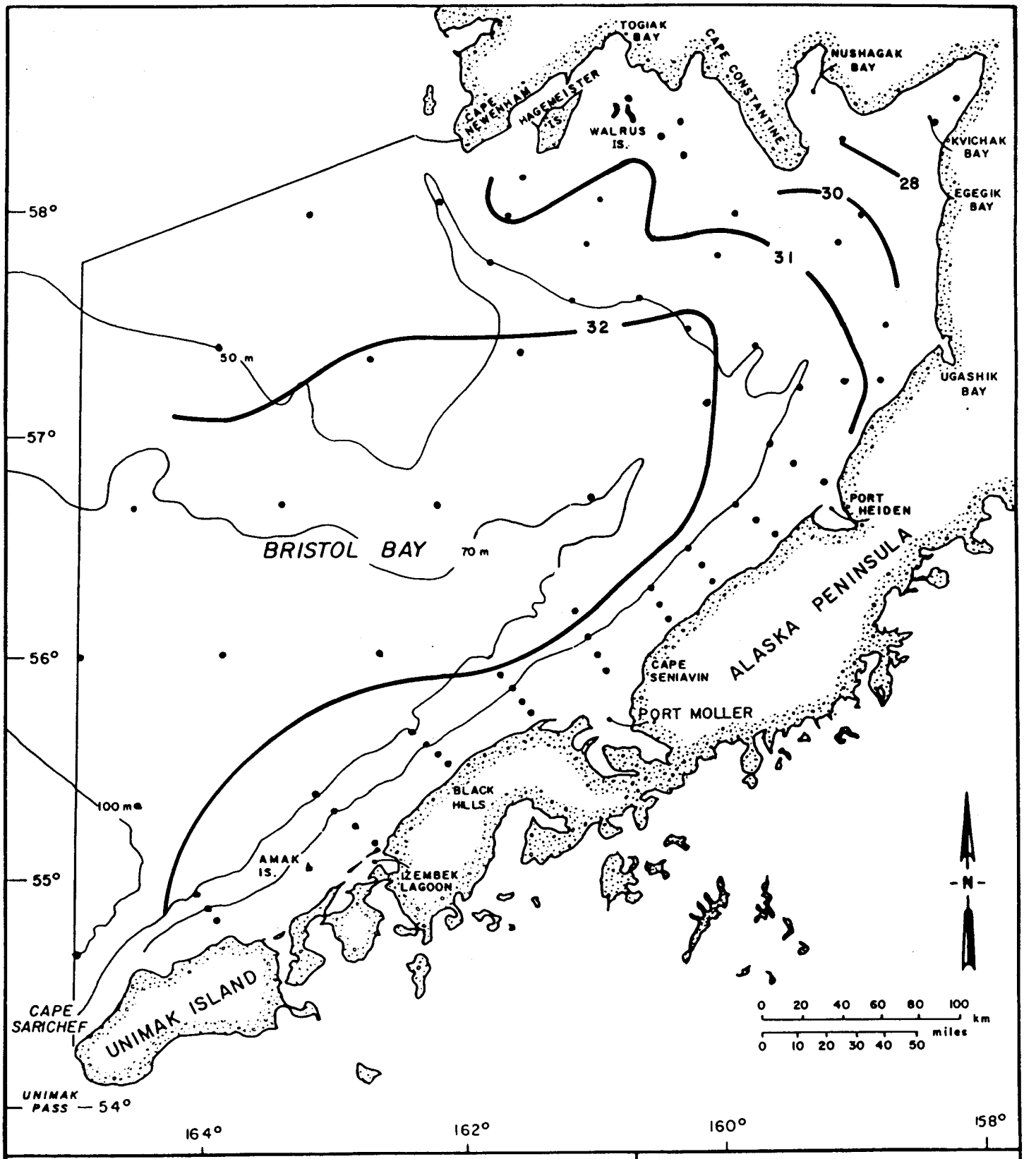
• = SAMPLING STATION
—30— = ISOHALINE (‰)

BRISTOL BAY RED KING CRAB

CRUISE 83-5

10 METER SALINITY CONTOURS

FEBRUARY 1984 | FIGURE 3.1-3



• = SAMPLING STATION

—30— = ISOHALINE (‰)

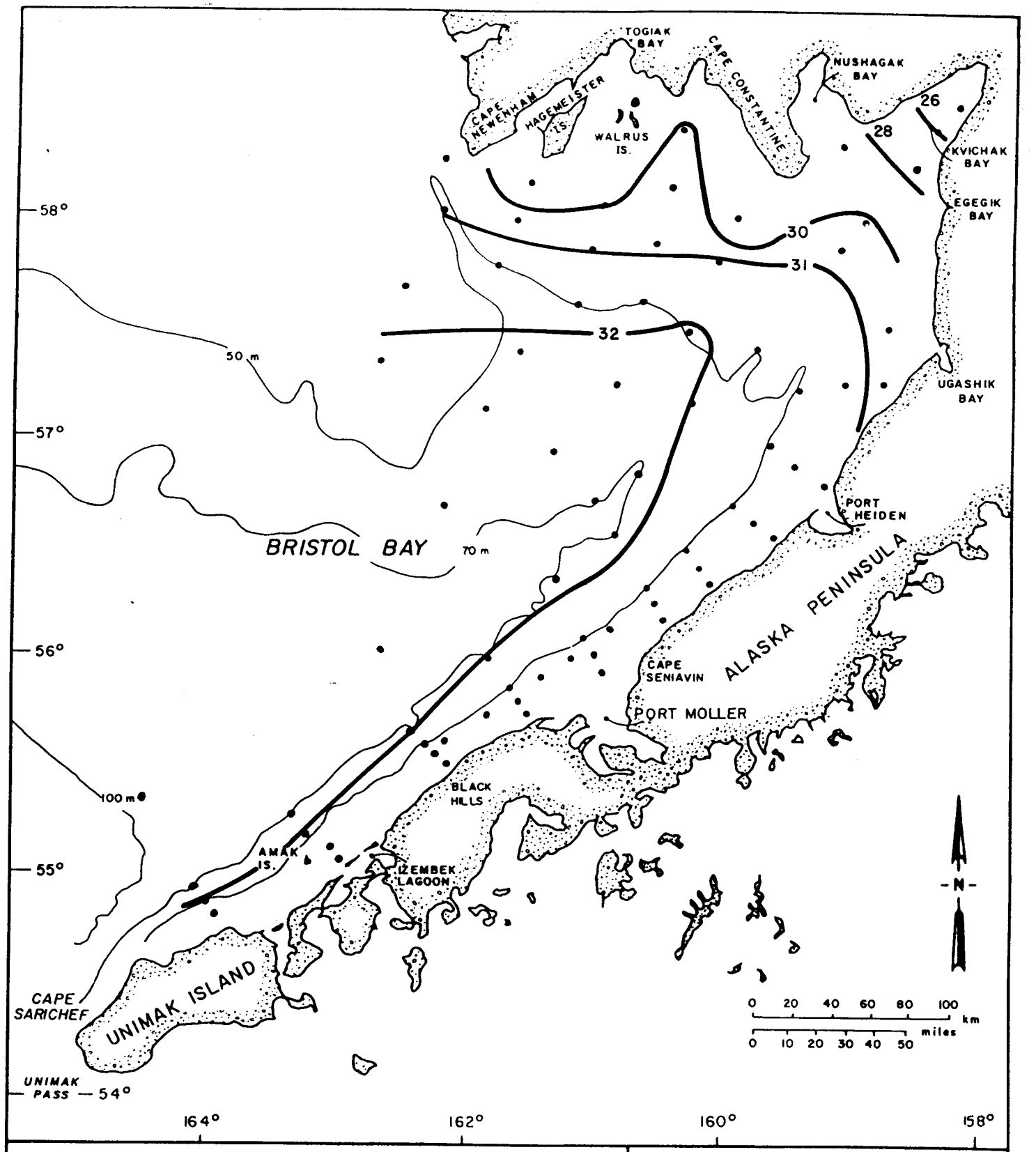
BRISTOL BAY
RED KING CRAB

CRUISE 83-1

BOTTOM SALINITY CONTOURS

VTN

FEBRUARY 1984 | FIGURE 3.1-4



• = SAMPLING STATION

—30— = ISOHALINE (‰)

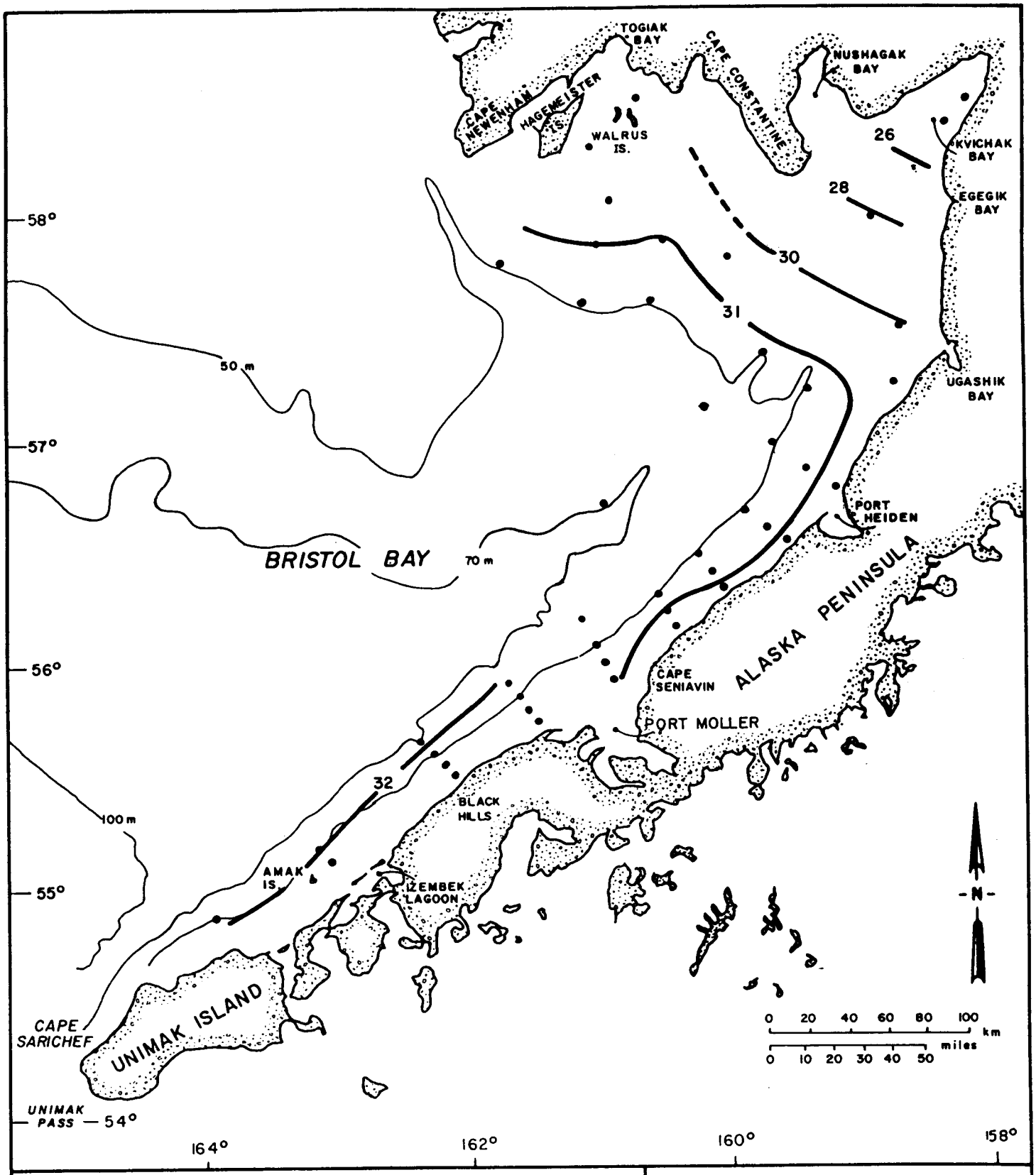
BRISTOL BAY RED KING CRAB

CRUISE 83-3

BOTTOM SALINITY CONTOURS

FEBRUARY 1984

FIGURE 3.1-5



● = SAMPLING STATION

—30— = ISOHALINE (‰)

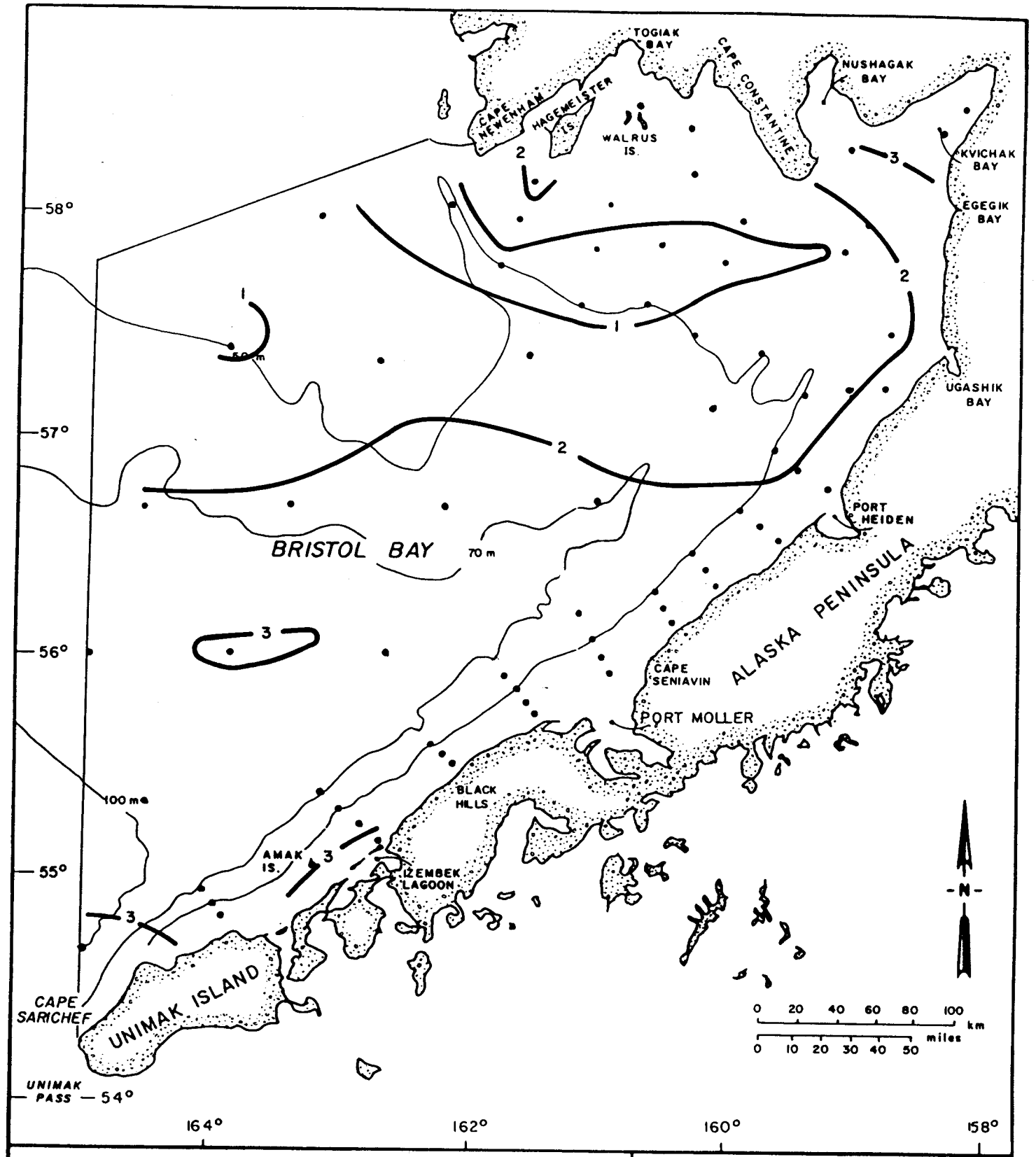
BRISTOL BAY
RED KING CRAB

CRUISE 83-5

BOTTOM SALINITY CONTOURS

FEBRUARY 1984

FIGURE 3.1-6



• = SAMPLING STATION

—5— = ISOTHERM (°C)

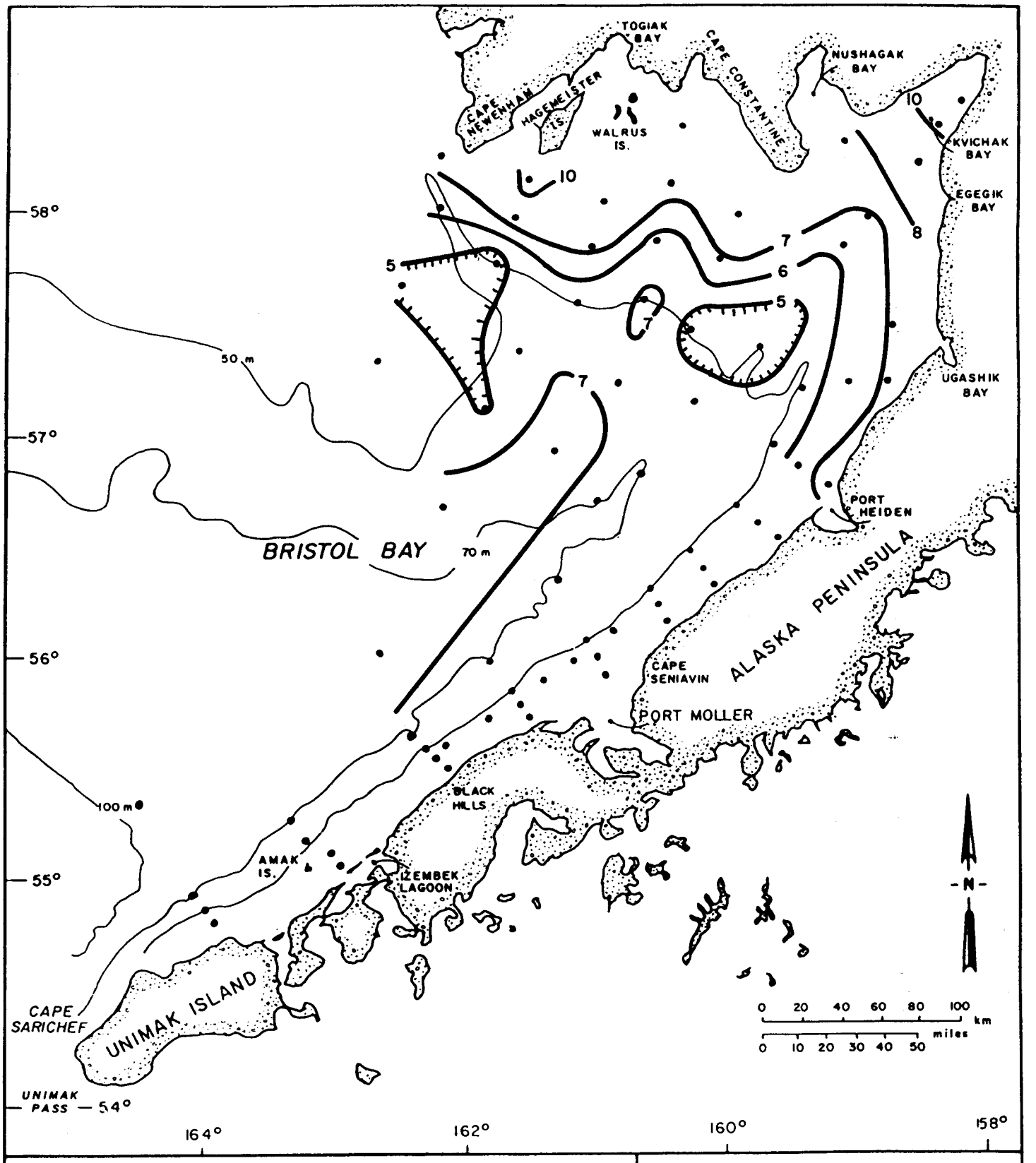
BRISTOL BAY
RED KING CRAB

CRUISE 83-1

10 METER TEMPERATURE CONTOURS

FEBRUARY 1984

FIGURE 3.1-7



• = SAMPLING STATION

— 5 — = ISOTHERM (°C)

BRISTOL BAY
RED KING CRAB

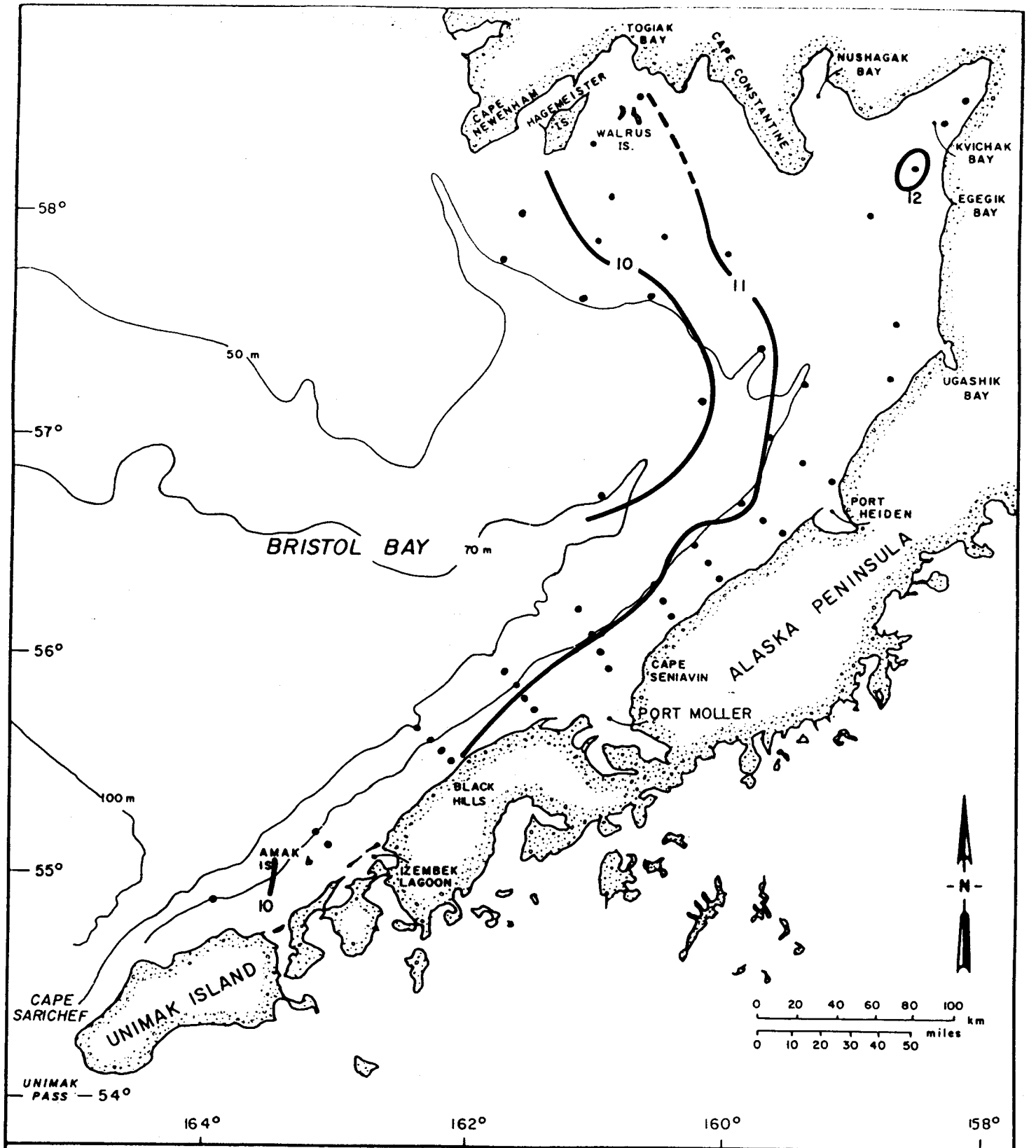
CRUISE 83-3

10 METER TEMPERATURE CONTOURS

VTN

FEBRUARY 1984

FIGURE 3.1-8



● = SAMPLING STATION

–5– = ISOTHERM (°C)

BRISTOL BAY
RED KING CRAB

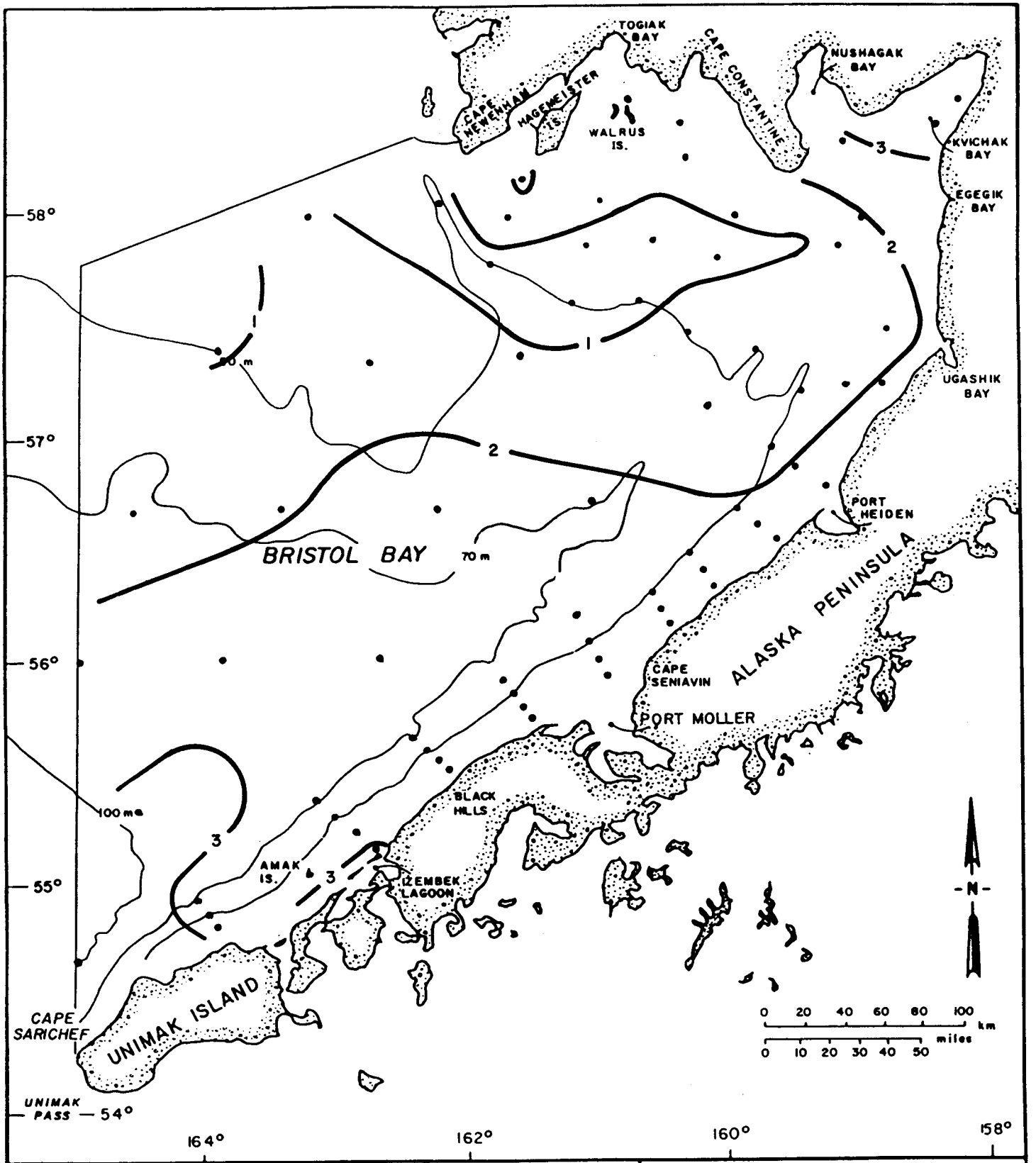
CRUISE 83-5

10 METER TEMPERATURE CONTOURS

VTN

FEBRUARY 1984

FIGURE 3.1-9



• = SAMPLING STATION

— 5 — = ISOTHERM (°C)

BRISTOL BAY RED KING CRAB

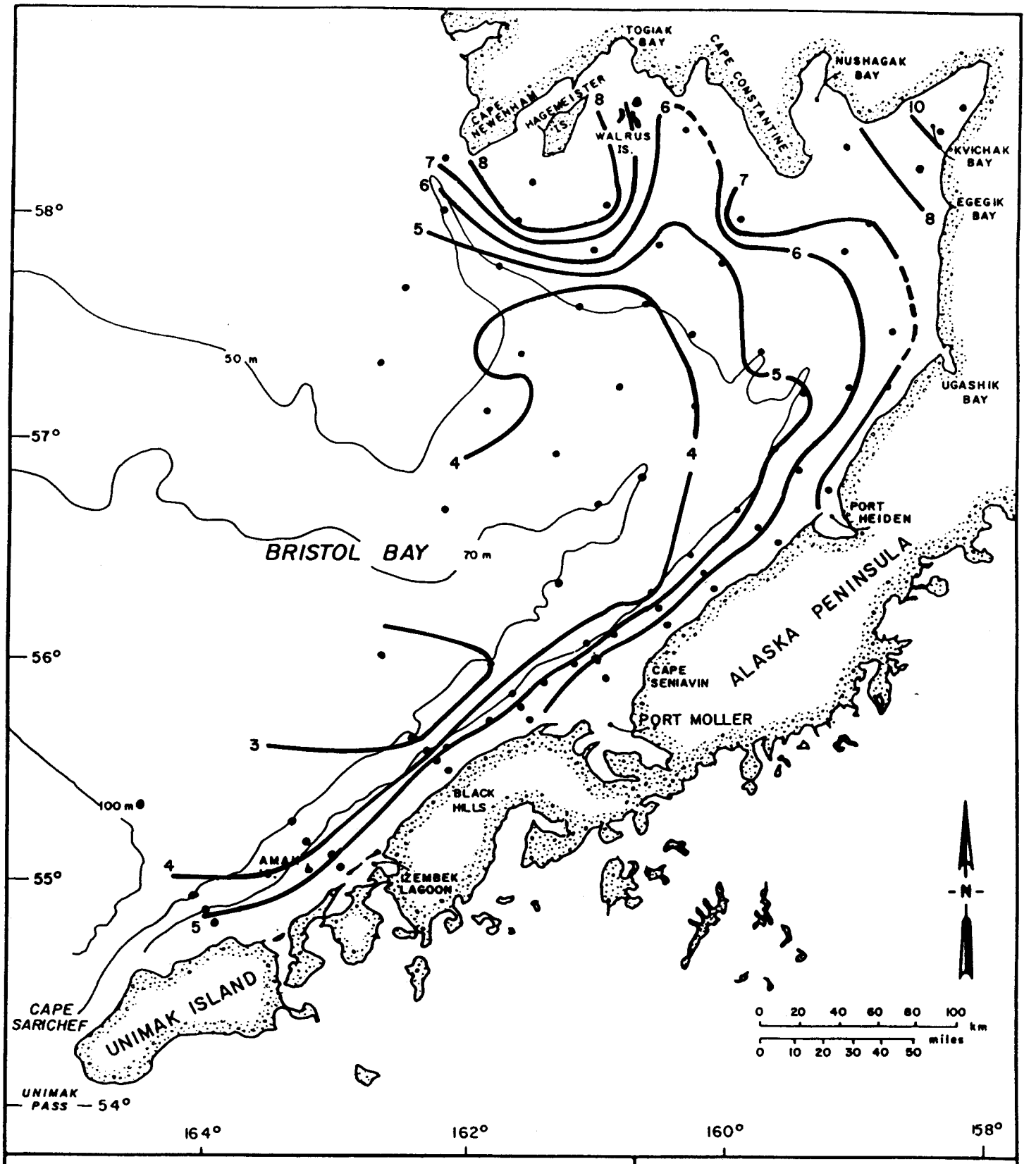
CRUISE 83-1

BOTTOM TEMPERATURE CONTOURS

VTN

FEBRUARY 1984

FIGURE 3.1-10



• =SAMPLING STATION

—5— =ISOTHERM (°C)

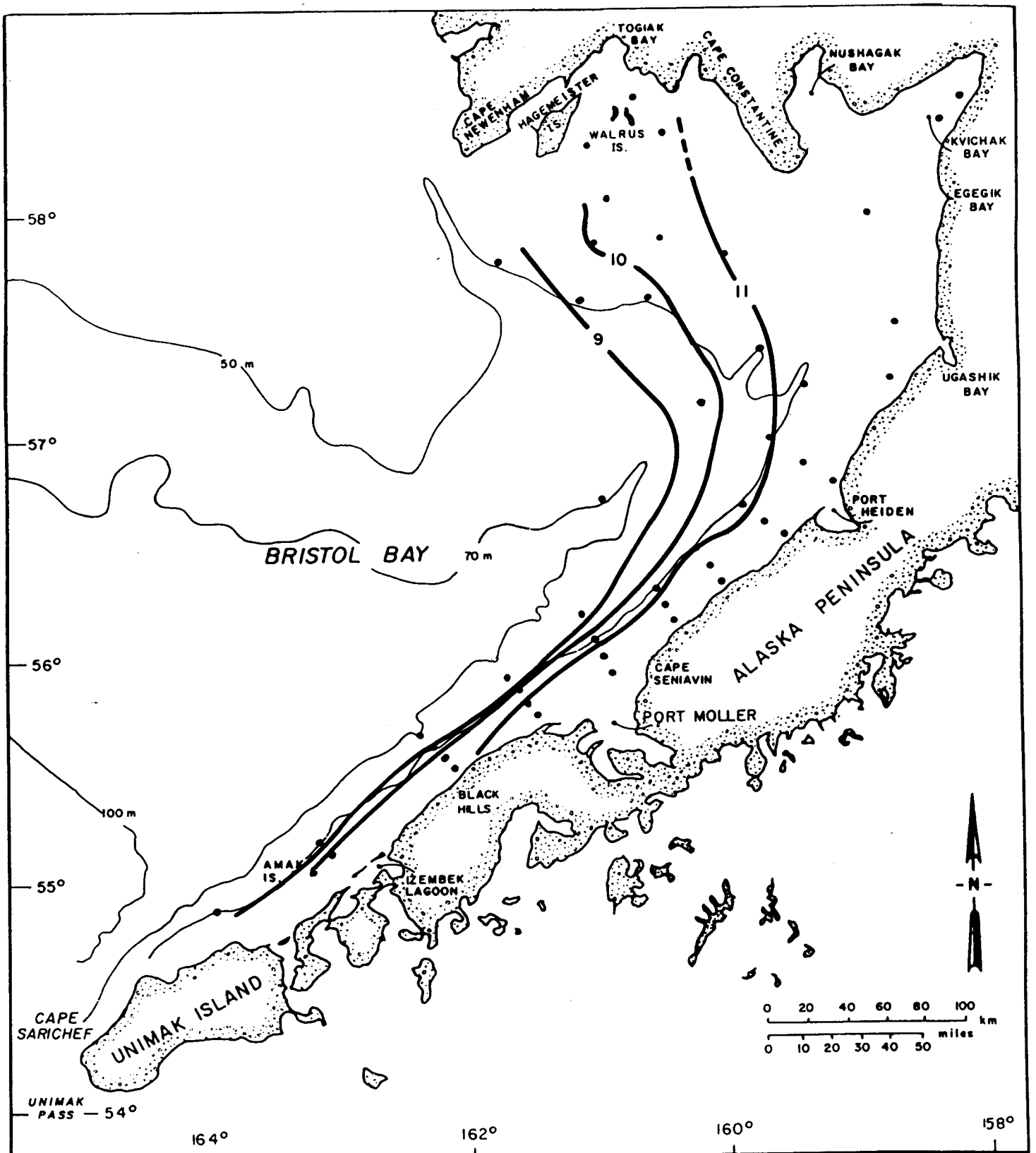
BRISTOL BAY RED KING CRAB

CRUISE 83-3

BOTTOM TEMPERATURE CONTOURS

FEBRUARY 1984

FIGURE 3.1-11



• = SAMPLING STATION

—5— = ISOTHERM (°C)

BRISTOL BAY
RED KING CRAB

CRUISE 83-5

BOTTOM TEMPERATURE CONTOURS

FEBRUARY 1984

FIGURE 3.1-12

little vertical temperature stratification inshore of the 50 m isobath. The high temperatures on the northern side of Bristol Bay during June and September were apparently related to warm fresh water moving generally west from Kvichak and Togiak Bays.

3.1.2 Substrate Characteristics

Sediment Analysis. The results of the sediment analyses are presented in Table 3.1-1, which reports the percent sand, gravel and silt, geometric mean diameter and sorting index for the 60 samples analyzed. Most samples in the study area were predominated by sand, as shown in Figure 3.1-13. At least one sample from each of the study areas except Bristol Bay contained >10 percent gravel. Six of the seven KB samples contained from 42 to 91 percent gravel, four of the fifteen TB samples contained 41 to 62 percent gravel, and two of the nine IL samples contained 30 to 54 percent gravel. By contrast, samples from the Bristol Bay subarea contained little or no gravel, but had the greatest amounts of silt, ranging from 0 to 33 percent. Station TB130, near Cape Newenham, had 16 percent silt; none of the remaining stations sampled had >5 percent silt. The geometric mean diameter for the BB samples was lowest and the sorting index was highest. Samples containing gravel were poorly sorted by comparison to the deeper, Bristol Bay samples. The percentage gravel information is presented as contours (by orders of magnitude) in Figure 3.1-14. This figure shows the apparent large-scale distribution of gravel deposits in the study area.

Observational data concerning substrate material in trynet and rock/dredge samples are presented in Figure 3.1-15. The distribution of gravel or larger sized substrates from these observations agrees fairly well with the distribution obtained from sediment sample data. The Shipek sampler used to obtain sediments works poorly in larger grained sediments, thus, shell and cobble substrates were not adequately sampled. Observations indicated that substrates with significant amounts of whole and broken shell debris were found at 50 m and deeper

TABLE 3.1-1

SEDIMENT SIZE CHARACTERISTICS

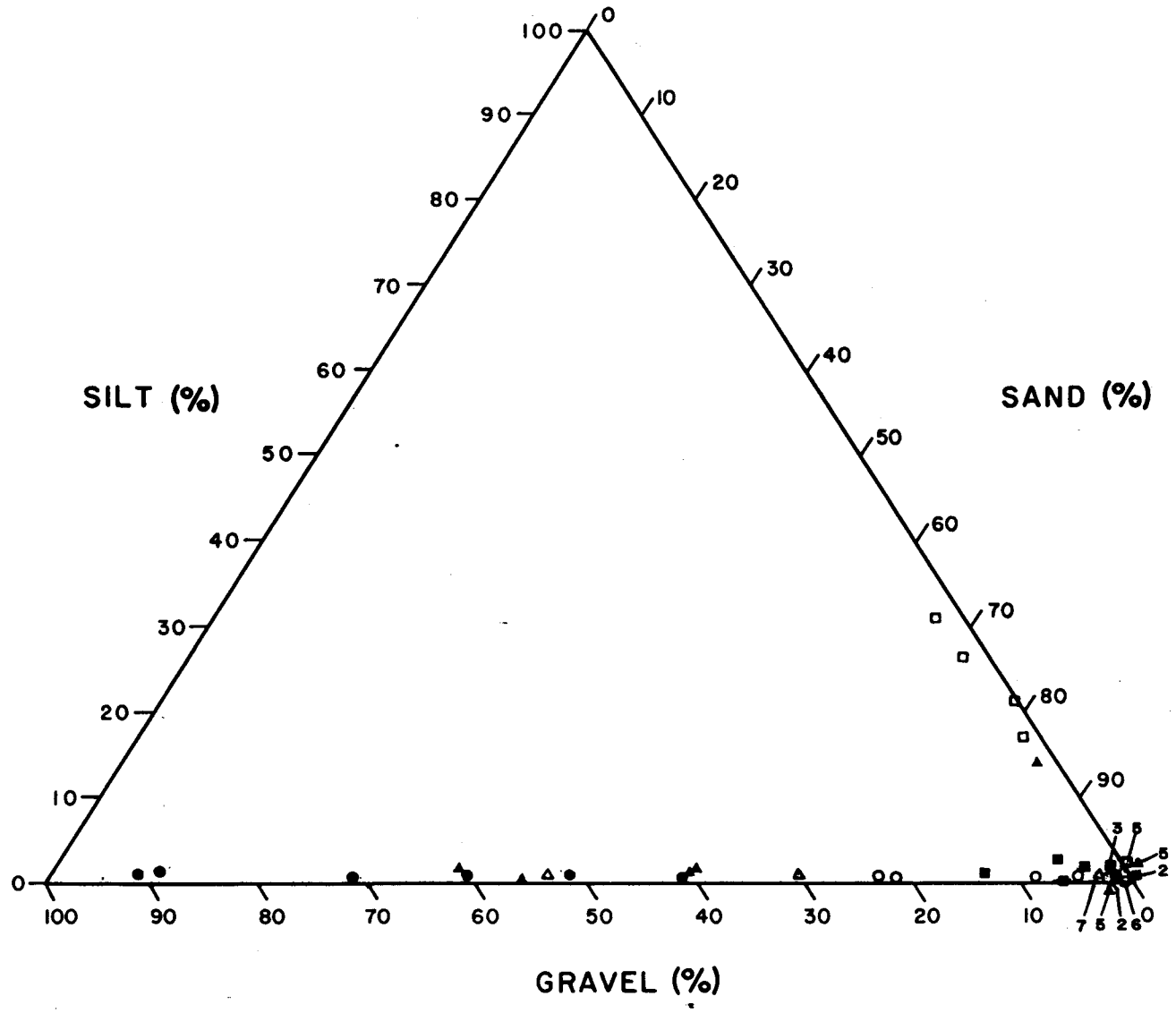
Station	Depth (m)	Grain Size Percent			Gm[a]	So[b]
		Gravel	Sand	Silt		
					DL[c]	DL
IL150	50	1.42	98.58	0	0.69	1.43
IL160	62	0	100.0	0	0.57	1.40
IL220	20	0	100.0	0	0.20	1.28
IL230	30	0	99.84	0.16	0.28	1.24
IL260	60	0.22	99.78	0	0.21	1.36
IL270	70	0	99.78	.22	5.34	2.08
IL420	17	53.55	46.45	0	3.60	1.48
IL430	33	30.25	69.75	0	0.45	1.52
IL470	67	.47	99.44	.09		
PM320	20	24.39	75.61	0	1.61	2.24
PM330	30	8.72	91.18	0.09	2.25	1.22
PM350	50	2.97	97.03	0	0.83	1.88
PM350	50	6.83	93.02	0.15	1.66	1.65
PM650	50	0	99.88	0.12	0.22	1.22
PM670	70	0	100.0	0	0.23	1.26
PM730	30	0	99.76	0.24	0.20	1.20
PM820	24	23.88	75.89	0.23	1.67	2.39
PM850	49	2.27	97.61	0.13	0.70	2.10
PM920	17	0	97.03	2.97	0.24	1.25
PM930	27	0.45	99.43	0.11	0.63	1.92
PM950	50	0.56	99.35	0.09	0.39	1.48
BB190	1	0	67.30	32.70	0.12	2.22
BB250	0	0	99.22	0.78	0.17	1.22
BB270	71	0	72.74	27.26	0.11	1.70
BB299	100	0	78.78	21.22	0.11	1.60
BB340	36	0	99.71	0.29	0.23	1.15
BB390	87	0	83.51	16.49	0.13	1.59
BB480	80	0	100.0	0	0.19	1.25
BB560	64	0	99.86	0.14	0.20	1.23
BB770	0	0	99.72	0.28	0.27	1.33
KB2*9	7	42.05	57.67	0.28	1.75	5.98
KB2*0	22	89.17	10.73	0.10	21.82	1.97
KB2*0	22	61.30	38.70	0	5.27	5.29
KB2*4	20	90.51	9.47	0.02	20.97	1.74
KB2*4	22	71.58	28.33	0.09	8.94	3.02
KB240	5	0.13	99.80	0.07	0.43	1.47
KB320	2	46.54	53.35	0.11	1.88	5.84

TABLE 3.1-1

(continued)

Station	Depth	Grain Size Percent			G_m[a]	S_o[b]
		Gravel	Sand	Silt		
PH130	28	4.31	95.69	0	1.15	1.79
PH150	50	0	99.65	0.35	0.31	1.30
PH220	20	5.32	92.31	2.38	0.28	1.28
PH230	29	5.49	94.42	0.09	0.42	1.46
PH250	55	0	99.56	0.44	0.31	1.43
PH320	17	0.27	99.46	0.27	0.32	1.23
PH320	20	2.20	92.69	5.11	0.60	2.37
PH330	29	14.30	85.64	0.06	1.25	2.24
PH350	51	0.35	99.57	0.09	0.41	1.53
TB130	30	0	84.10	15.90	0.13	1.61
TB150	49	0.53	98.95	0.53	0.24	1.12
TB230	27	54.18	45.49	0.33	4.47	2.47
TB250	47	1.04	98.60	0.37	0.24	1.18
TB329	27	61.92	34.95	3.13	4.27	9.37
TB320	20	41.67	58.21	0.12	2.78	1.93
TB330	31	3.44	96.43	0.12	0.49	1.65
TB350	50	0	99.79	0.21	0.22	1.18
TB429	29	0	92.21	7.79	0.11	1.25
TB431	30	0	94.87	5.13	0.13	1.26
TB450	(30)	40.81	58.69	0.50	2.36	2.56
TB450	(50)	0	99.92	0.08	0.23	1.26
TB520	20	0	99.72	0.28	0.23	1.19
TB540	40	0.24	99.57	0.18	0.25	1.26
TB550	53	0.50	99.19	0.31	0.29	1.28

(a) Geometric mean
(b) Sorting index
(c) Data loss (DL)



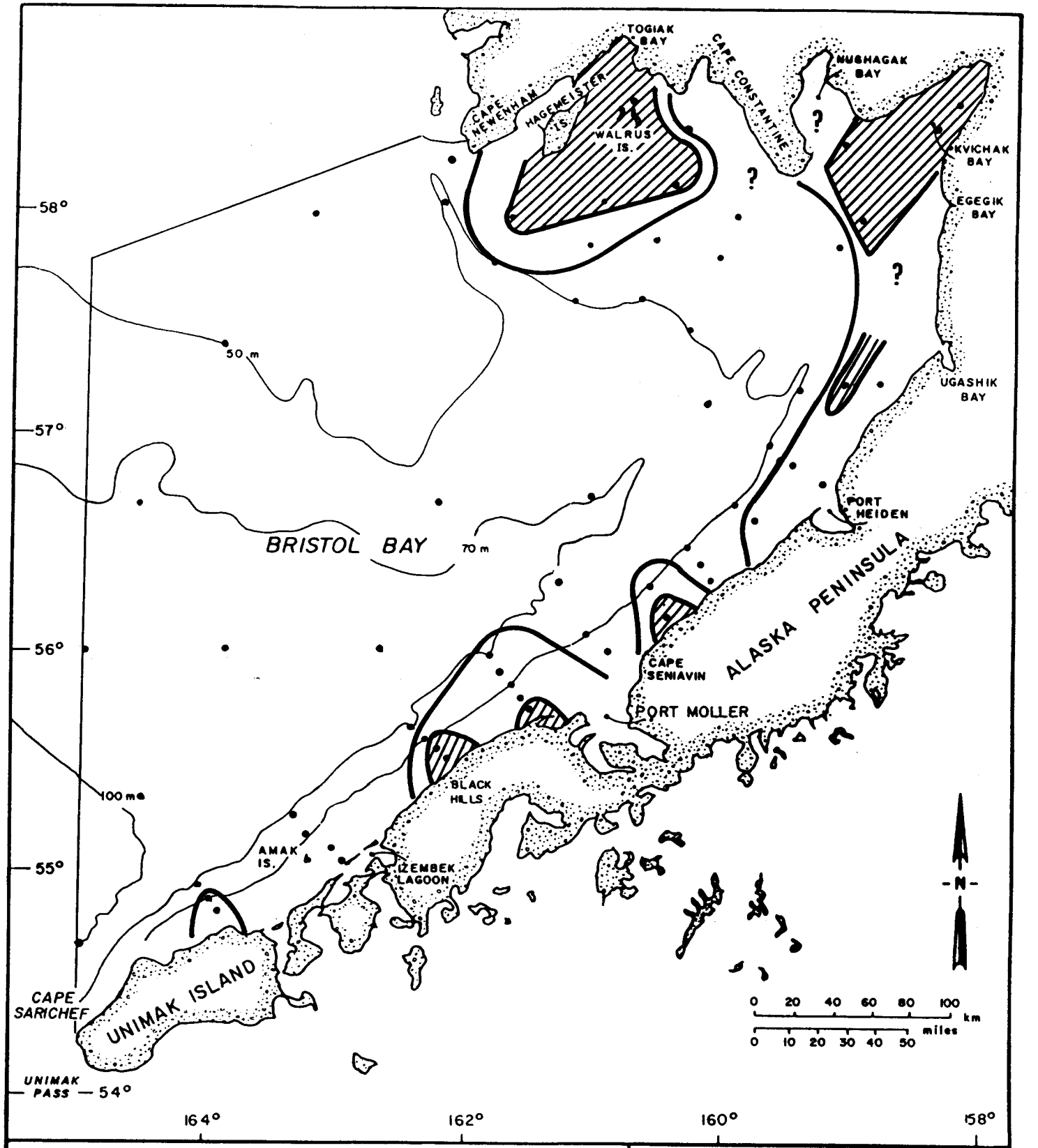
SYMBOL = SAMPLING AREA

- △ = IL
- ○ = PM
- □ = BB
- ● = KB
- ■ = PH
- ▲ = TB

BRISTOL BAY
RED KING CRAB

PERCENTAGE SILT, SAND AND GRAVEL IN SEDIMENT SAMPLES

FEBRUARY 1984 | FIGURE 3.1-13



• = SEDIMENT SAMPLING STATION

= >1% GRAVEL

= >10% GRAVEL

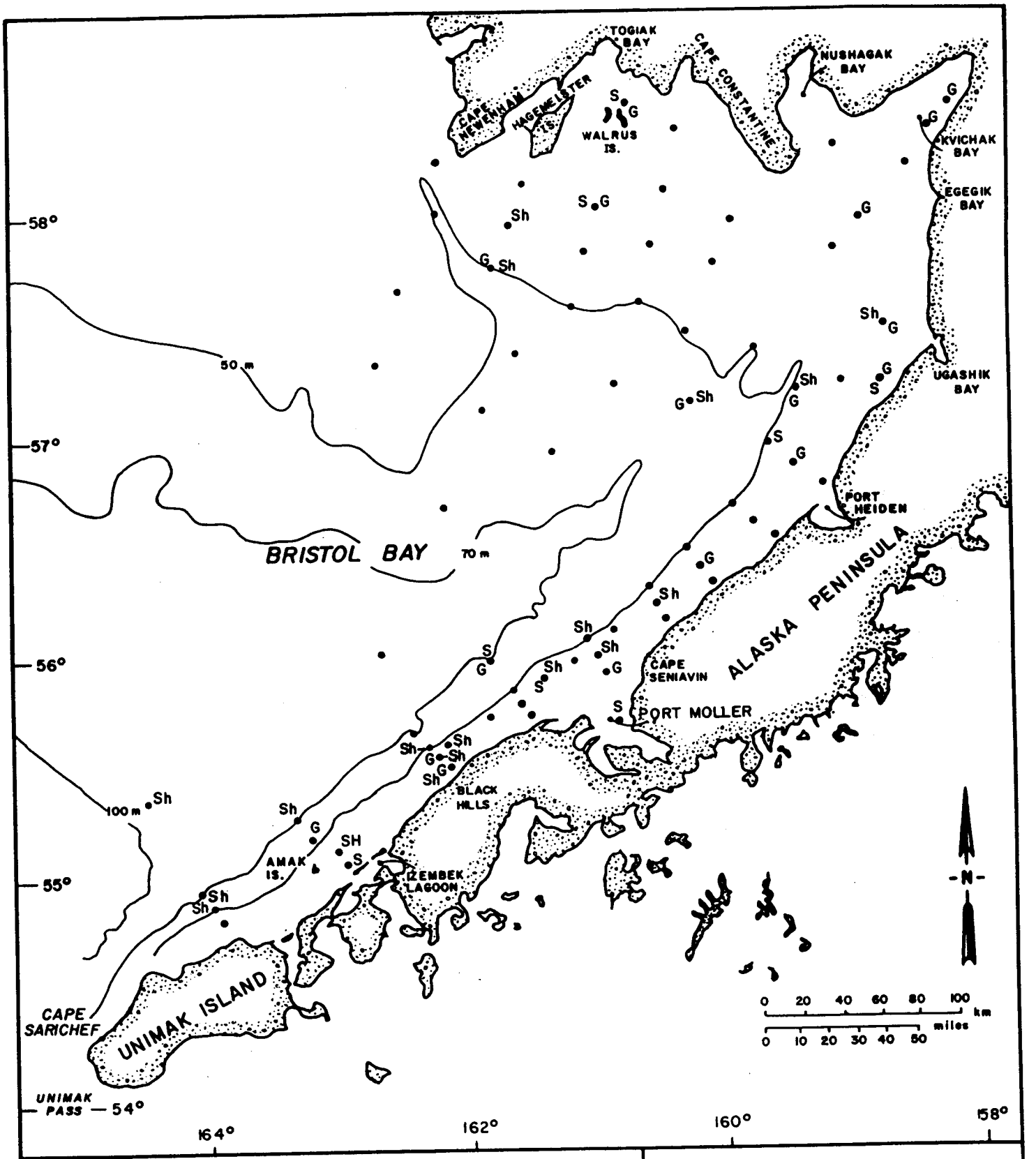
? = NO DATA

BRISTOL BAY RED KING CRAB

PERCENT GRAVEL CONTOURS IN BRISTOL BAY

VTN

FEBRUARY 1984 | FIGURE 3.1-14



G = GRAVEL OR GRAVEL AND COBBLE

S = SAND

Sh = SHELL DEBRIS

BRISTOL BAY RED KING CRAB

TRAWL SAMPLE OBSERVATIONAL SUBSTRATE DATA

FEBRUARY 1984 | FIGURE 3.1-15

between Unimak Island and Port Moller, off Port Heiden and off Hagemeister Island in the Togiak Bay area.

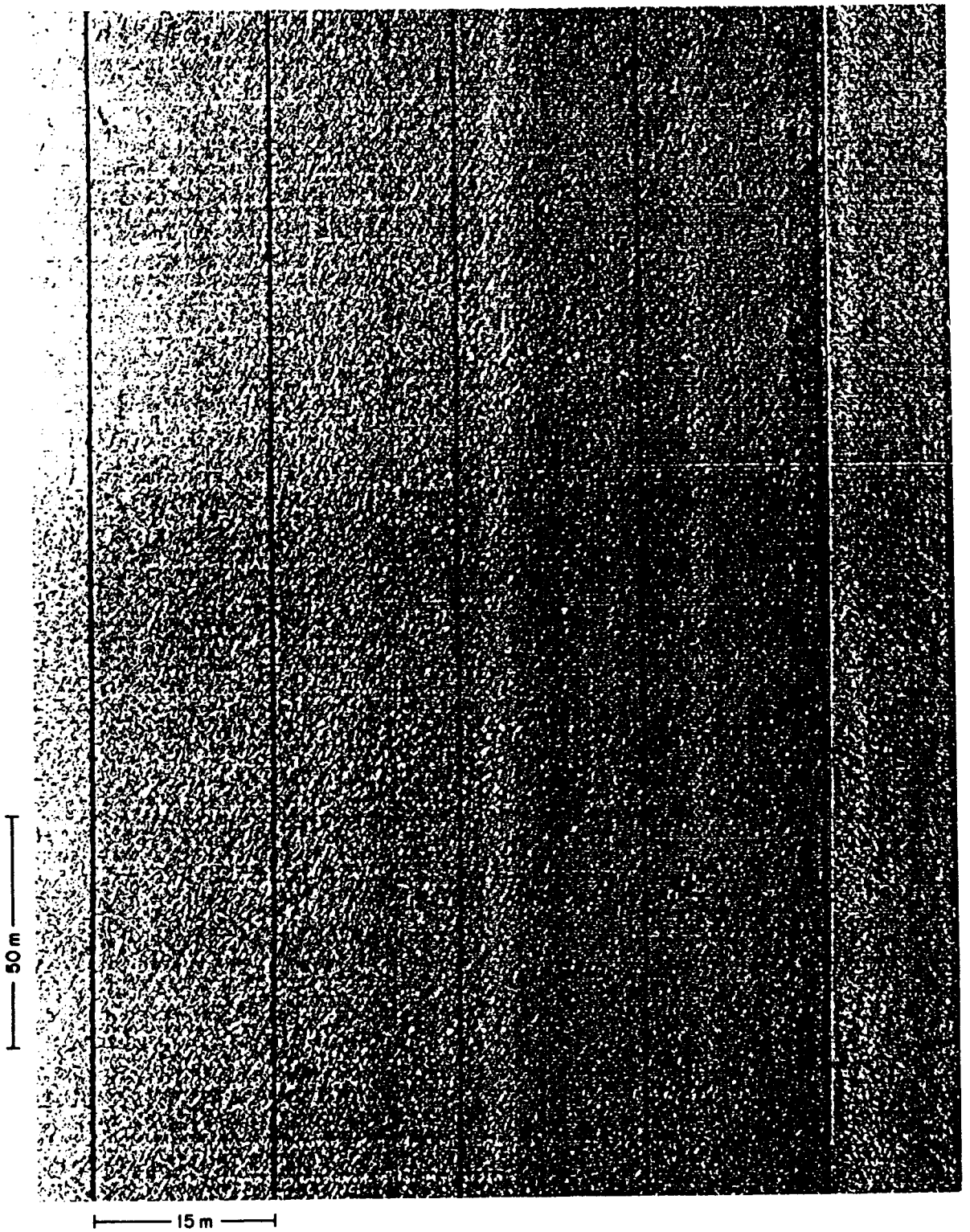
Side Scan Sonar. Side scan sonar surveys were successfully employed in order to discern gravel and cobble substrates from silt and sand substrates. Portions of sonar traces showing silt-sand and gravel-cobble areas are reproduced in Figures 3.1-16 and 3.1-17, respectively. Although the project budget precluded analysis of ground truth samples, subjective observations of Shipek dredges and try net and rock dredge hauls indicated that the samples support these side scan interpretations.

Intensive side scan sonar surveys, each approximately one nautical mile square (3.43 km^2), were conducted at stations PM630 and KB2*4 during cruise 83-5. The Port Moller survey exhibited no discernible heterogenity in the stubstrate. The Kvichak Bay survey yielded transects with apparent areas of gravel-cobble such as that shown in Figure 3.1-17. When the transects for the survey were joined and drawn to scale, the gravel-cobble areas emerged as long, narrow beds, oriented approximately parallel to the axis of Kvichak Bay. The beds were 20-30 m wide and between 50 and 800 m long. A graphic representation of the beds in the Kvichak Bay survey is shown in Figure 3.1-18.

3.2 Larval Distribution and Abundance

3.2.1 Horizontal Distribution and Abundance

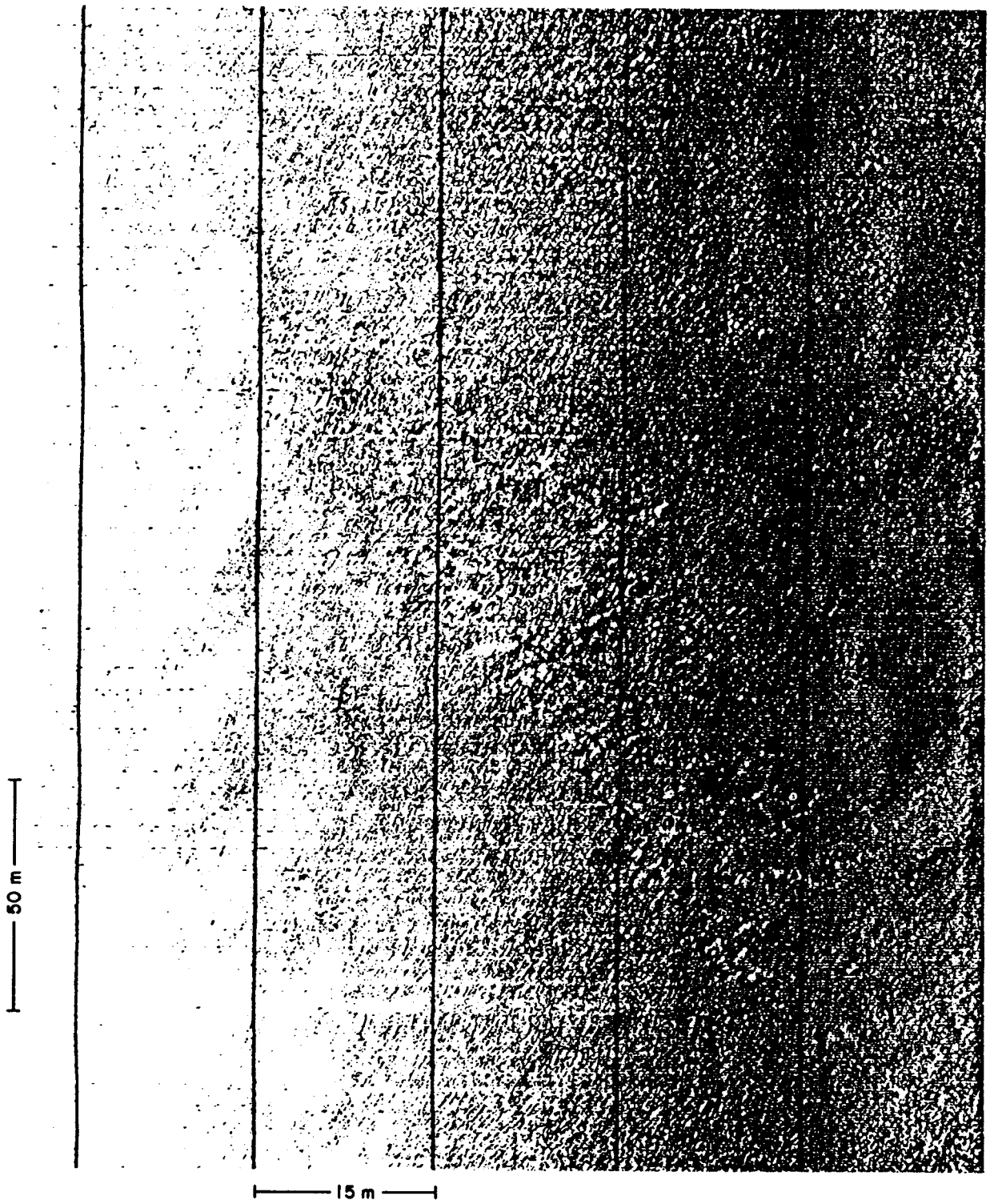
Distribution. Larval densities along the North Aleutian Shelf from Unimak Island to Port Heiden were very low during all times sampled (late April, late May, mid-June) in 1983 compared to densities recorded for 1982 over the same area. Data from the two week period of about April 23 to May 7 show that larvae were most abundant offshore of Black Hills to western Port Moller (Figure 3.2-1). Larvae were virtually absent in the area from western Unimak Island to Izembek Lagoon, and north of latitude 56°40' (about Port Moller) to the limit of sampling



BRISTOL BAY
RED KING CRAB

SIDE-SCAN SONAR TRACE SHOWING HOMOGENEITY INDICATIVE OF SILT-SAND SUBSTRATE

FEBRUARY 1984 | FIGURE 3.1-16

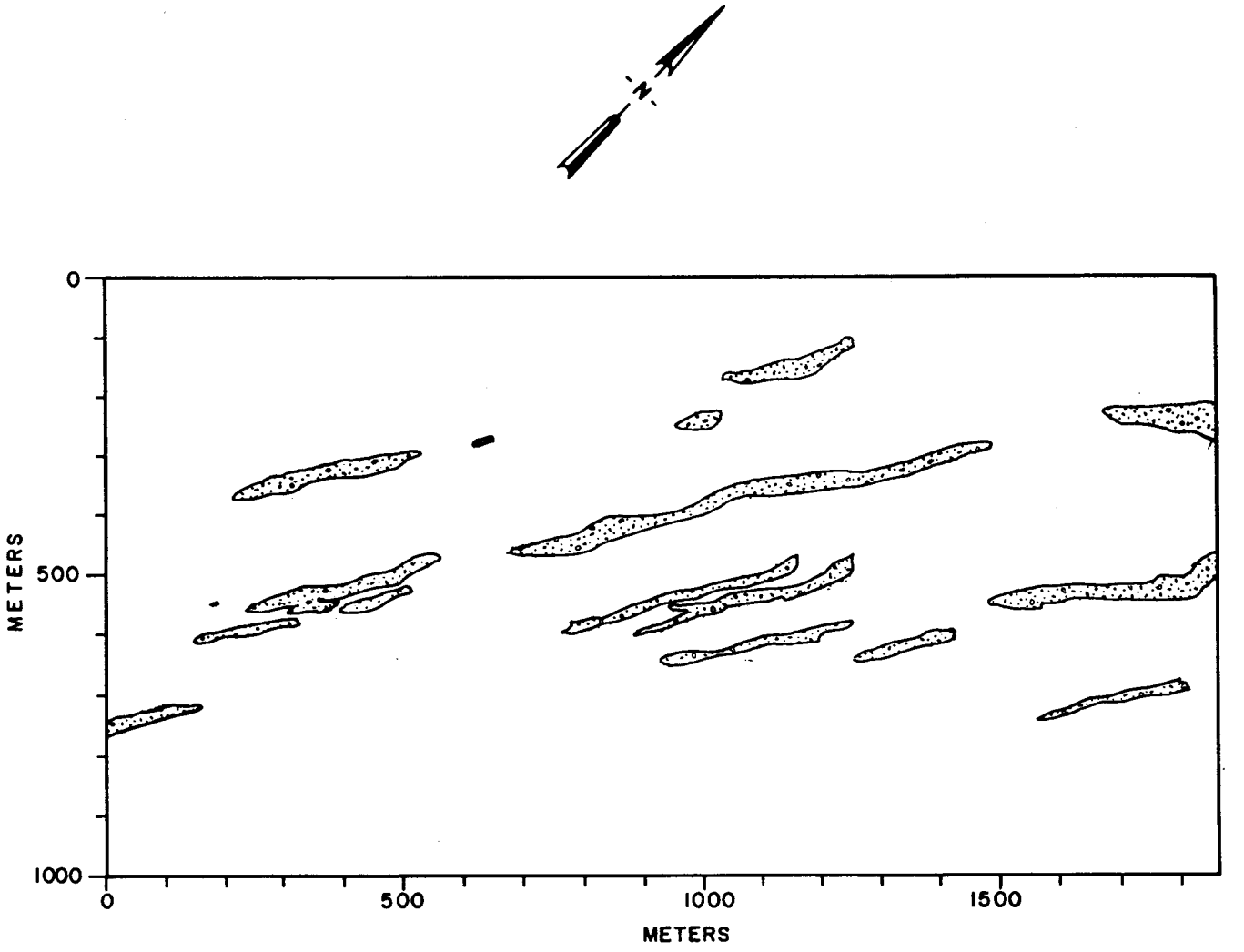


BRISTOL BAY
RED KING CRAB

SIDE-SCAN SONAR TRACE SHOWING HETEROGENEITY INDICATIVE OF GRAVEL-COBBLE SUBSTRATE

VTN

FEBRUARY 1984 | FIGURE 3.1-17



= APPARENT SILT-SAND SUBSTRATE

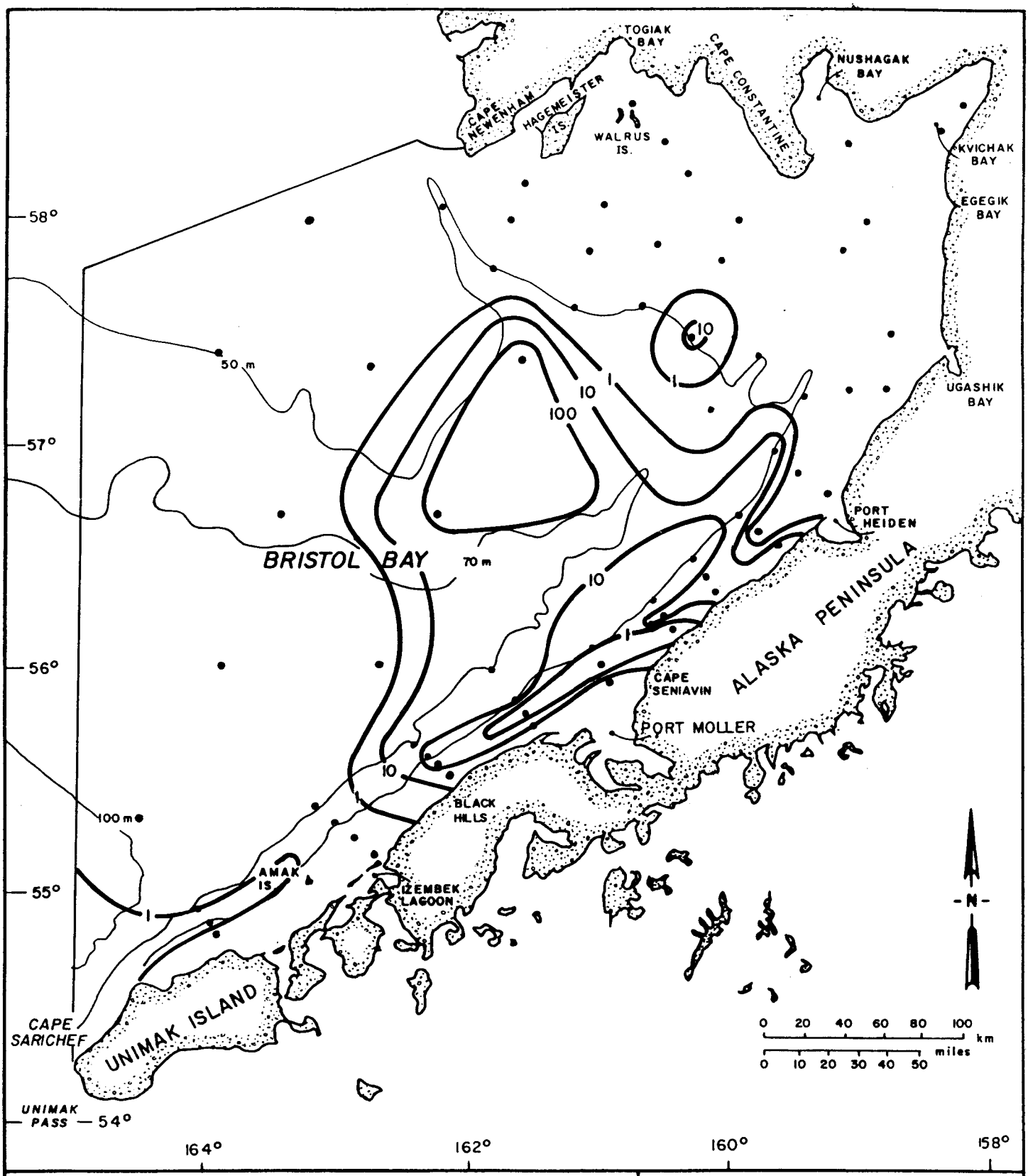
= APPARENT GRAVEL-COBBLE SUBSTRATE

(LOCATION SHOWN IN FIGURE 2.1-5)

BRISTOL BAY
RED KING CRAB

APPARENT SIZE AND ORIENTATION OF GRAVEL-COBBLE BEDS IN KVICHAK BAY

FEBRUARY 1984 | FIGURE 3.1-18



• = SAMPLING STATION

— 10 — = NUMBERS OF RED KING CRAB LARVAE PER 100 m²

BRISTOL BAY RED KING CRAB

CRUISE 83-1 LARVAL RED KING CRAB DISTRIBUTION

VTN

FEBRUARY 1984 | FIGURE 3.2-1

along the coast from Cape Newenham into Kvichak Bay. Greatest densities recorded were just over 1,000 larvae per 100 m^2 along the 50 m isobath in subareas IL and PM. Mean densities in these areas were still relatively low, 114 $\pm$ 311 and 137 $\pm$ 242 per 100 m^2, respectively, and elsewhere ranged from zero larvae in all of the Kvichak subarea to a mean of 133 per 100 m^2 in Inner Bristol Bay (Table 3.2-1). Densities were uniformly lowest nearshore (<50 m) throughout the entire study area.

Collections made during the first cruise in April 1983 apparently intercepted the commencement of hatchout and, thus, low densities could reflect a larval population not yet to full numerical strength. However, this possibility was not supported by subsequent sampling in the region from Unimak Island to Cape Seniavin during late May and mid-June. A series of zooplankton samples collected about May 27, 1983 (at the end of the Pribilof Island cruise) showed that larval abundance had increased off Port Moller, where highest densities were 1,175 to 3,300 larvae per 100 m^2 and averaged 902 larvae per 100 m^2 (Table 3.2-1). From there heading along the 50 m isobath to the southwest, densities were only a few hundred larvae per 100 m^2.

Nearshore larval density was extremely low in mid-June 1983 from Unimak Island through Cape Seniavin with mean values of about 230 larvae per 100 m^2 (Table 3.2-1, Figure 3.2-2). The moderate larval densities found off Black Hills to Port Moller in April and May had decreased by June due to either local mortality and/or transport to the northeast in nearshore currents (Armstrong, et al. 1983b; Haynes 1974). Further, larvae were scarce nearshore in water less than 50 m throughout the remaining survey area from Port Moller northeast to Kvichak Bay, then west to Cape Newenham. Instead, larvae were densest at stations between 50 to 70 m within or adjacent to subarea IB, Inner Bristol Bay (Figure 3.2-2). All nearshore areas at this time had mean abundances of about 200 to 400 larvae per 100 m^2 whereas the mean for subarea IL was 2,135 per 100 m^2 (Table 3.2-1). It should be noted that several of the

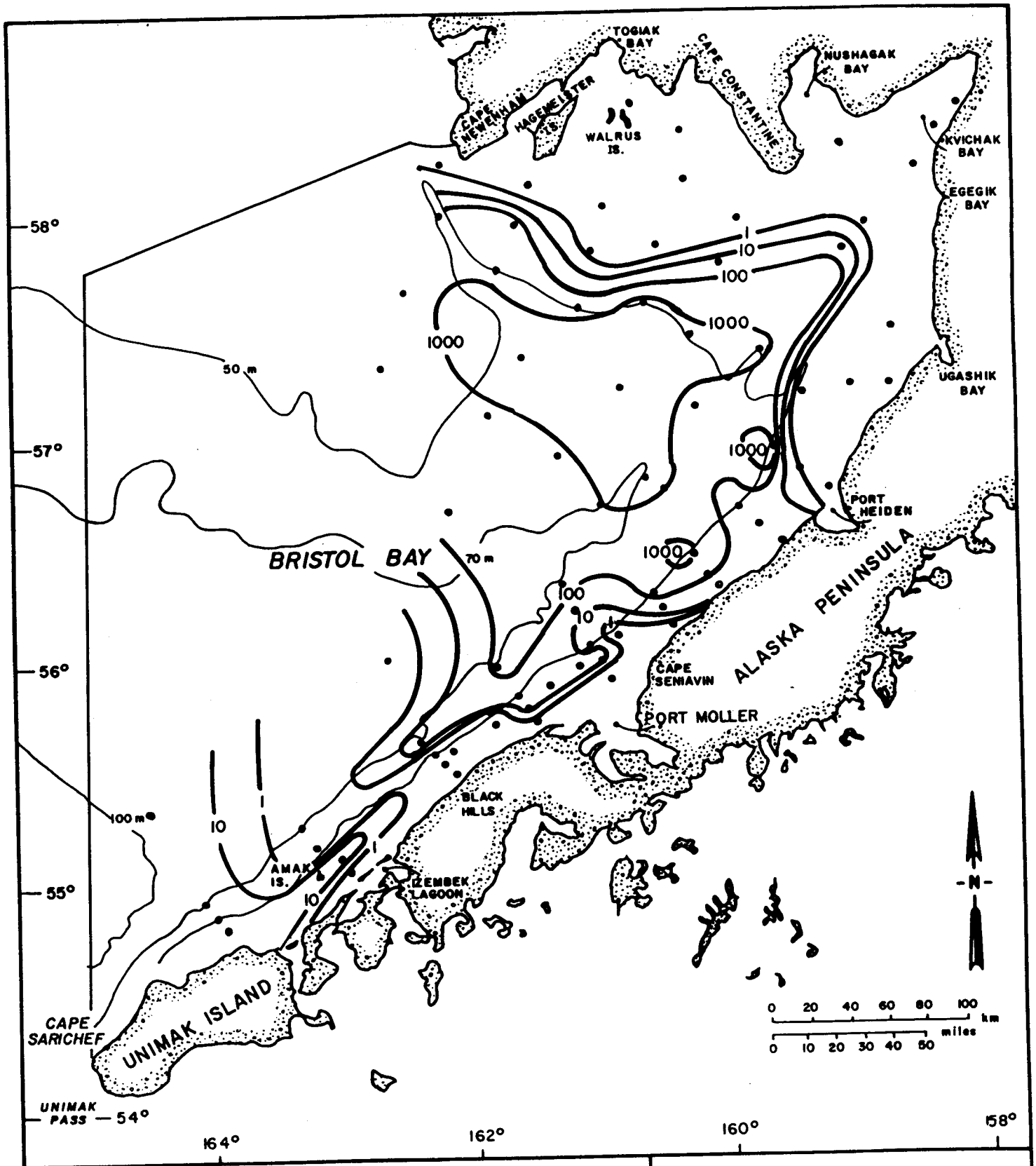
TABLE 3.2-1

MEAN LARVAL RED KING CRAB DENSITIES BY CRUISE AND SUBAREA[a]

Subarea	Cruise 83-1 (April-May)	Cruise 83-2 (May)	Cruise 83-3 (June)
OB	2.6 ± 6.9[b] (n = 8)	139 ± 119 (n = 6)	75.5 (n = 1)
IB	133 ± 174 (n = 6)	902 ± 982 (n = 8)	2134 ± 3137 (n = 11)
IL	114 ± 311 (n = 12)		43 ± 72.5 (n = 12)
PM	137 ± 242 (n = 18)		231 ± 404 (n = 22)
PH	32.8 ± 60.4 (n = 10)		208 ± 530.5 (n = 9)
KB	0 (n = 6)		389 ± 987 (n = 7)
TB	2.0 ± 7.5 (n = 15)		458 ± 760 (n = 14)

(a) Arithmetic means and standard deviations are given in this table to facilitate comparison with other studies; it is not suggested that normal statistics are applicable to non-transformed data.

(b) Larvae per 100 m^2.



• = SAMPLING STATION

—10— = NUMBERS OF RED KING CRAB LARVAE PER 100 m^2

BRISTOL BAY RED KING CRAB

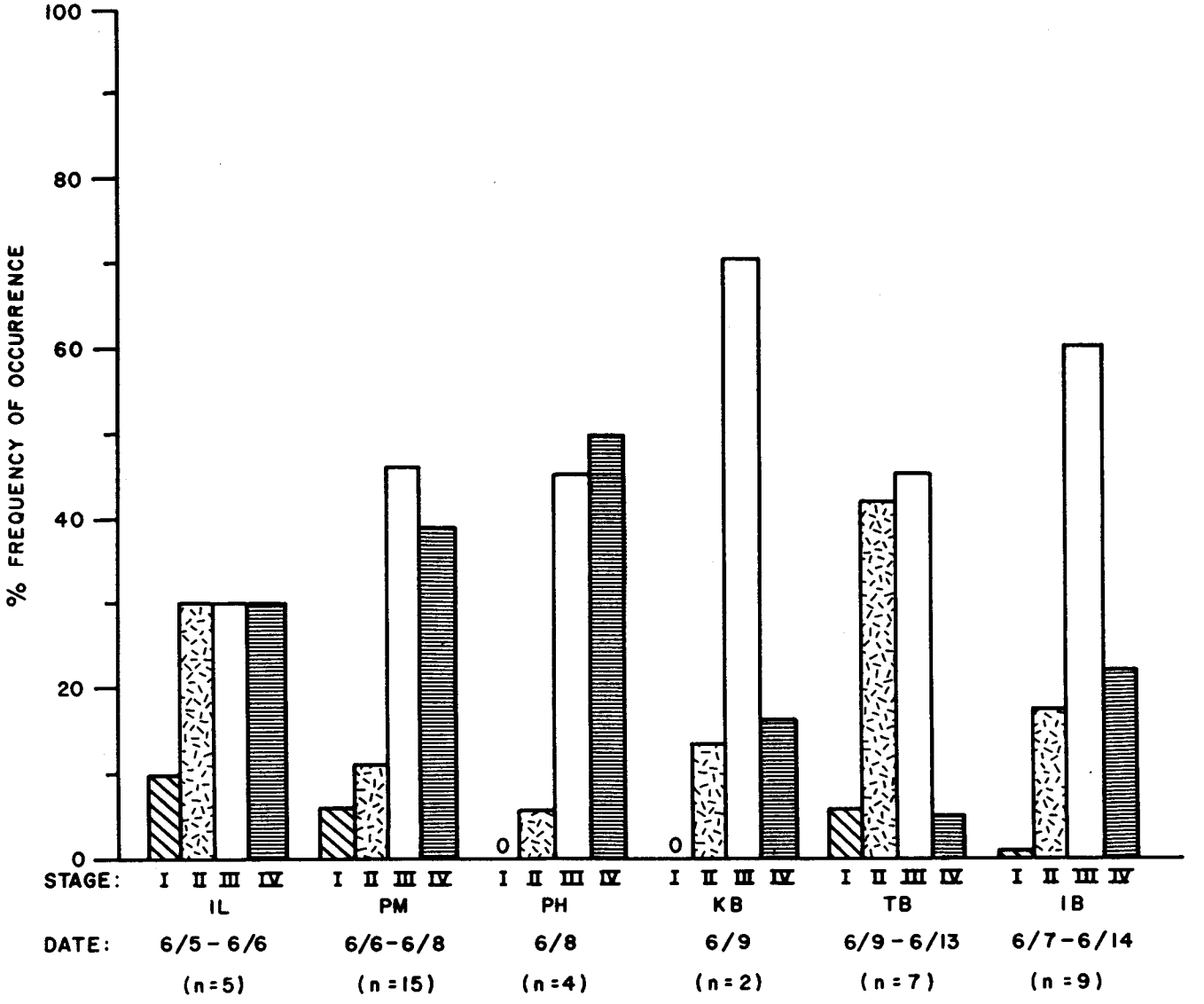
CRUISE 83-3
LARVAL RED KING CRAB DISTRIBUTION

FEBRUARY 1984 | FIGURE 3.2-2

stations in this area where larval king crab were abundant were also rich in phytoplankton; so much so that nets apparently clogged as evidenced by very low volumes filtered per unit time compared to other stations of comparable depth. Resultant calculations of high larval densities reflect either the actual at the time in Inner Bristol Bay, or possibly inflated values caused by inaccurate estimates of volume filtered.

Stage IV zoeae were the most advanced larvae collected during the second cruise through June 14. No megalops larvae were found in June 1983, although they were present between Unimak Island and Cape Seniavin at the same time in 1982 (Armstrong, et al. 1983b). No king crab larval stages were found in zooplankton samples collected in mid-September 1983. All larvae had apparently metamorphosed by this date and, as discussed in Section 3.4 on juveniles, young-of-the-year crab were caught at this time in areas largely outside the regions of high larval abundance.

Date of Hatch. The first zooplankton samples were collected during a sweep along the nearshore NAS from Unimak Island to Kvichak Bay in mid-April 1983. Few larvae were found during that first pass of the area and additional samples were taken as the ship left Bristol Bay between May 1 and 5. More red king crab larvae were found in this second group of samples, indicating that a substantial part of the 1983 hatch occurred in the last week of April through the first week of May. Hatch did not apparently continue for a prolonged period throughout the nearshore range of the population because: 1) average densities in April, May and June did not increase substantially (Table 3.2-1) in subareas IL and PM; and 2) zoeal stage frequency over these months showed a shift to later stages consistent with the molting schedule of a single, dominant cohort. There was no apparent and substantial hatch that occurred in late May and early June in subareas IL, PM and PH based on stage frequencies (Figure 3.2-3). Frequency of occurrence of larval stages in samples taken from eastern Unimak Island to Port Heiden over a



FREQUENCY OF OCCURRENCE CALCULATED FROM GEOMETRIC MEANS

BRISTOL BAY
RED KING CRAB

LARVAL STAGE FREQUENCY
BY SUBAREA DURING JUNE 1983

FEBRUARY 1984 | FIGURE 3.2-3

three-day period in June showed rather similar proportions; from 60 to 90 percent of the larvae were SIII and SIV.

Peak hatching may have occurred a week or two later in other parts of the species range encompassed by strata for Kvichak and Togiak Bay and Inner Bristol Bay (Figure 3.2-3). Frequency of occurrence of larval stages in these strata showed substantially fewer SIV and more SIII larvae, and in the Togiak strata (TB) up to 45 percent SII. Particularly in the case of Togiak, stations with high proportions of earlier SII larvae were those near the 50 m isobath on the edge of the Inner Bristol Bay (IB) stratum.

The possibility that colder water temperatures may have caused later hatchout in the area of Bristol Bay between 50 to 70 m is suggested by data for June 1983. Although near-surface temperatures were essentially the same in that region as elsewhere in June (5° to 7°C, Figure 3.1-8), bottom water temperatures were still 3° to 4°C (Figure 3.1-11), having been about 1°C in April (Figure 3.1-10). An ovigerous female caught in the area during the June cruise had eyed eggs still unhatched in early summer. Regional and interannual differences in bottom water temperature may significantly affect the rate of embryonic development in the egg and, in turn, the appropriate time of hatch each year (Armstrong, et al. 1983b). The occurrence of many SII larvae in the offshore area of Togiak in mid-June (stations collected June 12-14) indicates that they had hatched in the last week of May (based on the molt frequency data of Armstrong, et al. 1983), some three weeks later than the cohort off Port Moller.

Correlation to Physical Factors. Larval horizontal distribution and abundance were analyzed for relationships with station depth, salinity and temperature at 10 m, time of day when collected, and Julian date. Station depth yielded the sole significant correlation coefficient ($r=^{+}0.344$; 171 degrees of freedom), explaining only 11.8 percent of the variability in the data set. Residuals indicated the correlation

resulted from the apparent concentration of crab larvae along the 50 m isobath. Addition of the other independent variables in multiple regressions did not meet criteria for significance.

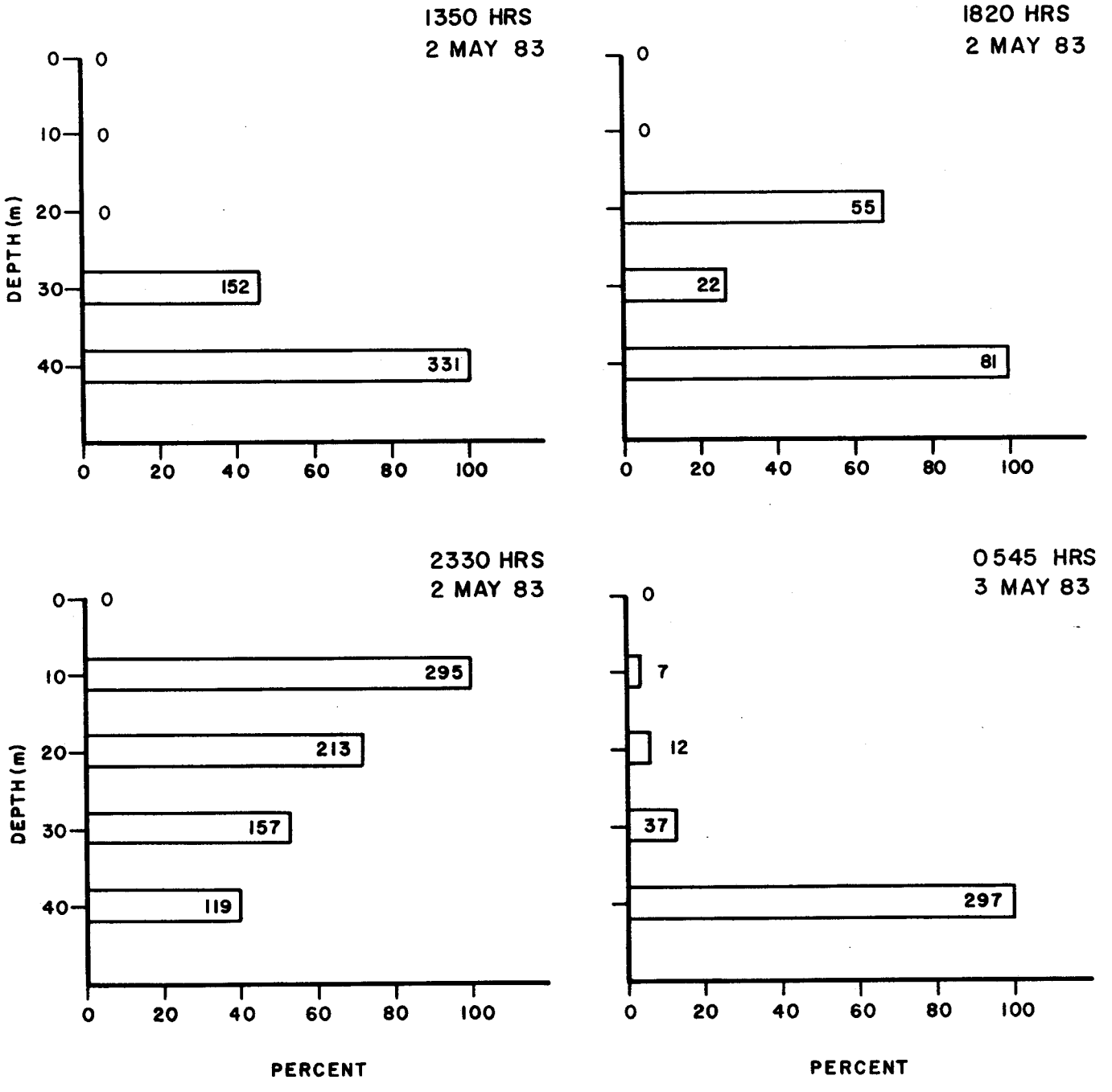
3.2.2 Vertical Distribution

During cruise 83-1 (April-May), a diel series of horizontal plankton tows was conducted at station PM350. The 40, 30, 20 and 10 meter samples were collected with a Tucker trawl; the surface sample was collected with a Sameoto Neuston sampler. The sampling was conducted at local noon, dusk, midnight and sunrise. The resulting larval red king crab densities are shown in Figure 3.2-4, and show strong evidence of diel vertical migration. No larvae were collected at the surface. The noon and midnight samples exhibit the greatest difference in vertical distribution; the dusk and dawn samples are intermediates.

During cruise 83-3 (June), a single vertical series of horizontal tows, 0-50 m, was conducted with the Tucker trawl. The larval red king crab densities are presented in Figure 3.2-5. This figure also indicates the zoeal stage distribution of the samples. The results do not show any difference in vertical distribution between stages. The two larger samples, from 20 and 50 m depth, contained very similar proportions of zoeal stages 2, 3 and 4.

3.3 Larval Development and Growth

The most appropriate time series by which to measure larval development was collected in the Port Moller subarea. Samples were collected at six times: 23-25 April; 1-2 May; 27 May; 6-8 June; 14-16 June; and 11-13 September (Table 3.3-1). Larvae were present from April until mid-June. First stage zoeae, though present until mid-June, were most abundant in early May. The next three zoeal stages were sequentially predominant over the second through fourth visits off Port Moller. This may be seen in Figure 3.3-1, which has averaged the results from the two visits



210

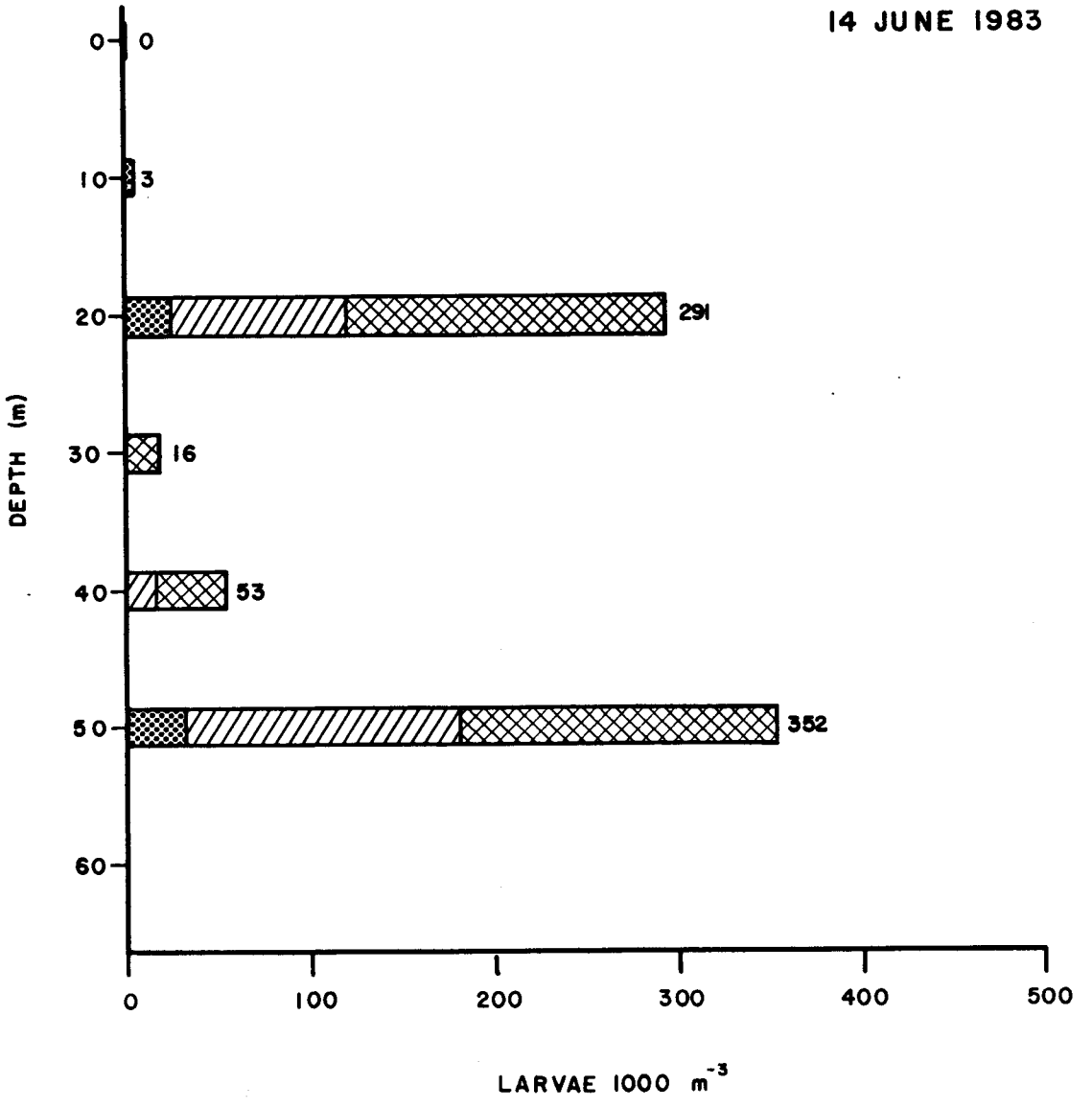
= Percent of Max. Density

210 = Actual Density per 1,000 m^3

BRISTOL BAY
RED KING CRAB

DIEL VERTICAL DISTRIBUTION OF
RED KING CRAB LARVAE

FEBRUARY 1984 | FIGURE 3.2-4



75 = DENSITY PER 1000 m^3

= ZOEAE STAGE 2

= ZOEAE STAGE 3

= ZOEAE STAGE 4

*MLST = MEAN LOCAL STANDARD TIME

BRISTOL BAY RED KING CRAB

VERTICAL DISTRIBUTION OF RED KING CRAB ZOEAE STAGES 2, 3 AND 4

FEBRUARY 1984

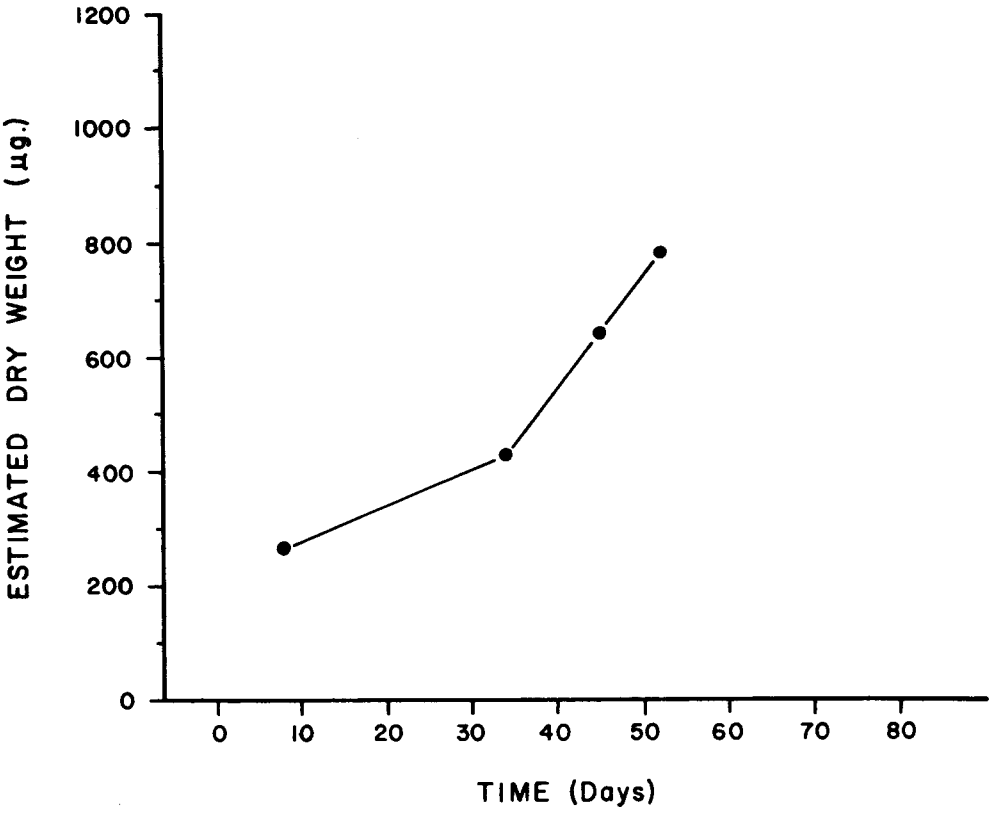
FIGURE 3.2-5

TABLE 3.3-1

GEOMETRIC MEAN DENSITIES OF LARVAL RED KING CRAB
IN THE PORT MOLLER SUBAREA BY DEVELOPMENTAL STAGE

Sampling Period	Growth Stage 1	2	3	4	5	Total
23-25 April	0.39(a)	-	-	-	-	0.39
1-2 May	312.28	0.39	-	-	-	312.67
27 May	10.91	195.53	15.42	0.46	-	222.32
6-8 June	0.01	0.14	0.48	0.23	-	0.86
14-16 June	0.02	0.07	0.23	0.12	-	3.77
11-13 September	-	-	-	-	-	-

(a) Numbers per 100 m^2 (area weighted)



BRISTOL BAY
RED KING CRAB

ESTIMATED GROWTH RATE OF
LARVAL RED KING CRAB
APRIL - JUNE 1983

FEBRUARY 1984 | FIGURE 3.3-1

during the June cruise (83-3). No megalopae (glaucothoe) were collected during this study.

Individual larval growth was substantial between late April and mid-June. The estimated daily individual growth rate rose from 4.58 ug dry weight per day between late April and mid-May to 18.74 ug dry weight per day between late May and mid-June (Figure 3.3-1). This occurred while the individual zoeae were increasing from an estimated individual mean of 265 ug to 878 ug dry weight.

3.4 Post-larval Size and Age Distribution

Cruise 83-1 (18 April - 7 May 1983). In April and May 1983, 131 red king crabs were collected from 21 stations (Table 3.4-1). The population was composed of 81 (62%) males, 43 (33%) juvenile females, and seven (5%) adult females, whose sizes ranged from 4-133 mm carapace length. Using Weber's age criteria (Weber 1967) only 7.6 percent of all crabs collected during April and May were one year-old. An additional 10 crabs (7.5%) were less than age 1 (0+ or 1982 YOY). A total of 18 1+ year-old (15-28 mm) and two 2 year-old crabs was found. Only two crabs were found in the 2+ age category. A total of 22 age 3 (50-67 mm) crabs were encountered; age 3+ and age 4 crabs numbered 11 and 10, respectively. Eight adult females were part of the age 4++ crabs.

The male:female ratios at ages 1, 2, 3, 4 and 4++ were 4:1, 2:1, 1:1, 0.6:1, and 1.3:1, respectively. The male:female ratio for all juvenile sizes through age 4 was 1.8:1 (Table 3.4-1).

Cruise 83-3 (2-17 June 1983). A total of 137 red king crabs was collected during the June cruises (Table 3.4-2). The crab population composition was 73 (53%) males, 49 (36%) immature females, 7 (5%) unidentified sex and 8 (6%) adult females. The sizes ranged from 3-126 mm carapace length. Only five age 1 crabs were collected. Thirteen crabs were younger than one year of age (1982 YOY). A total of 21 age

TABLE 3.4-1

NUMBER OF POST LARVAL RED KING CRAB BY SAMPLING LOCATION, SIZE AND AGE FROM CRUISE 83-1

Station	0+(a) <8(b)	1 9-14	1+ 15-28	2 29-41	2+ 42-49	3 50-67	3+ 68-73	4 74-82	4++ 82-133	Totals
PM820	5	1								6
PM250	1				1	1	1			4
PM230	3									3
KB2*4		7	14	2	1	2			2	28
KB2*0		1								1
TB329		1	1							2
TB230	1									1
IL430			1							1
PM730			1							1
PM620			1							1
TB550						8	1			9
TB431								1	1	2
TB350						8		1	4	13
BB557						3	9	7	8	27
BB770								1	5	6
IL160									15	15
PM370									2	2
BB760									1	1
KB250									1	1
TB250									6	6
BB450									1	1
Totals	10	10	18	2	2	22	11	10	46	131
%	7.6	7.6	13.7	1.5	1.5	16.8	8.4	7.6	35.1	100.0
Males	7	8	16	2	1	11	7	3	26	81
Females	3	2	2	0	1	11	4	7	20	50

(a) Age in years

(b) Carapace length in mm

TABLE 3.4-2

NUMBER OF POST LARVAL RED KING CRAB BY SAMPLING LOCATION, SIZE AND AGE FROM CRUISE 83-3 (JUNE)

Station	0+(a) <8(b)	1 9-14	1+ 15-28	2 29-41	2+ 42-49	3 50-67	3+ 68-73	4 74-82	4++ 83-126	Totals
PM350	1									1
PM650	1					2			1	4
PM930	2									2
PM350	3		1			10		1		15
TB329	1									1
IL430	1									1
PH230	2									2
PH250	2									2
KB2*0		1	6							7
KB2*2		3	4							7
KB2*4		1	1							2
KB2*6			7							7
KB2*9			1							1
KB150			1							1
PM730					1	1				2
PM620						1				1
TB550						10	4	4	5	23
BB557						7	4	8	4	23
TB450							1	1	1	3
BB770							1	1	4	6
BB665							2	2	4	8
TB350								1	6	7
BB670								1		1
PM670									3	3
KB250									1	1
TB330									2	2
TB250									2	2
BB450									1	1
BB555									1	1
BB760									2	2
BB560									1	1
Totals	13	5	21	0	1	31	12	19	38	140
%	9.3	3.6	15.0	0	0.7	22.1	8.6	12.6	27.1	100.0
Males	2	2	12	0	1	18	5	13	20	73
Females	1	3	9	0	0	13	7	6	18	57
Unid.	10	0	0	0	0	0	0	0	0	10

(a) Age in years

(b) Carapace length in mm

1+ crabs were found, no age 2 crabs and only one age 2+ crab was encountered. Age 3, age 3+ and age 4 crabs totaled 31, 12 and 19, respectively. A total of 38 age 4++ crabs was found, including eight adult females.

The male:female ratios at ages 1, 3, 4 and 4++ were 0.67:1, 1.4:1, 2.2:1 and 1.1:1, respectively. No age 2 crabs were found. The total male: female ratio for all juveniles through age 4 was 1.4:1 (Table 3.4-2).

Cruise 83-5 (9-23 September 1983). Epibenthic sampling for king crab in September yielded 184 crabs collected at 13 stations (Table 3.4-3). The population was composed of 79 (43%) males, 70 (38%) immature females, 35 (17%) crabs of unidentified sex and 3 (2%) adult females. The crabs sampled during September measured from 3-117 mm carapace length. True young-of-the-year crabs (3-8 mm) dominated, yielding 73% (n=134) of the catch. Most of the young-of-the-year crabs (95%) were 4-5 mm. Age 1 crabs totaled 24; age 1+ crabs totaled 24. Crabs belonging to age classes 2, 2+, 3, and 4 were not encountered. Only one crab was found in the age 3+ class. Among the five crabs over four years old (age 4++), three were adult females.

The male:female ratios at ages 1 and 4++ were 0.6:1 and 0.25:1, respectively. The male:female ratio of all juvenile crabs through age 4 was 1.1:1 (Table 3.4-3).

3.5 Juvenile Distribution and Abundance

The number of epifaunal samples and the number of stations sampled per cruise are presented by sampling subarea in Table 3.5-1. The distributions of samples by gear type are presented in Figures 3.5-1 through 3.5-3 and Appendix B. The inner and outer Bristol Bay (BB) subareas were sampled primarily with the trynet; the Kvichak Bay (KB) subarea was sampled primarily with the rock dredge. The remaining subareas were sampled with both gear types, although the trynet was generally more often used.

TABLE 3.4-3

NUMBER OF POST LARVAL RED KING CRAB BY SAMPLING LOCATION, SIZE AND AGE FROM CRUISE 83-5 (SEPTEMBER 1983)

Station	YOY(a) <8(b)	1 9-14	1+ 15-28	2 29-41	2+ 42-49	3 50-67	3+ 68-73	4 74-82	4++ 83-117	Totals
KB2*4	79		1							80
PH230	28	20	11							59
PH250	2									2
PH350	7									7
PM830	4									4
PH130	1									1
KB250	13									13
PM820		1	2							3
PM010		3								3
KB2*1			2							2
PM320			8							8
TB250							1		1	2
BB770									2	2
PM670									1	1
PM370									1	1
Totals	134	24	24	0	0	0	1	0	5	188
%	71.3	12.8	12.8	0	0	0	0.5	0	2.7	100.0
Males	58	7	13	0	0	0	0	0	1	79
Females	46	12	10	0	0	0	1	0	4	73
Unid.	30	5	0	0	0	0	0	0	0	35

(a) Age in years

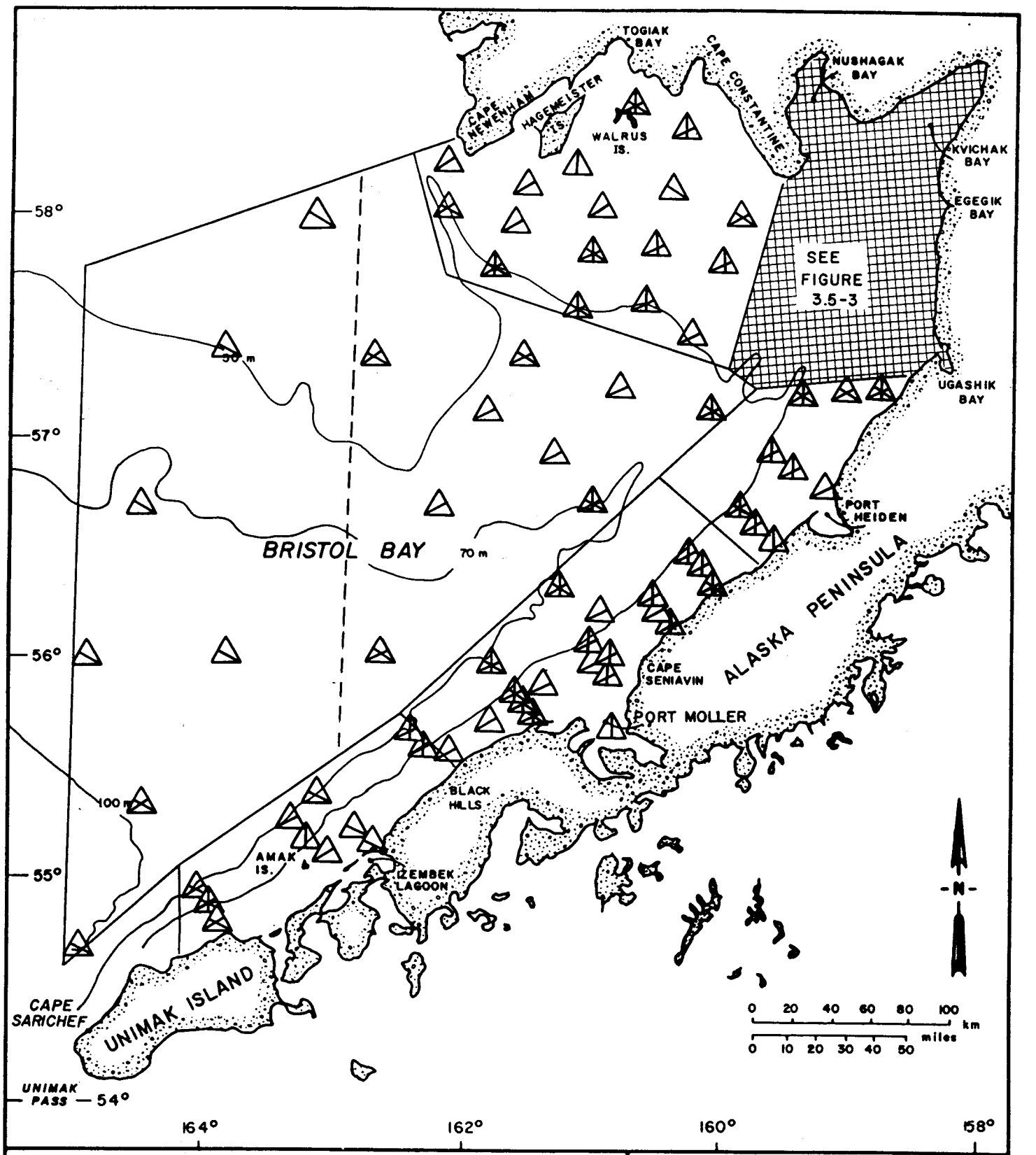
(b) Carapace length in mm

TABLE 3.5-1

SUMMARY OF EPIFAUNAL SAMPLES PER STATION BY SAMPLING SUBAREA DURING 1983

Cruise	BB	IL	PM	PH	KB	TB	Total
83-1:Apr-May	17/13[a]	12/10	20/14	9/8	12/7	17/15	87/67
83-3:June	11/10	13/11	30/23	13/8	22/14	21/16	90/82
83-5:Sept	2/2	7/7	20/15	8/8	12/6	10/10	54/48
Total	30/15	32/28	70/52	30/24	46/27	48/41	

[a] Fraction = Number of epifaunal samples/Number of stations sampled



△ = CRUISE 83-1

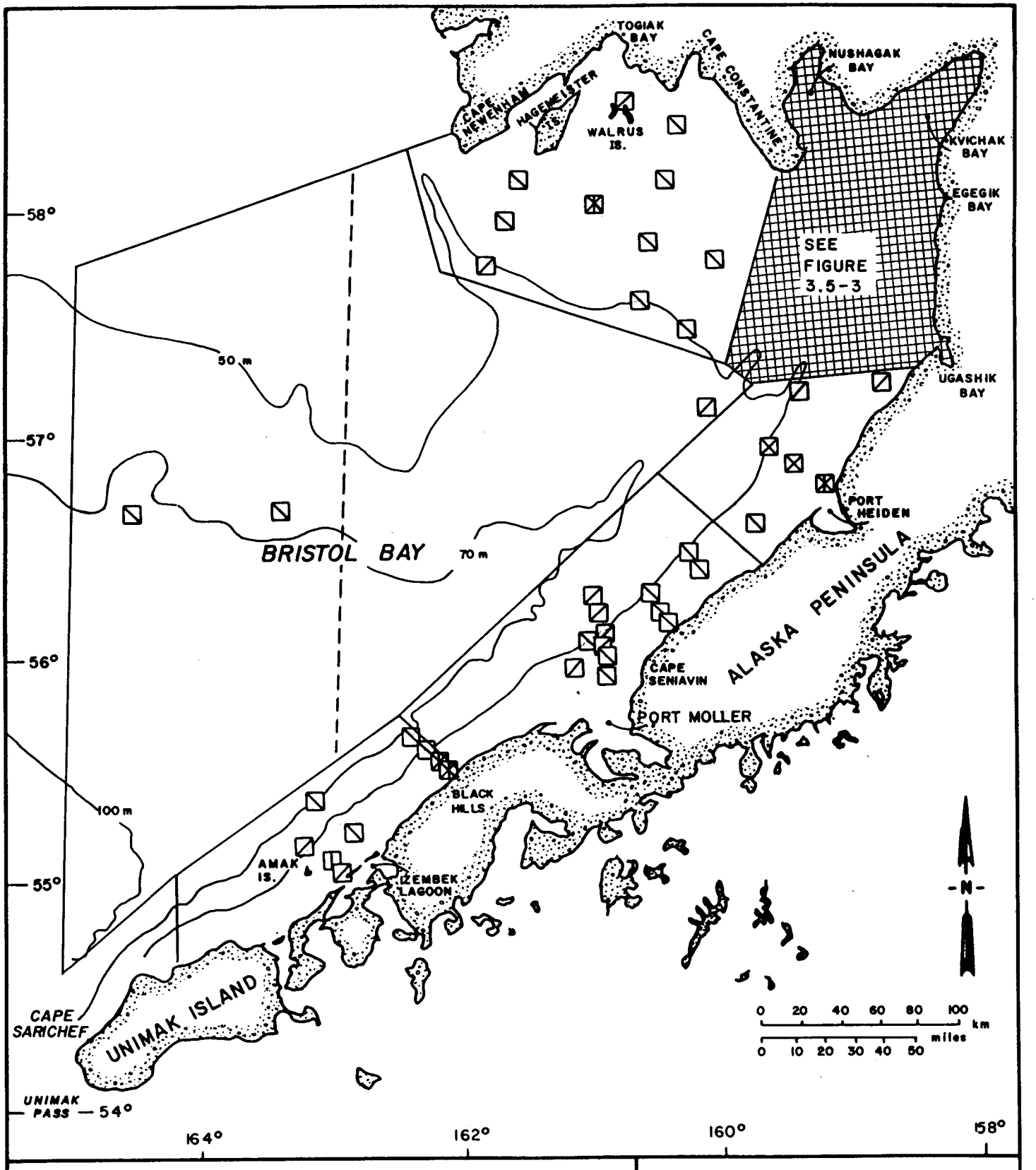
△ = CRUISE 83-3

△ = CRUISE 83-5

BRISTOL BAY RED KING CRAB

TRYNET SAMPLING STATIONS BY CRUISE

FEBRUARY 1984 | FIGURE 3.5-1



☒ = CRUISE 83-1

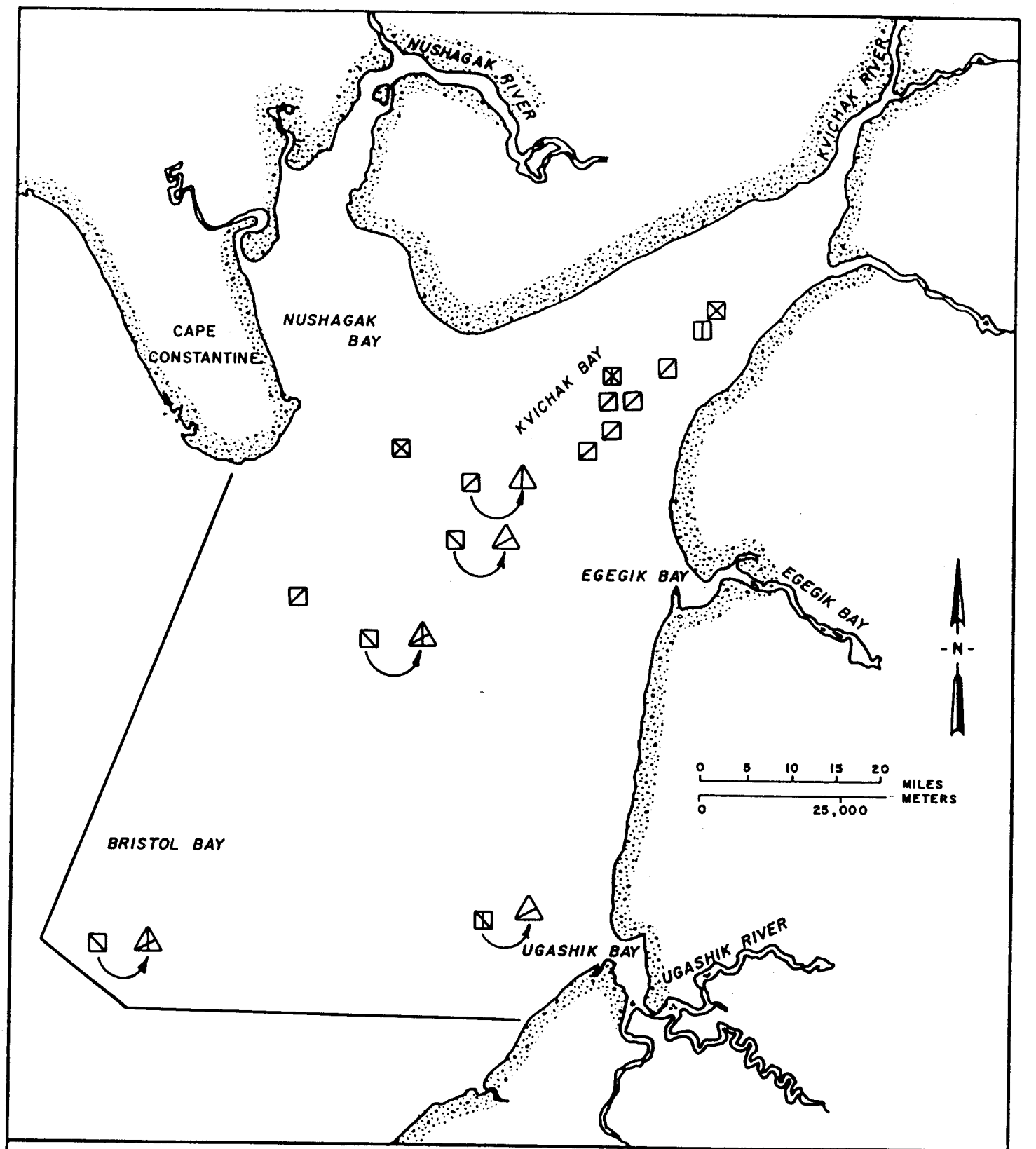
☒ = CRUISE 83-3

☐ = CRUISE 83-5

BRISTOL BAY RED KING CRAB

ROCK DREDGE SAMPLING STATIONS BY CRUISE

FEBRUARY 1984 | FIGURE 3.5-2



△ = CRUISE 83-3
△ = CRUISE 83-5
} TRYNET

▨ = CRUISE 83-1
▨ = CRUISE 83-3
▥ = CRUISE 83-5
} ROCK DREDGE

BRISTOL BAY RED KING CRAB

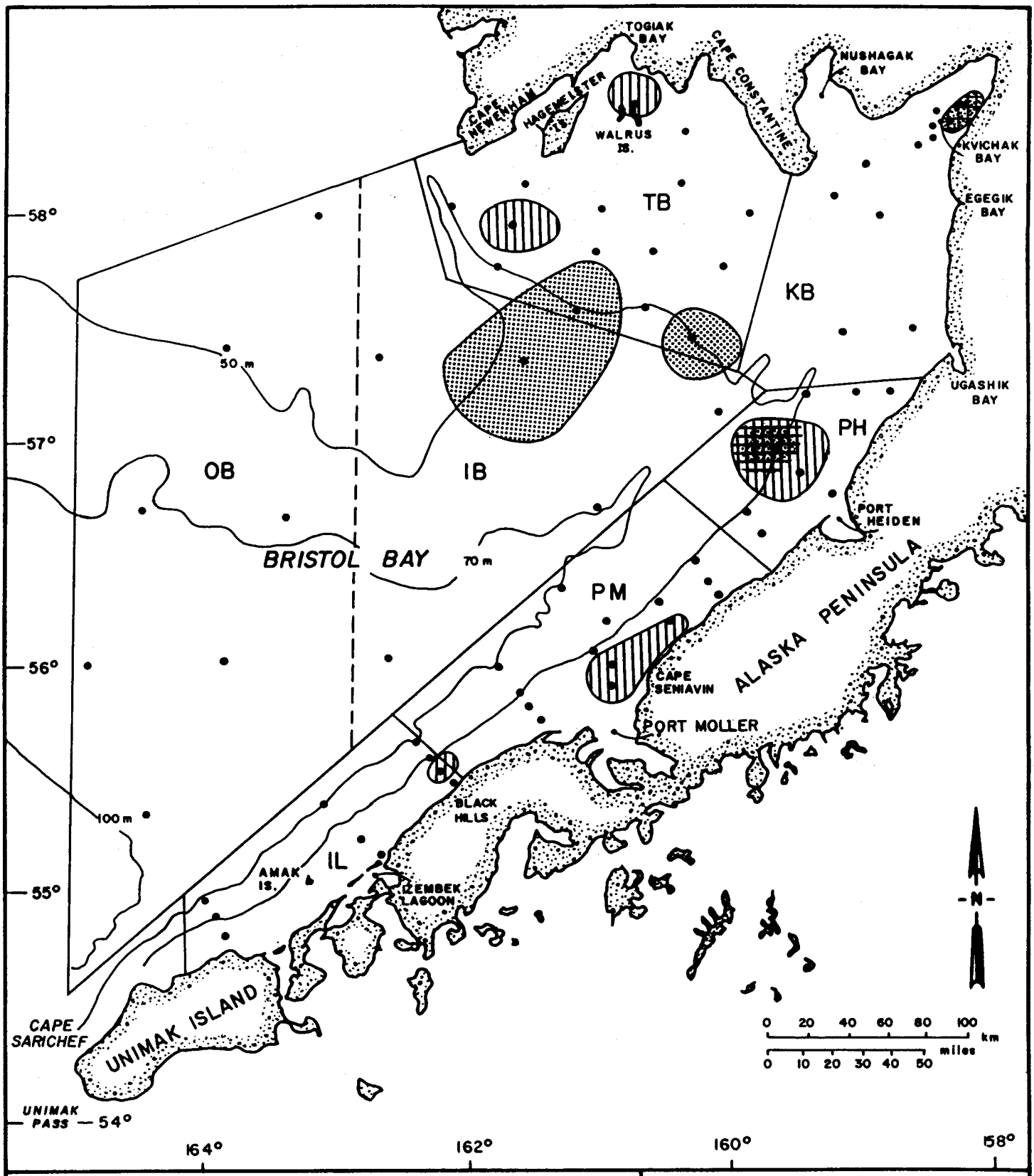
TRYNET AND ROCK DREDGE SAMPLING STATIONS IN KVICHAK BAY BY CRUISE

vtn

FEBRUARY 1984 | FIGURE 3.5-3

A total of 317 crabs age 3 and younger was collected during the study. The distribution of these crabs, divided into apparent age groups, is shown by cruise in Figures 3.5-4, 3.5-5 and 3.5-6. All of the crabs in this size range were collected at 50 m or shallower depths, primarily in the four easternmost subareas: Port Moller (PM), Port Heiden (PH), Kvichak Bay (KB) and Togiak Bay (TB). The numbers of crabs collected per cruise from each of these subareas are summarized in Table 3.5-2. The KB and PH subareas yielded the greatest total numbers of small crabs, partially due to the greater number of samples taken in these areas (Table 3.5-1). Catch per station data, calculated as the sum of the mean catches per station divided by the number of stations sampled per subarea, are also presented in Table 3.5-2. Crab densities in the KB and PH subareas were generally higher than in other subareas during each cruise, with the exception of the TB area during April-May. The high value for the PH subarea during cruise 83-5 is primarily the result of a single catch of small crabs (59) at station PH230, using the trynet. The high value for the KB subarea during the same cruise is the result of six rock dredge hauls in the vicinity of station KB2*4 that each contained from seven to 37 small crabs, and a single trynet haul at station KB250 that contained 13 small crabs. The large catch at station PH230 consisted of almost equal numbers of YOY individuals and one year-old (1+) individuals, whereas the majority of crabs from the KB stations were young-of-the-year (Section 3.4).

The relative abundance of the age groups of juvenile crabs over the length of the study is presented in Figure 3.5-7. The catch per station data represent the mean number of crabs per station divided by the number of stations sampled in the entire study area for each of the three cruises. The greatest changes were the increase in numbers of young-of-the-year, 1 and 1+ crabs and the decrease in numbers of age 3 crabs. Age 2 and 2+ crabs were caught in very small numbers during April-May and June only.



AGE GROUPS

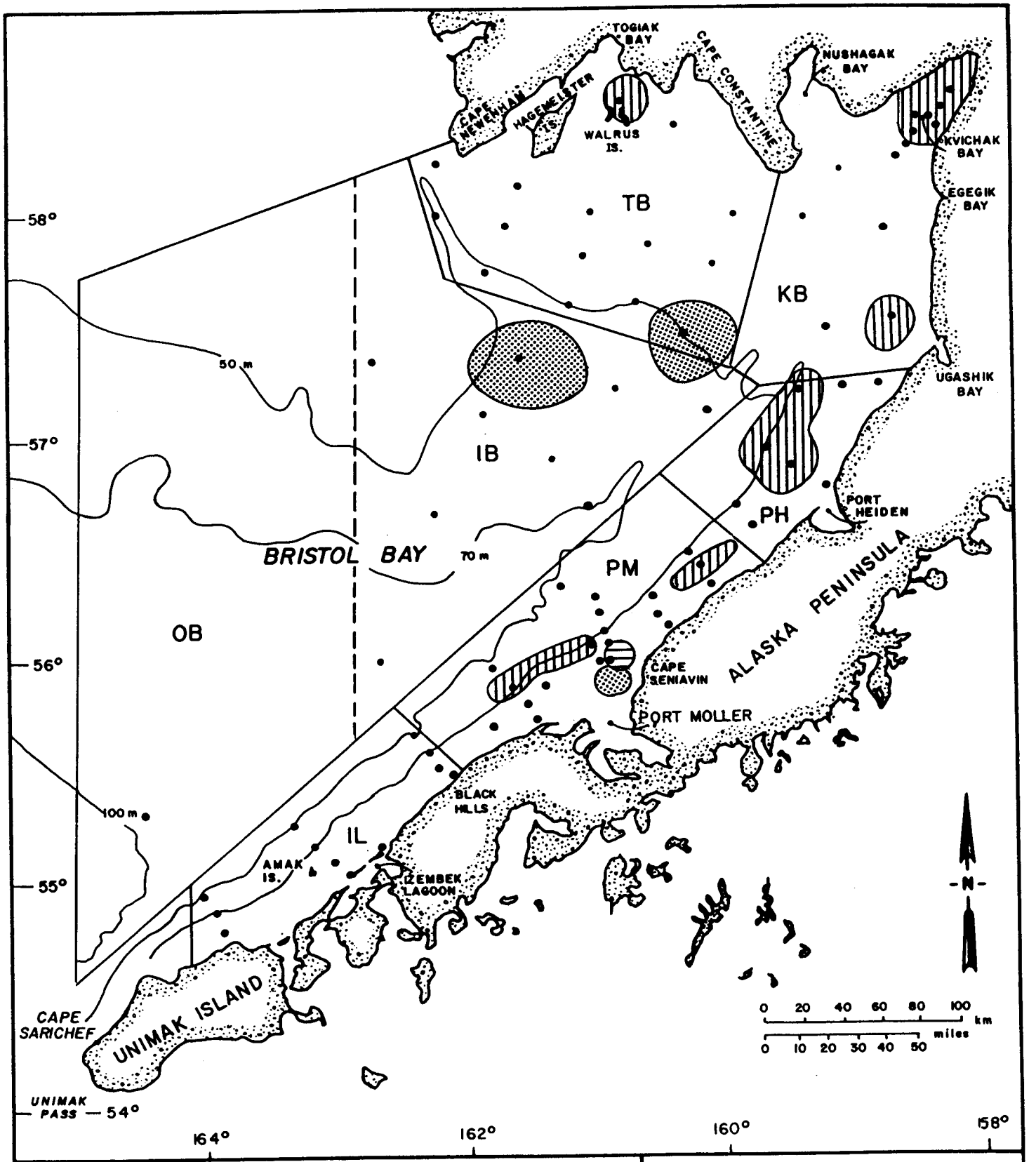
0+
1
1+
2
2+
3

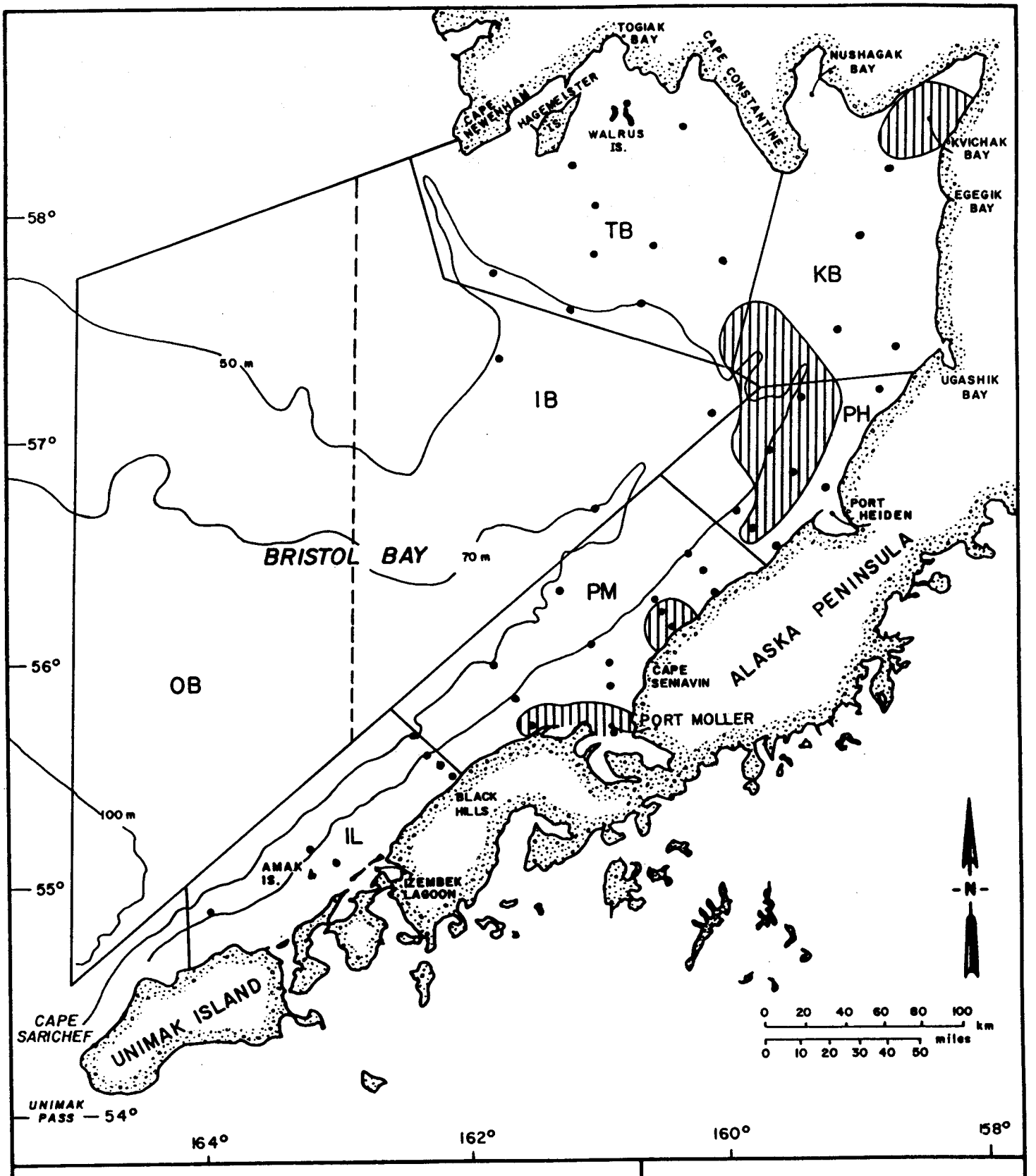
358

BRISTOL BAY RED KING CRAB

DISTRIBUTION OF RED KING CRAB AGE 3 AND YOUNGER DURING CRUISE 83-1

FEBRUARY 1984 | FIGURE 3.5-4


TOGIAK BAY
CAPE CONSTANTINE
NUSHAGAK BAY
CAPE NEWENHAM
HAGEMEISTER IS.
WALRUS IS.
KVICHAK BAY
EGEGIK BAY
TB
KB
58°
50 m
UGASHIK BAY
57°
IB
PH
PORT HEIDEN
BRISTOL BAY
70 m
PM
ALASKA PENINSULA
OB
56°
CAPE SENIAVIN
PORT MOLLER
BLACK HILLS
100 m
IL
AMAK IS.
IZEMBEK LAGOON
55°
N
0 20 40 60 80 100 km
0 10 20 30 40 50 miles
CAPE SARICHEF
UNIMAK ISLAND
UNIMAK PASS
54°
164°
162°
160°
158°
AGE GROUPS
0+
1
1+
2
2+
3
359
VTN
BRISTOL BAY
RED KING CRAB
DISTRIBUTION OF RED KING CRAB AGE 3 AND YOUNGER DURING CRUISE 83-3
FEBRUARY 1984
FIGURE 3.5-5



AGE GROUPS

YOY
1
1+

2
2+

3 -

360

BRISTOL BAY RED KING CRAB

DISTRIBUTION OF RED KING CRAB AGE 3 AND YOUNGER DURING CRUISE 83-5

FEBRUARY 1984 | FIGURE 3.5-6

TABLE 3.5-2

TOTAL NUMBERS OF RED KING CRAB AGE 3 AND YOUNGER COLLECTED BY SAMPLING SUBAREAS

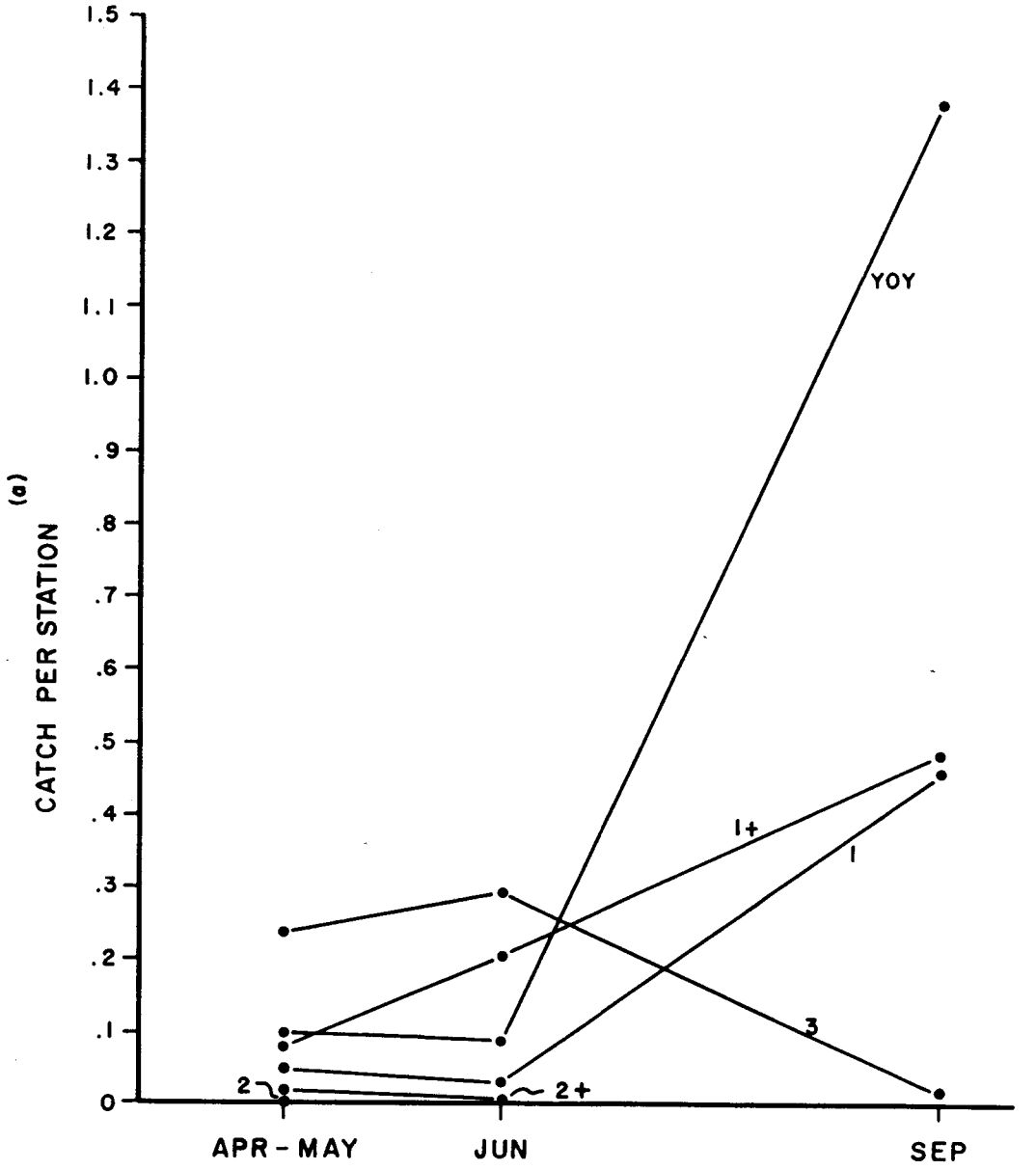
A. Total Numbers

Cruise	Sampling Subarea BB	IL	PM	PH	KB	TB	Total
83-1:Apr-May	3	1	8	6	27	19	64
83-3:June	7	1	9	16	24	11	68
83-5:Sept	0	0	18	69	95	0	182
Total	10	2	35	91	146	30	314
%	3.2	0.6	11.2	29.0	46.5	9.6	

B. Catch Per Station[a]

Cruise	Sampling Subarea BB	IL	PM	PH	KB	TB
83-1:Apr-May	0.2	0.1	0.3	0.6	0.8	1.0
83-3:June	0.7	0.1	0.3	1.0	1.4	0.6
83-5:Sept	0	0	1.1	8.6	4.4	0

(a) Catch per station = Mean number of crabs per station divided by number of stations sampled



AGE GROUPS:

YOY = YOUNG OF THE YEAR AND 0+

1-3 = AGE IN YEARS

(a) = SUM OF MEAN NUMBER OF INDIVIDUALS PER STATION DIVIDED BY THE TOTAL NUMBER OF STATION SAMPLED.

NORTH ALEUTIAN BASIN

RED KING CRAB

AVERAGE CATCH PER STATION OF RED KING CRAB AGE 3 AND YOUNGER

FEBRUARY 1984

FIGURE 3.5-7

The results of correlation analysis indicated that several physical and biological factors were related to the density distribution of red king crabs. Tables 3.5-3, 3.5-4 and 3.5-5 present the correlation matrices for cruises 83-1, 83-3 and 83-5, respectively. Generally, king crab density for age groups young-of-the-year through age 2 was negatively correlated with depth, whereas the density of crabs age 2+ and older was positively correlated with depth. Young-of-the-year crab density was positively correlated with gravel presence in sediments and with bottom water temperature. None of these correlations was statistically significant.

Variables related to the density distribution of 0+ or young-of-the-year crabs were bryozoan biomass during the April-May cruise ($r=0.5280$), sea urchin biomass during the June and September cruises ($r=0.7011$; $r=0.5746$, respectively), and polychaetes and gravel during the September cruise ($r=0.8607$, $r=0.6090$, respectively). Densities of age 1, 1+ and 2 crabs were significantly correlated with sea urchins ($r=0.7239$) during the April-May cruise, and with polychaetes and salinity ($r=0.5225$, $r=0.6404$, respectively), during the September cruise. Densities of crabs age 2+ and 3 were correlated with the sea onion ($r=0.6965$) during the April-May cruise, and with age 3+ and older red king crabs ($r=0.5975$) during the June cruise.

The results of multiple linear regression analysis are presented in Appendix E. For age class 0+, the sea star (Asterias amurensis) biomass was the most important variable for data from the April-May cruise, while sea urchin (Strongylocentrotus droehbachiensis) biomass was the most important variable in June. During September, three variables each accounted for 74 percent or more of the variability in YOY crabs for the single variable model; these were: polychaete biomass ($r^2=0.7418$); salinity ($r^2=0.8211$); and sea urchin biomass ($r^2=0.9982$).

Sea urchin biomass was also important in the regression models using data for age 1 through 2 crabs, accounting for 95 percent of the vari-

TABLE 3.5-3

CORRELATION MATRIX FOR RED KING CRAB ABUNDANCE AND ENVIRONMENTAL FACTORS DURING CRUISE 83-1 (APRIL-MAY)[a]

	Red King Crab Age				Biological Factors										Physical Factors			
	0+	1-2	2+ & 3	3++	Bryozoa	Flat-fish	Other	Round-fish	Sea onion	Sea star	Sea urchin	Shrimps	Sponge	Poly-chaetes	Depth	Gravel	Tempera-ture	Sal-inity
0+	1.000	-0.006	0.015	-0.021	0.528	0.012	0.200	-0.006	-0.068	0.451	-0.021	0.187	0.056	-0.028	-0.149	0.088	0.047	0.009
1-2		1.000	0.271	0.380	-0.021	-0.079	0.284	-0.056	-0.053	-0.032	0.975	0.001	0.469	-0.009	-0.191	0.483	0.073	-0.427
2+ and 3			1.000	0.408	-0.026	-0.066	0.073	-0.053	0.696	0.700	0.267	0.002	0.412	-0.022	0.006	0.036	-0.124	-0.276
3++				1.000	-0.050	-0.061	0.089	0.010	0.416	0.274	0.374	-0.031	0.484	-0.045	0.047	0.063	-0.249	-0.138
Bryozoa					1.000	0.033	0.025	-0.025	-0.044	0.325	-0.021	0.066	0.094	-0.017	-0.083	-0.022	0.019	0.056
Flatfish						1.000	-0.128	0.114	0.016	-0.035	-0.087	0.067	-0.026	0.028	-0.085	-0.224	-0.095	0.079
Other							1.000	-0.034	-0.014	0.045	0.277	-0.074	0.183	-0.025	0.036	0.138	0.118	-0.260
Roundfish								1.000	-0.091	-0.101	-0.059	-0.045	-0.082	0.063	0.302	-0.150	0.191	0.252
Sea onion[b]									1.000	-0.567	-0.055	-0.036	0.438	-0.045	0.182	-0.177	-0.179	0.323
Sea star[c]										1.000	-0.049	0.126	0.260	-0.023	-0.066	-0.139	-0.134	-0.027
Sea urchin[d]											1.000	0.098	0.461	-0.009	-0.200	0.523	0.060	-0.550
Shrimps												1.000	-0.056	0.087	-0.355	0.201	0.181	-0.580
Sponge													1.000	-0.042	-0.004	0.171	-0.121	-0.134
Polychaetes[e]														1.000	-0.080	0.019	-0.012	-0.071
Depth															1.000	-0.530	-0.015	0.560
Gravel																1.000	0.241	-0.657
Temperature																	1.000	-0.018
Salinity																		1.000

(a) 0.555 = Significant at $p<0.01$
(b) Boltenia ovifera
(c) Asterias amurensis
(d) Strongylocentrotus droebachiensis
(e) Tube-building polychaetes only

TABLE 3.5-4

CORRELATION MATRIX FOR RED KING CRAB ABUNDANCE AND ENVIRONMENTAL FACTORS DURING CRUISE 83-3 (JUNE)[a]

	Red King Crab Age				Biological Factors										Physical Factors			
	0+	1-2	2+ & 3	3++	Bryozoa	Flat-fish	Other	Round-fish	Sea onion	Sea star	Sea urchin	Shrimps	Sponge	Poly-chaetes	Depth	Gravel	Tempera-ture	Sal-inity
0+	1.000	-0.016	0.061	-0.077	0.256	-0.164	0.108	0.115	-0.072	0.074	0.701	0.032	0.004	-0.031	-0.113	0.079	0.014	0.084
1-2		1.000	0.050	-0.051	-0.053	-0.090	-0.031	-0.054	-0.049	-0.044	-0.030	-0.029	0.004	-0.021	-0.144	-0.071	-0.018	-0.015
2+ and 3			1.000	0.597	-0.065	-0.024	0.463	0.130	0.112	0.303	-0.049	-0.037	0.264	-0.033	0.099	-0.117	-0.138	0.157
3++				1.000	-0.051	0.024	0.125	0.069	0.588	-0.067	-0.065	-0.058	0.311	-0.045	0.249	-0.106	-0.110	-0.222
Bryozoa					1.000	-0.125	0.050	0.009	-0.025	0.056	0.102	0.046	0.071	-0.044	-0.034	-0.061	0.053	0.087
Flatfish						1.000	-0.186	0.155	-0.070	-0.009	-0.071	0.018	-0.050	-0.126	-0.332	-0.007	-0.430	-0.382
Other							1.000	0.325	0.190	0.100	-0.008	0.159	0.320	-0.069	0.078	-0.071	-0.236	0.212
Roundfish								1.000	-0.143	0.096	0.035	0.482	-0.037	-0.070	-0.221	0.459	-0.040	-0.017
Sea onion[b]									1.000	-0.198	0.055	-0.053	0.389	-0.036	0.366	-0.110	-0.080	0.220
Sea star[c]										1.000	-0.015	-0.114	-0.015	-0.017	-0.187	-0.058	-0.105	0.088
Sea urchin[d]											1.000	-0.034	0.169	-0.025	-0.134	-0.048	0.029	0.070
Shrimps												1.000	-0.052	-0.025	-0.131	0.463	0.112	-0.157
Sponge													1.000	-0.037	0.243	-0.149	-0.071	-0.190
Polychaetes[e]														1.000	0.124	-0.073	-0.115	0.073
Depth															1.000	-0.401	-0.329	0.500
Gravel																1.000	0.203	-0.258
Temperature																	1.000	-0.756
Salinity																		1.000

(a) 0.555 = Significant at $p<0.01$

(b) Boltenia ovifera

(c) Asterias amurensis

(d) Strongylocentrotus droehbachiensis

(e) Tube-building polychaetes only

TABLE 3.5-5

CORRELATION MATRIX FOR RED KING CRAB ABUNDANCE AND ENVIRONMENTAL FACTORS DURING CRUISE 83-5 (SEPTEMBER)[a]

	Red King Crab Age				Biological Factors										Physical Factors			
	YOY	1-2	2+ & 3	3++	Bryozoa	Flat-fish	Other	Round-fish	Sea onion	Sea star	Sea urchin	Shrimps	Sponge	Poly-chaetes	Depth	Gravel	Tempera-ture	Sal-inity
YOY	1.000	0.224	0.000	-0.043	-0.060	-0.076	0.059	-0.022	-0.055	-0.030	0.575	0.032	0.197	0.861	-0.196	0.609	0.199	-0.483
1-2		1.000	0.000	-0.085	-0.188	-0.107	-0.046	-0.084	-0.080	-0.078	0.385	0.020	-0.019	0.522	-0.339	0.210	0.248	-0.640
2+ and 3			0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
3++				1.000	0.052	0.020	0.062	-0.174	0.539	-0.159	-0.058	-0.111	0.022	-0.055	0.432	-0.152	-0.506	0.124
Bryozoa					1.000	-0.090	-0.032	-0.012	0.042	0.081	0.441	0.074	-0.057	-0.081	-0.297	-0.031	0.030	-0.061
Flatfish						1.000	-0.074	0.612	-0.024	0.430	0.099	0.001	-0.115	-0.095	-0.077	-0.162	0.053	0.120
Other							1.000	-0.120	0.010	-0.140	0.014	-0.078	-0.006	-0.005	-0.020	0.081	0.096	0.019
Roundfish								1.000	-0.175	0.318	0.024	0.179	-0.178	-0.039	-0.160	-0.022	0.106	0.063
Sea onion[b]									1.000	-0.147	0.001	-0.090	0.002	-0.073	0.476	-0.132	-0.249	-0.137
Sea star[c]										1.000	0.113	0.061	-0.118	0.006	-0.059	-0.221	-0.029	0.050
Sea urchin[d]											1.000	0.116	0.091	0.489	-0.304	0.624	0.192	-0.485
Shrimps												1.000	-0.093	0.003	-0.198	0.465	0.097	-0.146
Sponge													1.000	0.153	-0.140	0.528	0.017	-0.036
Polychaetes[e]														1.000	-0.197	0.504	0.222	-0.401
Depth															1.000	-0.493	-0.442	0.429
Gravel																1.000	0.218	-0.633
Temperature																	1.000	-0.327
Salinity																		1.000

(a) 0.555 = Significant at $p<0.01$

(b) Boltenia ovifera

(c) Asterias amurensis

(d) Strongylocentrotus droebachiensis

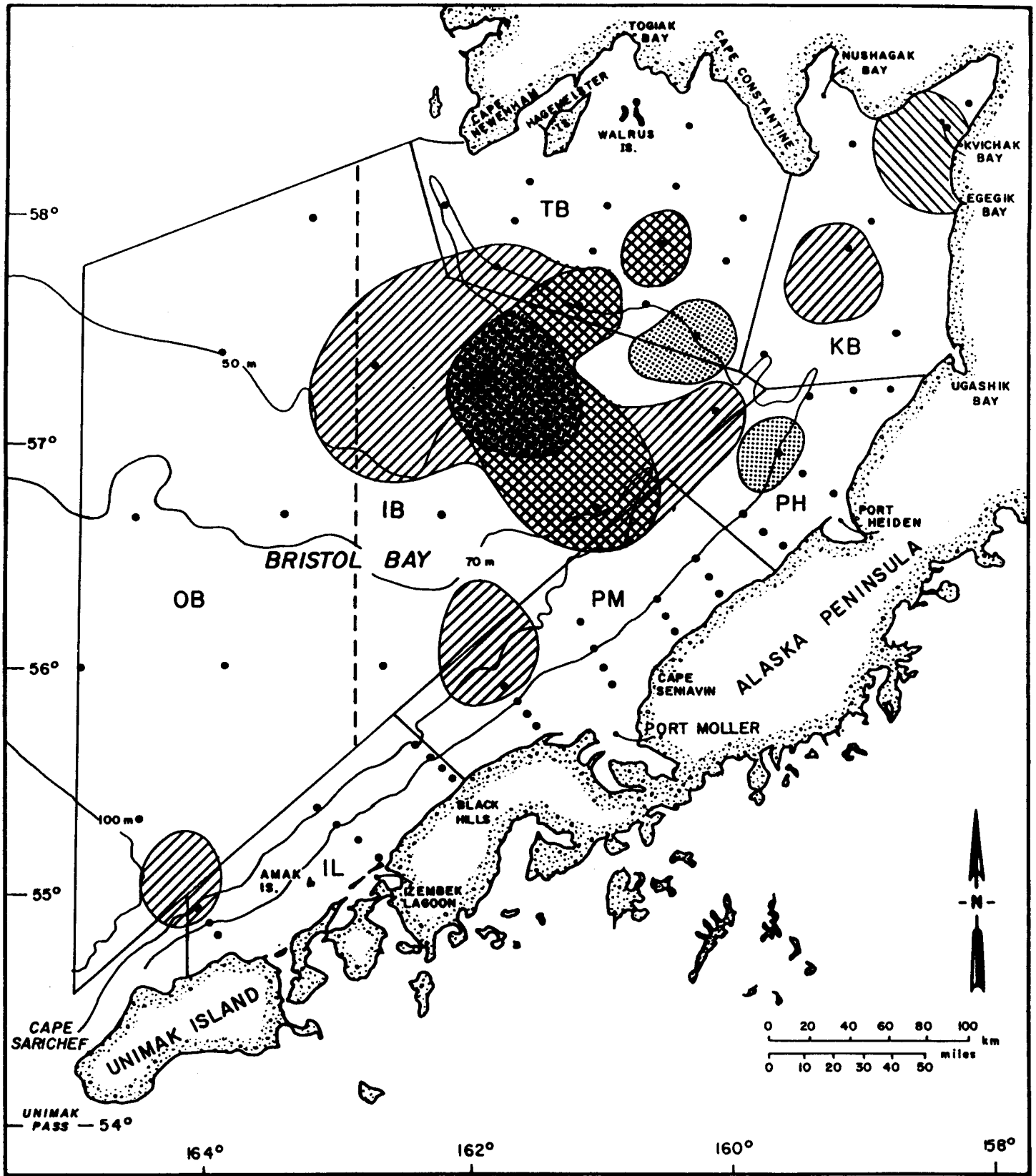
(e) Tube-building polychaetes only

ability (r^2=0.9530) in the single variable model for the April-May cruise data. Using the September data, the combination of polychaete and sea urchin biomass in the two-variable model accounted for 92 percent of the variability (i.e., r^2=0.9239). The sea urchin was again an important variable in the analysis of data for age 2+ and 3 crabs during April-May, accounting for 57 percent of the variability (r^2=0-.5699) in the single variable model.

3.6 Adult Distribution Patterns

The distribution of red king crab >68 mm carapace length is shown in Figures 3.6-1, 3.6-2 and 3.6-3 for cruises 83-1, 83-3 and 83-5, respectively. These larger crabs were found primarily at depths >50 m in the TB and IB subareas. The total numbers of larger crabs collected and the calculated catch per station are presented in Table 3.6-1, which shows that relatively few large crabs were collected during this study. The greatest numbers of crabs were taken from BB and TB stations; the 15 individuals from the IL subarea during cruise 83-1 were taken in a single trynet haul. Most large crabs captured were taken with the trynet, although a few were collected in rock dredge hauls from the KB and TB subareas.

The decrease in the catch of large crabs during the September cruise (83-5) resulted partially from a decreased sampling effort, especially in the BB subarea, as indicated by the station locations in Figure 3.6-3. This decline also reflects an assumed shift in the distribution of these crabs. Although the majority of large crabs were found in the inner BB and TB subareas, some were found in the IL, PM, PH and KB subareas during April-May and June (Figures 3.6-1 and 3.6-2, respectively). Also, while the majority of crabs were found at depths between 50 and 70 m, some were found at shallower depths during the first two cruises, such as stations KB2*4 and KB2*9 (both 14 m depth) and TB330 (30 m depth). During the September cruise (83-5), a few crabs were found along the edge of the PM subarea and inner BB at 70 m depth, and



AGE:

3+ =

4 =

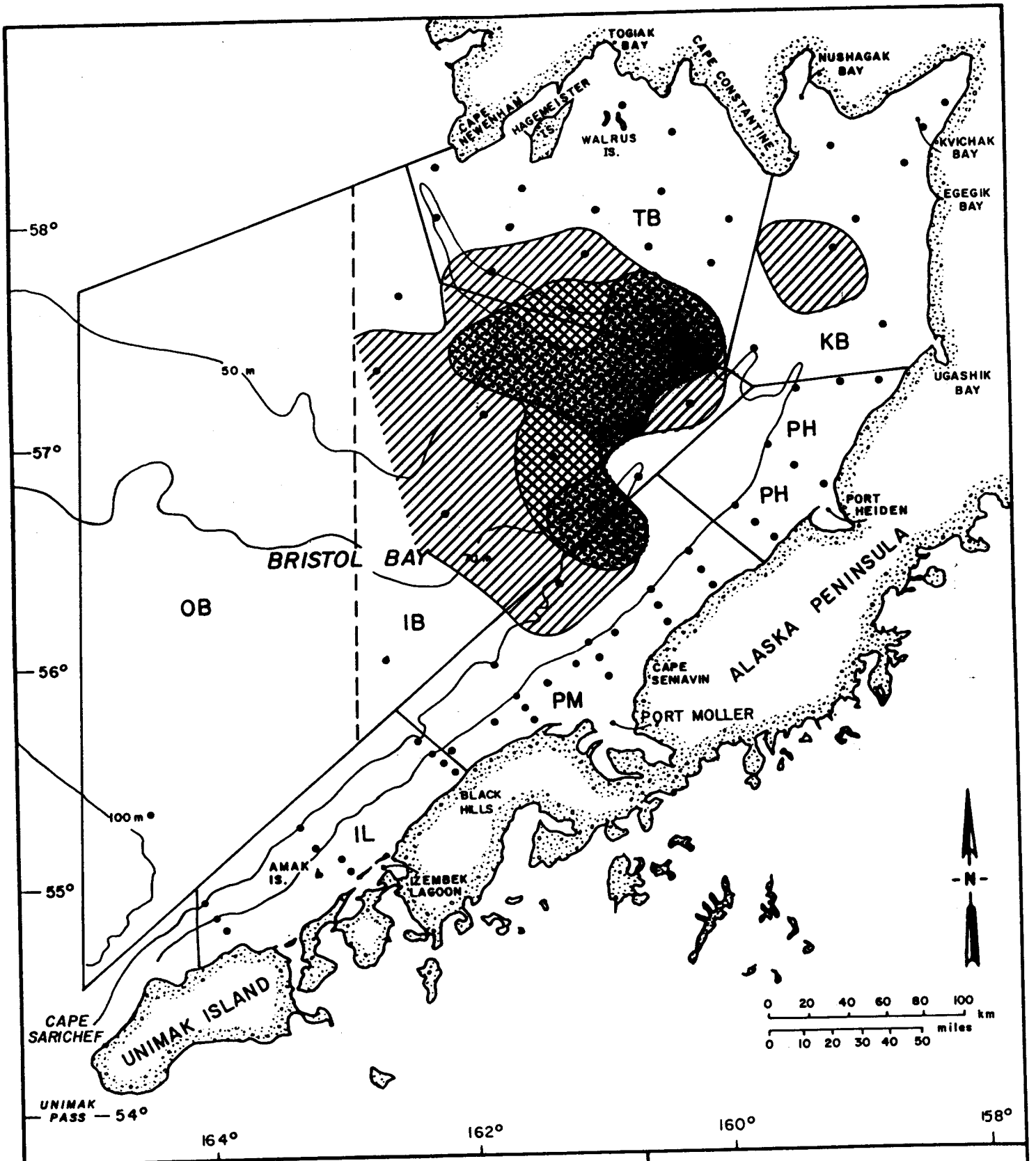
4+ =

• = SAMPLING STATION

BRISTOL BAY RED KING CRAB

DISTRIBUTION OF RED KING CRAB OLDER THAN 3 YEARS DURING CRUISE 83-1

FEBRUARY 1984 | FIGURE 3.6-1



AGE:

3+ =

4 =

4+ =

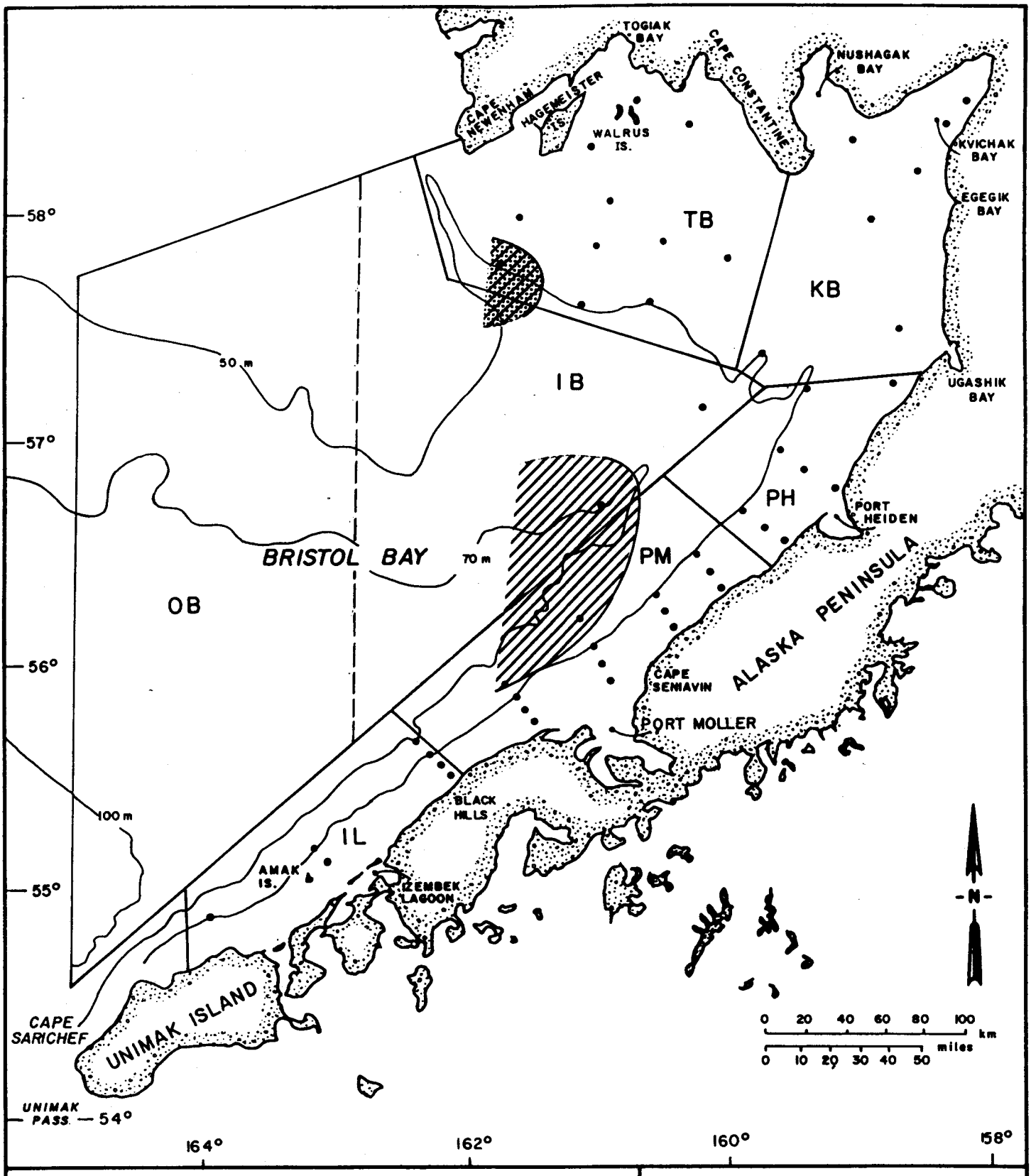
• = SAMPLING STATION

BRISTOL BAY RED KING CRAB

DISTRIBUTION OF RED KING CRAB OLDER THAN 3 YEARS DURING CRUISE 83-3

FEBRUARY 1984

FIGURE 3.6-2



AGE:

3 + =

4 =

4 + =

• = SAMPLING STATION

370

BRISTOL BAY RED KING CRAB

DISTRIBUTION OF RED KING CRAB OLDER THEN 3 YEARS DURING CRUISE 83-5

FEBRUARY 1984 | FIGURE 3.6-3

TABLE 3.6-1

TOTAL NUMBERS AND CATCH PER STATION OF RED KING CRAB >60 MM LENGTH

A. Total Numbers

Cruise	Sampling Area BB	IL	PM	PH	KB	TB	Total
83-1:Apr-May	11	15	2	0	3	9	40
83-3:June	11	0	3	0	1	9	24
83-5:Sept	2	0	2	0	0	1	5
Total	24	14	7	0	4	19	69

B. Catch Per Station[a]

Cruise	Sampling Area BB	IL	PM	PH	KB	TB
83-1:Apr-May	2.7	1.5	0.1	0.3	0.2	1.5
83-3:June	4.1	0	0.1	0.7	<.1	2.1
83-5:Sept	1.0	0	0.1	0	0	0.2

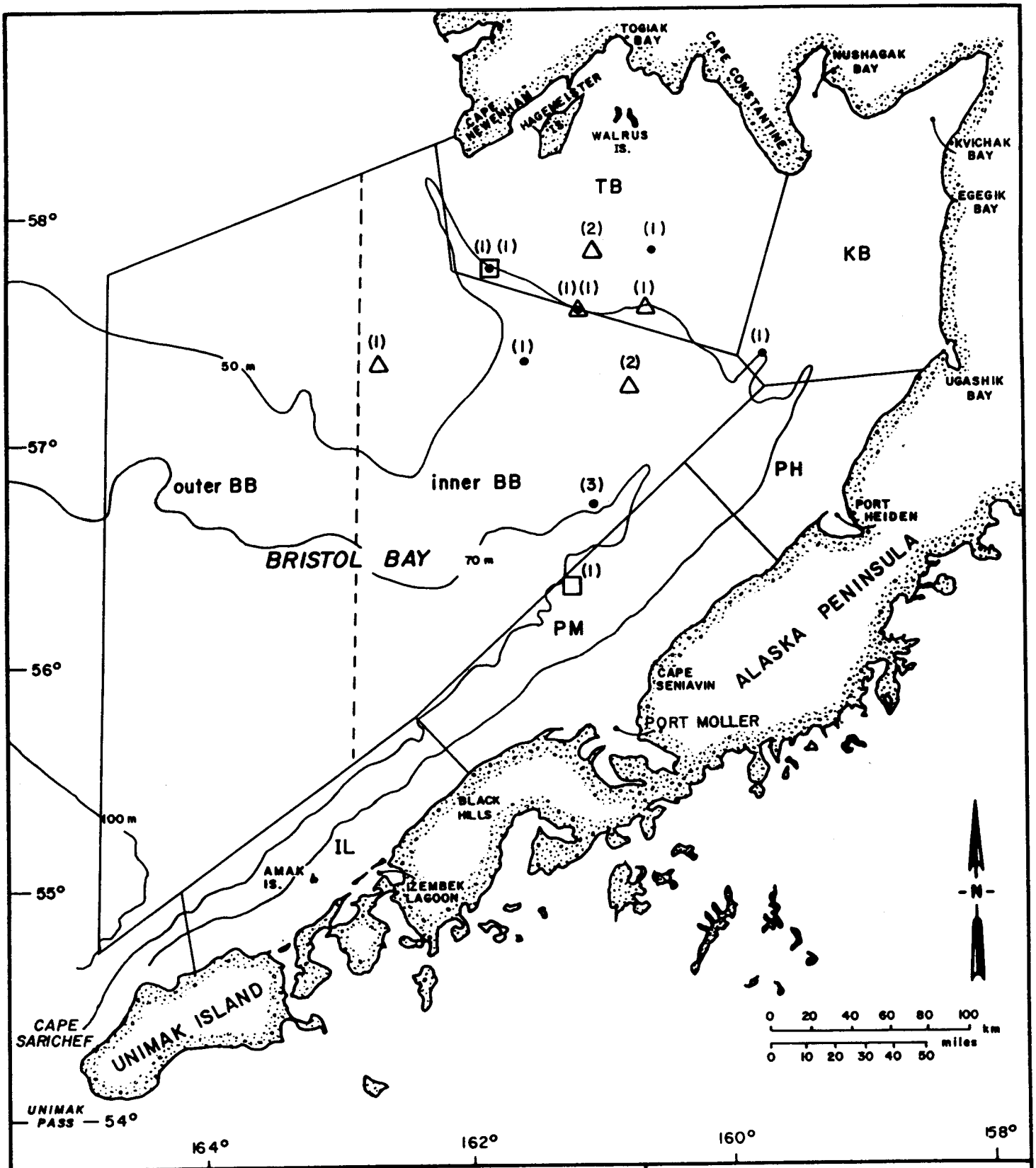
(a) Catch per station = Mean number of crabs per station divided by number of stations sampled

at one 50 m deep TB station west of the TB stations where crabs had been previously found (Figure 3.6-3).

Results of correlation analysis using densities of age 3+ and older red king crabs (Tables 3.5-3 to 3.5-5) indicated a positive, although not significant, correlation with depth and a general negative correlation with bottom water temperature. Densities of these crabs correlated with sea onion biomass during the June and September cruises ($r=0.5877$, $r=0.5391$, respectively). Bottom water temperature showed a strong negative correlation during September ($r=0.5056$).

Multiple linear regression results are shown in Appendix E. Sea urchin biomass was the most important single variable ($r^2=0.4224$) during April-May, with the greatest variability explained in the five-variable model by the combination of sea urchin, flatfishes, roundfishes, salinity and temperature ($r^2=0.6149$). Analyses of data from the September cruise resulted in the sea onion being most important in the single variable model ($r^2=0.3873$); sea onion and temperature were most important in the two-variable model ($r^2=0.5714$); and the combination of sea onion, temperature, bryozoa, flatfishes and roundfishes accounted for the greatest variability in the five-variable model ($r^2=0.6212$).

A small number of ovigerous female red king crabs were collected during this study; their distribution is shown in Figure 3.6-4. Most of the ovigerous females found were in the vicinity of the 50 m isobath separating the TB and BB subareas. Three individuals were found at 70 m in the eastern part of subarea BB during the April-May cruise, and one individual was found at 70 m along the PM-BB border during the September cruise. The biological information collected for ovigerous females is summarized in Table 3.6-2. Egg condition information shown in the table indicates that larvae were hatching as late as the June cruise in some areas.



● = CRUISE 83-1

△ = CRUISE 83-3

□ = CRUISE 83-5

(N) = NUMBER OF OVIGEROUS CRABS COLLECTED

BRISTOL BAY RED KING CRAB

DISTRIBUTION OF OVIGEROUS FEMALE RED KING CRAB

FEBRUARY 1984 | FIGURE 3.6-4

TABLE 3.6-2

SUMMARY OF BIOLOGICAL INFORMATION COLLECTED
FOR OVIGEROUS FEMALE RED KING CRAB

Cruise	Station	Carapace Length (mm)	SC[a]	Color[b]	Condition[c]	Clutch Size[d]	Wet Weight (g)
83-1	BB770	90	1	2	1		
		92	1	2	1		
		120	3		2		
	KB250	85	3		2		523
	TB431	89	1	2	1		
	TB350	88	2	3	1		
	BB557	83	2		2		
	TB250	90	3		2		
83-3	TB330	111	2	2	1	7	862
		96	2	2	1	6	636
	TB450	118	4	3	2	4	1,331
	TB350	97	2	3	1		665
	BB450	120	2	2	1	3	918
	BB665	92		5	1		632
		93		5	1		586
83-5	TB250	105	1	3	1	6	707
	PM670	96	1	3	1	6	739

(a) SC = Shell condition: 1 = Hard shell with sharp vertical spines
2 = Clean shell, ventral spines dull
3 = Old shell, small amount of growth
4 = Very old shell, lots of growth, scars, dirty

(b) Egg color: 2 = Purple
3 = Brown
5 = Purple/brown

(c) Egg condition: 1 = Pie-eyed
2 = Eyed

(d) Clutch size: 3 = 1/4 full
4 = 1/2 full
6 = full
7 = bulging

3.7 Epibenthic Associations

A variety of fish and invertebrate species was collected and enumerated in trynet and rock dredge samples. A general picture of distributional patterns of species groups, or associations, can be derived from the collection data. Trynet samples provided a more reliable quantitative data set due to the efficiency of the sampling gear on the bottom types sampled. The rock dredge data were much less reliable, and many rock dredge hauls were treated qualitatively.

Trynet biomass data, expressed as mean catch per unit effort (CPUE, g m^{-2}), were used to assess the relative importance of major taxonomic groups (Table 3.7-1). Trynet samples were dominated by pleuronectids, asteroids and ascidians. The pleuronectids were represented primarily by yellowfin sole (Limanda aspera) and rock sole (Lepidopsetta bilineata), the asteroids were primarily Asterias amurensis, and the ascidians were almost all Boltenia ovifera. Pleuronectids ranged from 41 to 51 percent, asteroids from 18 to 33 percent, and ascidians from 3.3 to 7.7 percent of the total mean CPUE per cruise. These three groups combined ranged from 72.7 to 85.3 percent of the total mean CPUE per cruise.

Fish taxa of secondary importance in trynet samples included the codfishes (Gadidae) and sculpins (Cottidae); these groups accounted for from 3 to 13 percent of fish mean CPUE (% catch) per cruise, and from 2 to 8 percent of the total mean CPUE (% total) per cruise. Invertebrate taxa of secondary importance included the sand dollar, Echinarachnius parma (Echinoidea), sponge (Porifera), red king crab (Paralithodes) and crangon shrimps (Crangonidae). Marine tube-building worms (Polychaeta) were important in the April-May samples.

The total mean CPUE for trynet samples increased from 5.6 g m^{-2} during the April-May cruise to 15.4 gm^{-2} during June and 17.40 g m^{-2} during September. These increases were largely a result of greater flatfish and sea star catches during the latter two cruises (Table 3.7-1).

TABLE 3.7-1

SUMMARY OF TRYNET CATCH PER UNIT EFFORT BY TAXONOMIC GROUP AND CRUISE DURING 1983

	Cruise 83-1 (April-May)			Cruise 83-3 (June)			Cruise 83-5 (September)		
	CPUE[a]	Percent Catch	Percent Total	CPUE	Percent Catch	Percent Total	CPUE	Percent Catch	Percent Total
Vertebrates									
Rajidae	0.0000	0.00	0.00	0.0243	0.28	0.16	0.0000	0.00	0.00
Pleuronectidae	2.7126	82.55	48.67	7.9384	90.36	51.60	7.1529	89.42	41.10
Agonidae	0.0079	0.24	0.14	0.0164	0.19	0.11	0.0330	0.41	0.19
Ammodytidae	0.0071	0.21	0.13	0.0148	0.17	0.10	0.0046	0.06	0.03
Clupeidae	0.0001	0.00	0.00	0.0000	0.00	0.00	0.0000	0.00	0.00
Cottidae	0.1107	3.37	1.99	0.4243	4.83	2.76	0.3080	3.85	1.77
Trichodontidae	0.0001	0.00	0.00	0.0012	0.01	0.01	0.0017	0.02	0.01
Gadidae	0.4419	13.45	7.93	0.2898	3.30	1.88	0.4202	5.25	2.41
Hexagrammidae	0.0004	0.01	0.01	0.0110	0.13	0.07	0.0335	0.42	0.19
Cyclopteridae	0.0000	0.00	0.00	0.0013	0.01	0.01	0.0012	0.01	0.01
Osmeridae	0.0025	0.08	0.05	0.0374	0.43	0.24	0.0048	0.06	0.03
Stichaeidae	0.0018	0.06	0.03	0.0257	0.29	0.17	0.0389	0.49	0.22
Pholidae	0.0001	0.00	0.00	0.0005	0.01	0.00	0.0006	0.01	0.00
Zoarcidae	0.0007	0.02	0.01	0.0000	0.00	0.00	0.0003	0.00	0.00
Total	3.2859	100.00	58.95	8.7851	100.00	57.10	7.9996	100.00	45.96
Invertebrates									
Anthozoa	0.0286	1.25	0.51	0.1067	1.62	0.69	0.2171	2.31	1.25
Polychaeta	0.1713	7.49	3.07	0.0000	0.00	0.00	0.0277	0.29	0.16
Cirripedia	0.0043	0.19	0.08	0.0454	0.69	0.30	0.0000	0.00	0.00
Pandalidae	0.0008	0.04	0.01	0.1675	2.54	1.09	0.0648	0.69	0.37
Hippolytidae	0.0000	0.00	0.00	0.0003	0.00	0.00	0.0002	0.00	0.00
Crangonidae	0.0559	2.45	1.00	0.1321	2.00	0.86	0.1550	1.65	0.89
Cancer	0.0000	0.00	0.00	0.0007	0.01	0.00	0.0036	0.04	0.02
Majidae	0.0591	2.58	1.06	0.0905	1.37	0.59	0.1007	1.07	0.58
Paguridae	0.0146	0.64	0.26	0.0187	0.28	0.12	0.0267	0.28	0.15
Paralithodes	0.2224	9.72	3.99	0.1839	2.79	1.20	0.0359	0.38	0.21
Erimacrus	0.0045	0.20	0.08	0.0004	0.01	0.00	0.0203	0.22	0.12
Gastropoda	0.0464	2.03	0.83	0.0561	0.85	0.36	0.0220	0.23	0.13
Pelecypoda	0.0120	0.52	0.21	0.0127	0.19	0.08	0.0197	0.21	0.11
Asteroidea	1.0196	44.57	18.29	3.9982	60.58	25.99	5.7531	61.17	33.05
Echinoidea	0.2086	9.12	3.74	0.1559	2.36	1.01	2.0420	21.71	11.73
Gorgonocephalid	0.0132	0.58	0.24	0.0136	0.21	0.09	0.0279	0.30	0.16
Holothuroidea	0.0000	0.00	0.00	0.0323	0.49	0.21	0.1042	1.11	0.60
Porifera	0.1090	4.76	1.96	0.3944	5.98	2.56	0.2031	2.16	1.17
Ascidiacea	0.3174	13.87	5.69	1.1897	18.03	7.73	0.5813	6.18	3.34
Total	2.2877	100.00	41.05	6.5993	100.00	42.90	9.4053	100.00	54.04
GRAND TOTAL	5.5737		100.00	15.3845		100.0	17.4049		100.00

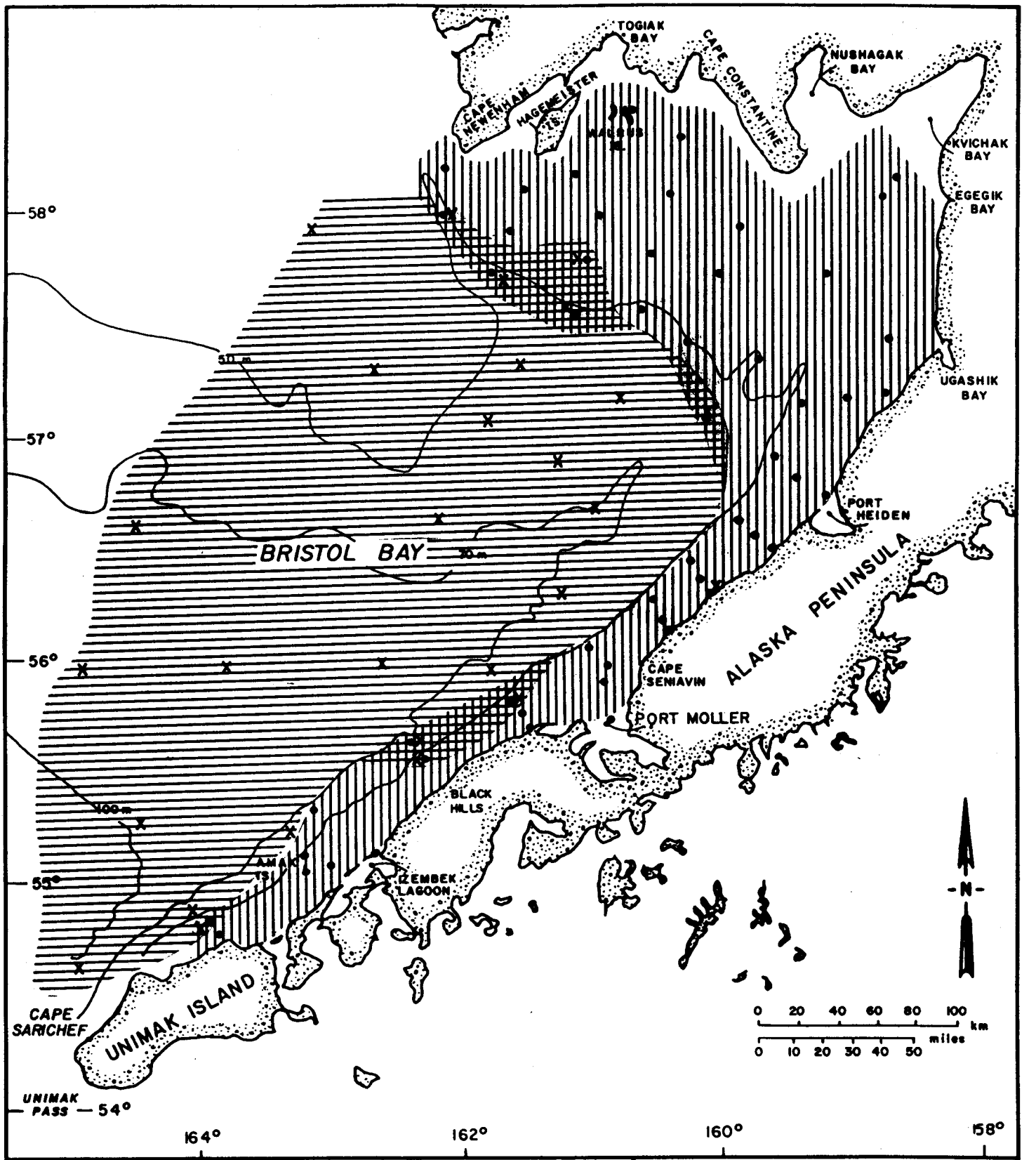
(a) CPUE = Catch per unit effort ($g\ m^{-2}$)

Dendrograms and two-way tables (not illustrated) were generated by multivariate methods (EAP 1982). Similarity analysis of biomass data from trynet samples resulted in the identification of two major sample groups. The distribution of samples in these two groups is displayed in Figure 3.7-1. The two groups, an offshore and nearshore group, overlap between the 50 and 70 m isobaths along the Alaska Peninsula and along the 50 m isobath in the northeast portion of the study area. The average depth of the 43 samples in the offshore group was about 62 m; the 99 samples in the nearshore group averaged about 36 m depth.

Similarity analysis resulting in species groups exhibited a great degree of species overlap between sample groups, indicating widespread distributions for many of the species taken in trynet samples. A group of three species occurred at their maximum biomass in the offshore samples: the red king crab, the ascidian Boltenia ovifera ; and the Tanner crab (Chionoecetes bairdi). The king crabs in these offshore samples were primarily adults and older juveniles. The species characteristic of nearshore trynet samples included: yellowfin sole (Limanda aspera); rock sole (Lepidopsetta bilineata); sea star (Asterias amurensis); hermit crab (Pagurus ochotensis); Pacific cod (Gadus macrocephalus); and pollock (Theragra chalcogramma). These species were also present in offshore samples, but at lower biomass values.

Two major sample groups were also identified from similarity analysis of rock dredge biomass data; their distributions are shown in Figure 3.7-2. Samples in group AB had a more widespread distribution than those in group CD, which was found along shore and in shallow areas. The 33 group AB samples had an average depth of approximately 37 m; the 34 group CD samples averaged about 23 m depth.

The four species groups identified from the rock dredge data formed two major groups. The species characteristic of sample group AB were essentially those described for the trynet nearshore group. Rock dredge hauls in sample group CD were generally devoid of the major species of



= NEARSHORE ASSEMBLAGE

X = OFFSHORE ASSEMBLAGE

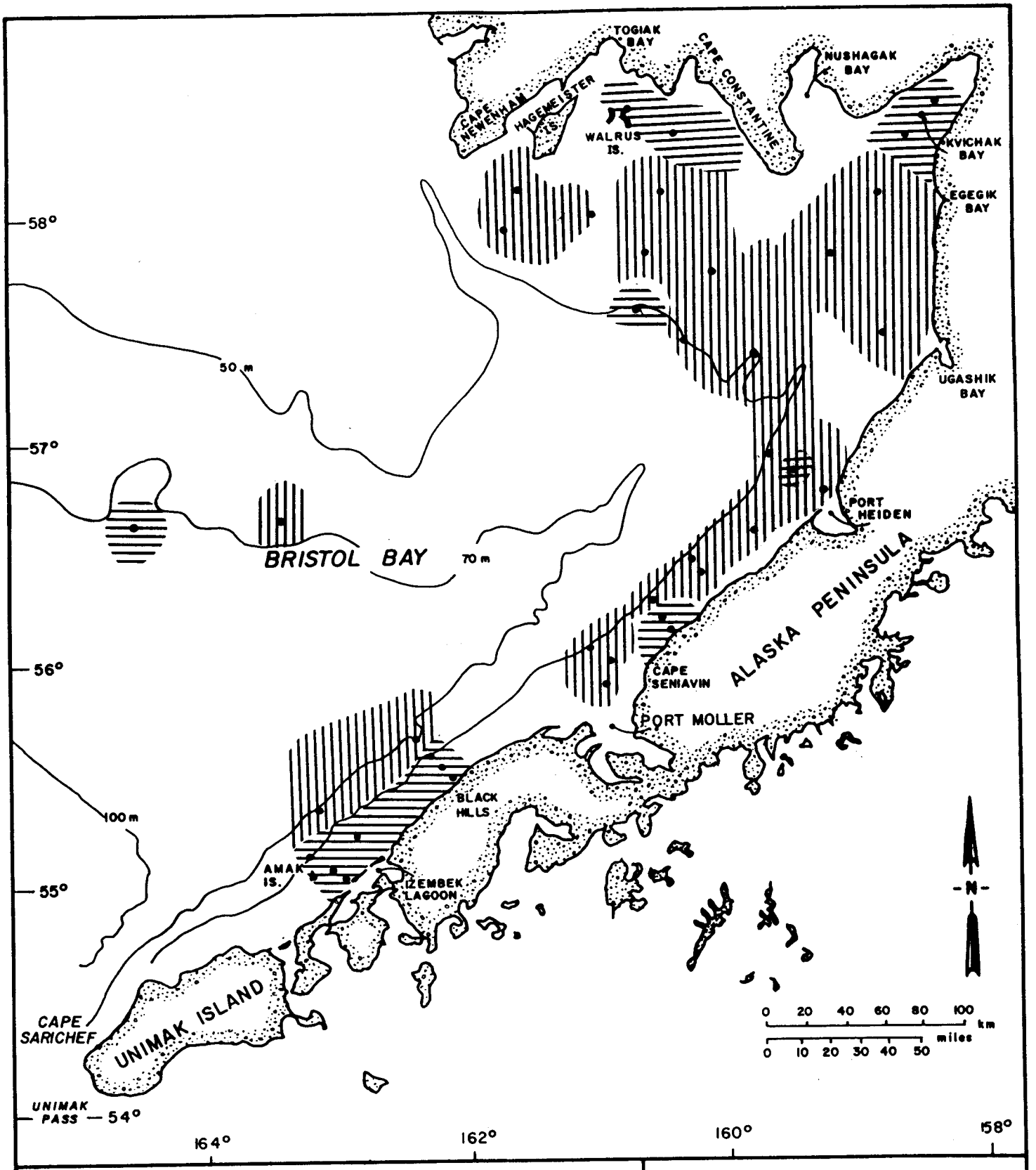
= TRYNET SAMPLING STATIONS, ALL CRUISES COMBINED

BRISTOL BAY RED KING CRAB

DISTRIBUTION OF TRYNET SAMPLE GROUPS FROM CLUSTER ANALYSIS

VTN

FEBRUARY 1984 | FIGURE 3.7-1



= GROUPS A, B

= GROUPS C, D

• = ROCK DREDGE SAMPLING STATIONS, ALL CRUISES COMBINED

BRISTOL BAY RED KING CRAB

DISTRIBUTION OF ROCK DREDGE SAMPLE GROUPS FROM CLUSTER ANALYSIS

FEBRUARY 1984 | FIGURE 3.7-2

group AB, especially the fish species. They were characterized by a number of invertebrates, including urchin (Strongylocentrotus droehbachiensis), a hermit crab (Pagurus beringanus), sea star (Henricia sp.) and gastropods. Small juvenile red king crabs, ages YOU and 0+ through 1+, were fond primarily in the group CD samples, whereas older juveniles were found primarily in group AB samples.

SECTION 4.0

DISCUSSION

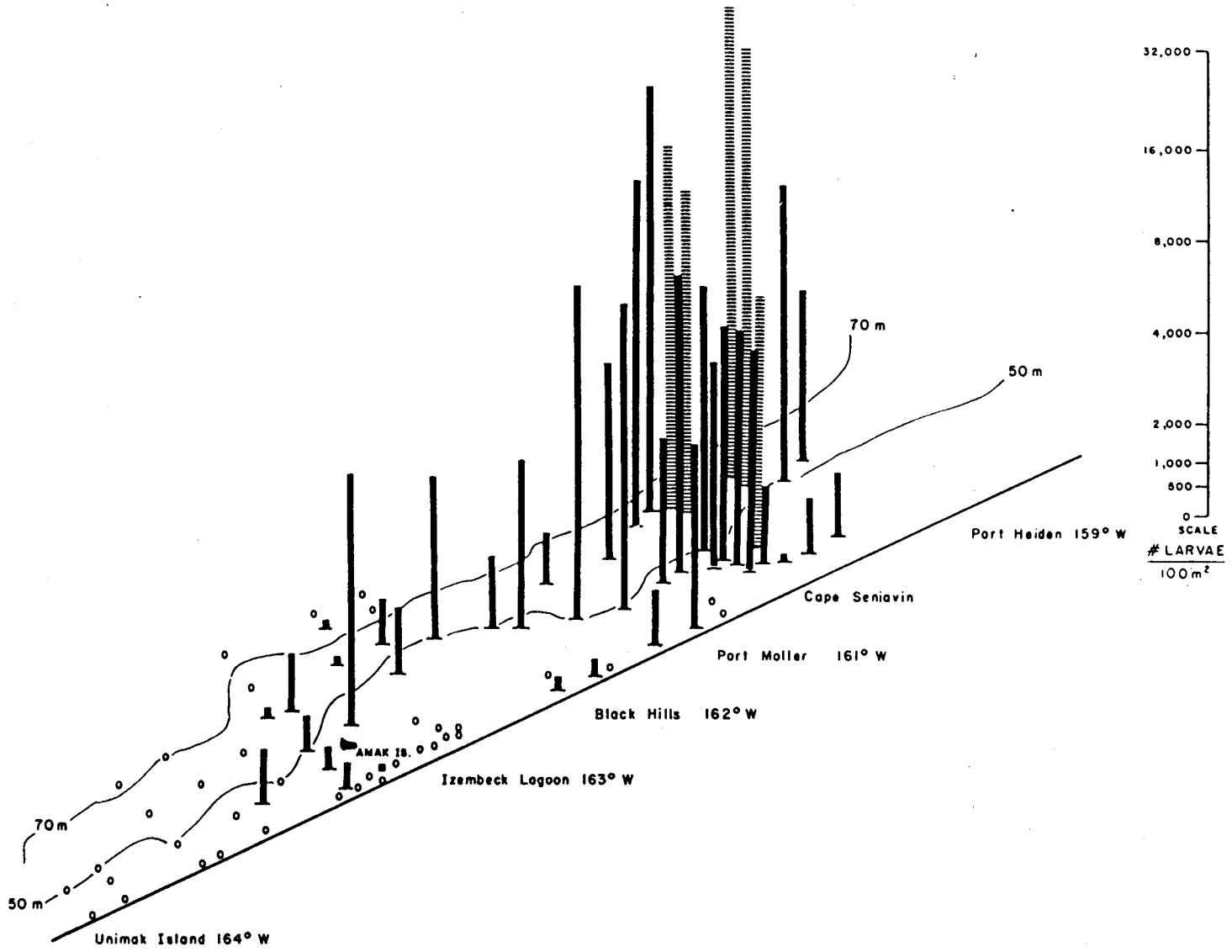
4.1 Larval Distribution and Abundance

4.1.1 Interannual Comparison of Larval Abundance

The extensive discussion of larval population dynamics given by Armstrong, et al. (1983b) presented evidence that larvae are distributed nearshore along the NAS in most years, are virtually absent offshore over the middle and outer shelf domains, and are present but poorly studied in Inner Bristol Bay. By comparing larval data sampled in successive years along the NAS, it was found that larval densities in the western region* were generally low in recent years. In the years 1976 and 1977, larval densities were high at a mean value of 13,200 larvae per 100 m^2, but in the years 1978 to 1982 were 400 to 700 per 100 m^2 (Armstrong, et al. 1983b). These authors suggested that the reduction in larvae along the western NAS had been caused, in part, by a shift of mature females offshore and to the east in the southeastern Bering Sea, and by a reduction in the female population. Again in 1982, mean larval density throughout subarea IL was low, 440 per 100 m^2, due in part to a large number of zero stations in very shallow water (<30 m) and off Unimak Island (Figure 4.1-1). However, densities were very high along the 50 m isobath from Izembek Lagoon to Black Hills with a mean of 2,600 larvae per 100 m^2. Densities were uniformly high in subarea PM (Port Moller) in 1982 where the mean density was 7,800 per 100 m^2.

In marked contrast, larval densities in June 1983 throughout all of subareas IL and PM over a distance of 300 km were the lowest yet calculated, including information from 1969 and 1970 (Haynes 1974). A mean

* This area extends west from 162°W longitude at Black Hills and is defined as subarea IL (Izembek Lagoon) in the present study.



NOTE: Longitudes of Shoreward Stations are approximate.

Difference in appearance of bars is for visual aid only.

BRISTOL BAY
RED KING CRAB

LARVAL DENSITIES
DURING JUNE 1982

FEBRUARY 1984 | FIGURE 4.1-1

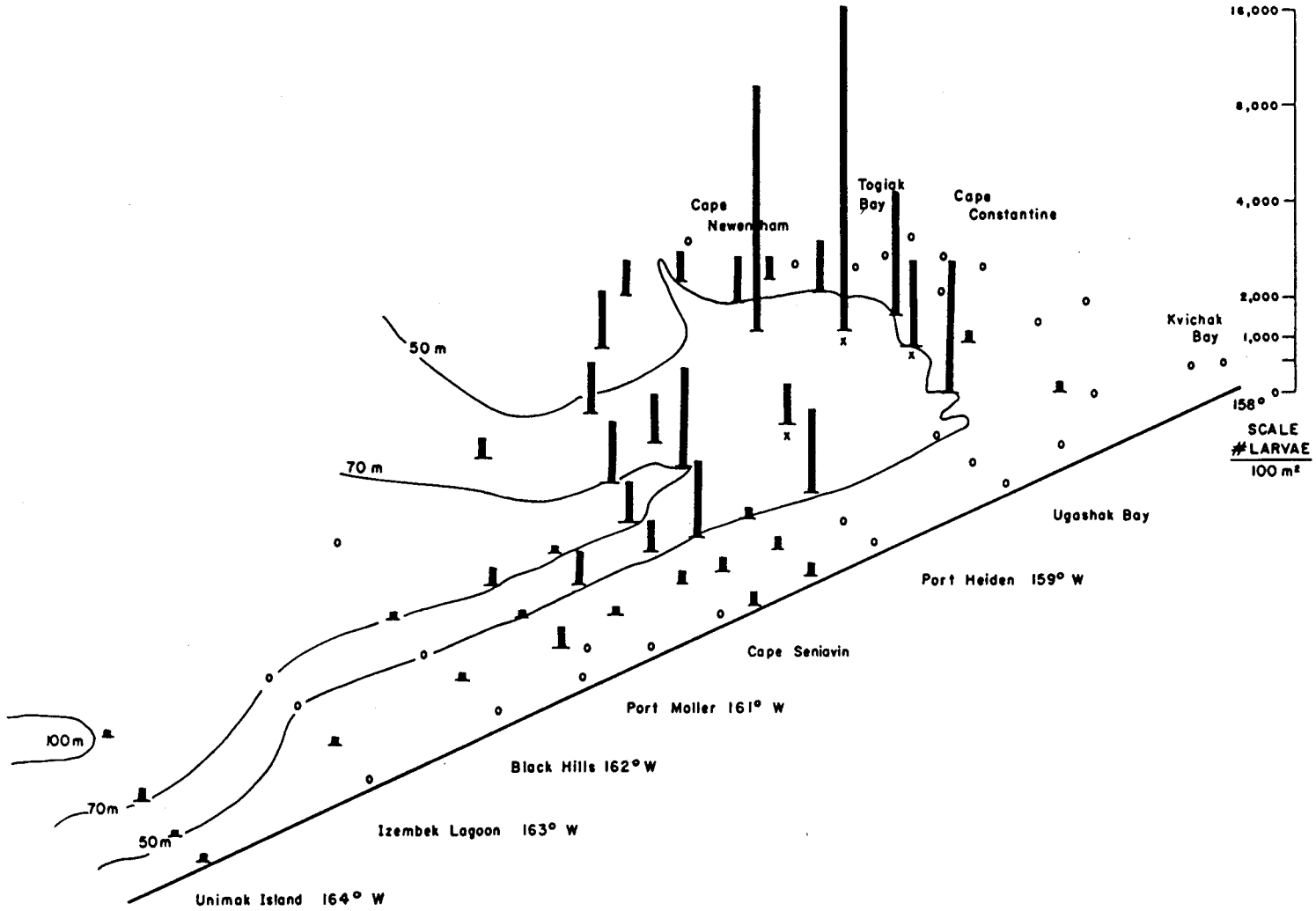
density of 43 larvae per 100 m^2 was derived for subarea IL, and 230 per 100 m^2 was the mean off Port Moller (Figure 4.1-2).

This 33-fold reduction in NAS larvae in 1983 was a persistent feature along the entire nearshore survey area during June, and suggests that either substantial reproductive failure and/or inordinate larval mortality occurred along the nearshore perimeter of the southeastern Bering Sea population, or that this area is not as important to species propagation as previously argued by some authors (Armstrong, et al. 1983b). The only substantial numbers of larvae found in June 1983 were offshore between 50 and 70 m over strata IB of Inner Bristol Bay where the mean density was 2,100 larvae per 100 m^2 (Figures 3.2-2 and 4.1-2). Considering previous evidence of moderate to high larval densities in this area (2,000-10,000 per 100 m^2; Armstrong, et al. 1983b; Haynes 1974), the importance of offshore central Bristol Bay as larval spawning ground should be reconsidered.

4.1.2 Female Stocks, Larval Hatch and Transport

The dilemma faced in assigning great importance to offshore areas as spawning habitat is to make the spatial connection between the occurrence of pelagic larvae there and the areas of apparent larval metamorphosis and settlement to the benthos as defined in this study. During a previous decade of NMFS groundfish surveys throughout the southeastern Bering Sea, 0+ and 1+ crab were virtually never taken in benthic trawls. Armstrong et al. (1983b) speculated that this failure to catch very young age groups was the result of either large, ineffective gear (for such small crab) and/or minimal effort in nearshore areas where larvae were hypothesized to settle given patterns of pelagic distribution.

Small juvenile crab ($\leq$10 mm) were caught in April, June and September 1983 (see Section 3.4). Small crab taken in April were certainly of the 1982 0+ year class, those in June questionable, and the large numbers of



NOTE: Longitudes of Shoreward Stations are approximate.

BRISTOL BAY
RED KING CRAB

LARVAL DENSITIES
DURING JUNE 1983

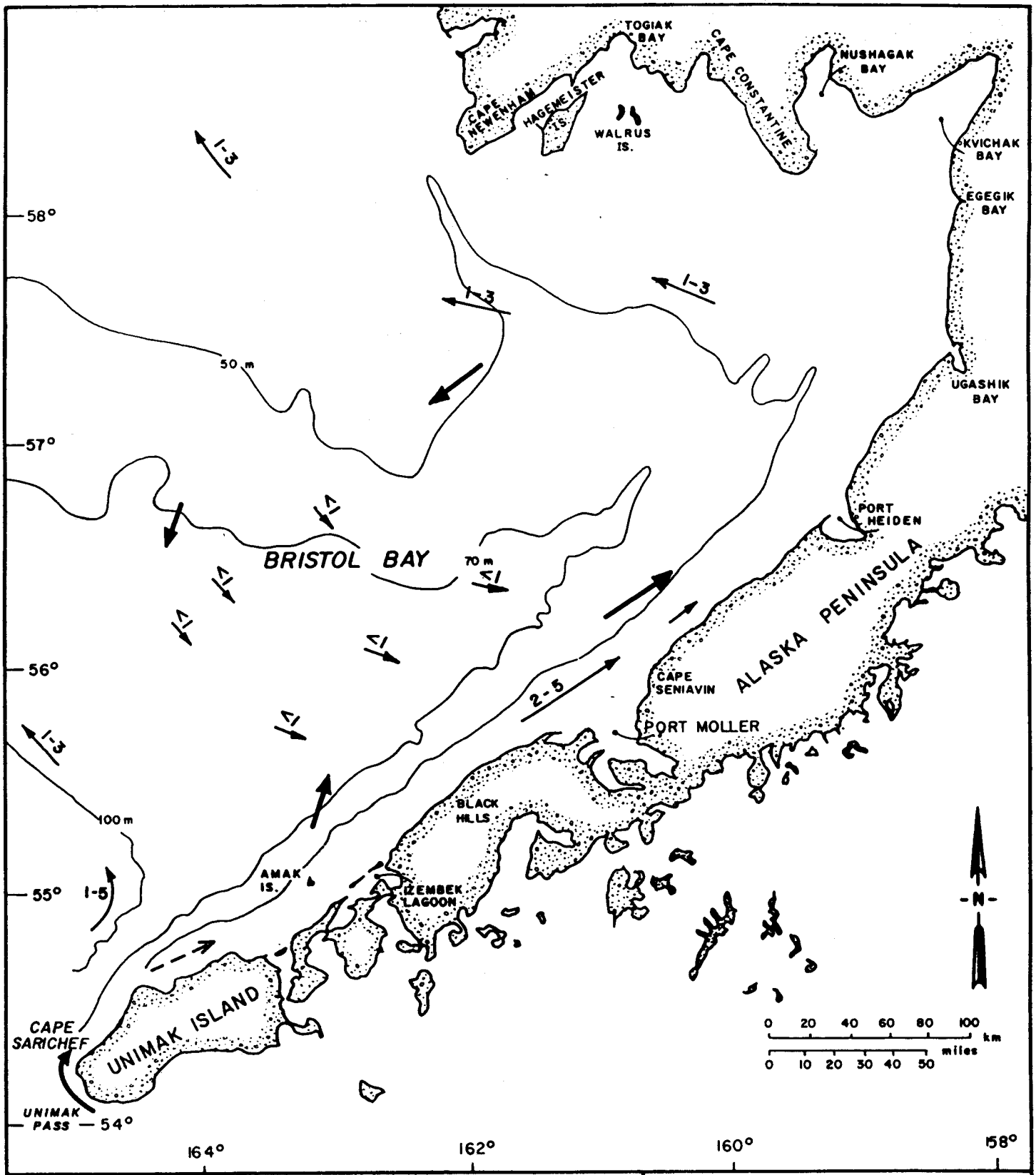
FEBRUARY 1984 | FIGURE 4.1-2

about 5 mm carapace length caught in September were undoubtedly 1983 young-of-the-year crab. In all months, small juveniles were usually found inside the 50 m isobath where larvae were rare in 1983, but common in previous years. It is not difficult to imagine that nearshore 0+ juveniles are the survivors of nearshore larvae, entrained and transported in slow, longshore currents (Figure 4.1-3) that move counterclockwise to the northeast into Bristol Bay (Kinder and Schumacher 1981b; Schumacher and Reed 1983). Larvae settle out of this current at fortuitous points along the NAS based on rates of development, but likely survive only in areas where appropriate substrate affords refuge (off Port Moller, Cape Seniavin, Port Heiden, Kvichak and Togiak Bays).

The origin of larvae in high abundance between 50 to 70 m is uncertain. Possibly they were hatched between Black Hills and Cape Seniavin in early May, and were transported north-northeast in prevailing currents. Water conditions in June showed two pockets of colder water (5°C or less) at points along the 50 m isobath north of 57°N that may have funneled warmer coastal water between Cape Seniavin and Port Moller offshore (Figure 3.1-8). Or as suggested previously, larvae in this area were hatched later than those nearshore and were a separate, more abundant cohort. The arguments in favor of an offshore cohort are: 1) colder bottom water temperatures (Figures 3.1-10 and 3.1-11) that may have slowed somewhat the rate of egg development and thus delayed hatch; and 2) the greater proportion of younger SII and SIII larvae found in this region (subarea IB; 50 m isobath border of TB) than elsewhere throughout the study area where SIII and SIV were common (Figure 3.2-3).

Larvae hatched offshore between 50 and 70 m in inner Bristol Bay were more difficult to account for as benthic 0+ juveniles in shallower water and, in fact, such larvae (and the spawning females) were thought to be superfluous to annual reproductive effort by Armstrong, et al. (1983b).

This notion was based on models of current speed and direction that considered the water of the eastern middle shelf domain to be essentially static with virtually no net direction (Kinder and Schumacher



NET CIRCULATION IN CM S^{-1} (KINDER & SCHUMACHER (1981)

INTERMITTENT CIRCULATION (KINDER & SCHUMACHER 1981)

NET CURRENT (HEBARD 1959)

BRISTOL BAY RED KING CRAB

KNOWN CIRCULATION PATTERNS IN BRISTOL BAY

FEBRUARY 1984 | FIGURE 4.1-3

1981b). Larvae hatched in this region would be expected to develop and settle out essentially in the same area as the origin of hatch; an area which may not be amenable to survival of small juveniles.

The notion of a confined water mass with no component of lateral transport must not be correct, or the process may not be operative in all years. Despite the near absence of larvae nearshore in June 1983 (Figure 3.2-2 and 4.1-2), young-of-the-year juveniles were found three months later in Kvichak Bay about 150 km northeast of the center of offshore larval abundance (Figure 3.5-6). Juvenile settlement in an area far removed from the apparent centers of larval hatch in 1983 and in an area more or less "up current" from central Bristol Bay, argues that a model of a rigid, cold water mass that guides but does not exchange with a nearshore counter current is inappropriate for the observed phenomena in upper layer water.

The relationship between female stocks and the magnitude of recruit populations has never been well defined for red king crab. Reeves and Marasco (1980) hypothesized that: 1) high female abundance and full copulation is not required for maximum recruitment, but; 2) mature female abundance could decline beyond a level such that recruitment is reduced. This theoretical female population size is about 20 million based on their analyses. Armstrong, et al. (1983b) added that the total population of females in the southeastern Bering Sea may not be so important a gauge of potential recruitment as is the size of regional populations where larvae have the greatest chance of settlement to optimal substrates. As they pointed out from NMFS data, mature female populations declined in the southeastern Bering Sea between 1977 and 1981 and became less common in nearshore, warmer water habitats. This trend has continued in 1982 and 1983 as mature female populations have declined to 55 million and 10 million, respectively, presently a level below Reeves and Marasco's theoretical recruitment optimum. Nearshore abundance has further declined such that ovigerous females were rather rare along the entire North Aleutian Shelf from Unimak Island to Kvichak

Bay and west to Cape Newenham. The 1983 population was centered over Bristol Bay between 50 to 70 m and, in general, reflected closely the abundance of larvae in the water column.

4.1.3 Vertical Distribution

The May time series demonstrated the presence of diel vertical migration in first stage red king crab zoeae. This behavior had been suggested previously (Takeuchi 1962, trans. 1967; Haynes 1977), but not quantitatively documented. Kurata (1960) has suggested that if larval red king crab vertically migrate, there should be less vertical migration in the later stages as they adopt a more benthic behavior. No support was found for any changes in vertical migration for the first three zoeal stages.

Diel vertical migration in larval decapods may have an important effect on the horizontal distribution of these stages, particularly in areas where current direction and/or velocity change with depth. Larval blue crabs (Callinectes sapidus) vertically migrate and are thus retained in Atlantic Coast estuaries where habitat is suitable instead of being dispersed into the open ocean (Sulkin and Van Heukelem 1982). Epifanio and Dittel (1982) hypothesize that successful recruitment of C. sapidus is due to "the evolution of behaviorial traits (i.e., rhythmic vertical migration) that allow larvae to take advantage of . . . advective flows." Cronin and Forward (1982) further argue that such rhythmic behavior may be widespread among estuarine planktonic larvae, particularly where tides exert strong dynamic effects.

Rhythmic vertical migration in larval red king crabs may have similar biological significance. Hebard (1959) reported that currents in the shallow Bristol Bay region are strongly influenced by tides. He further learned that surface and bottom currents there flow in different directions. Since red king crabs dwell primarily in and apparently evolved in shallow Alaskan coastal waters (Makarov 1938) which are characterized

by strong tides, then similar larval behavioral traits would have a similar biological significance.

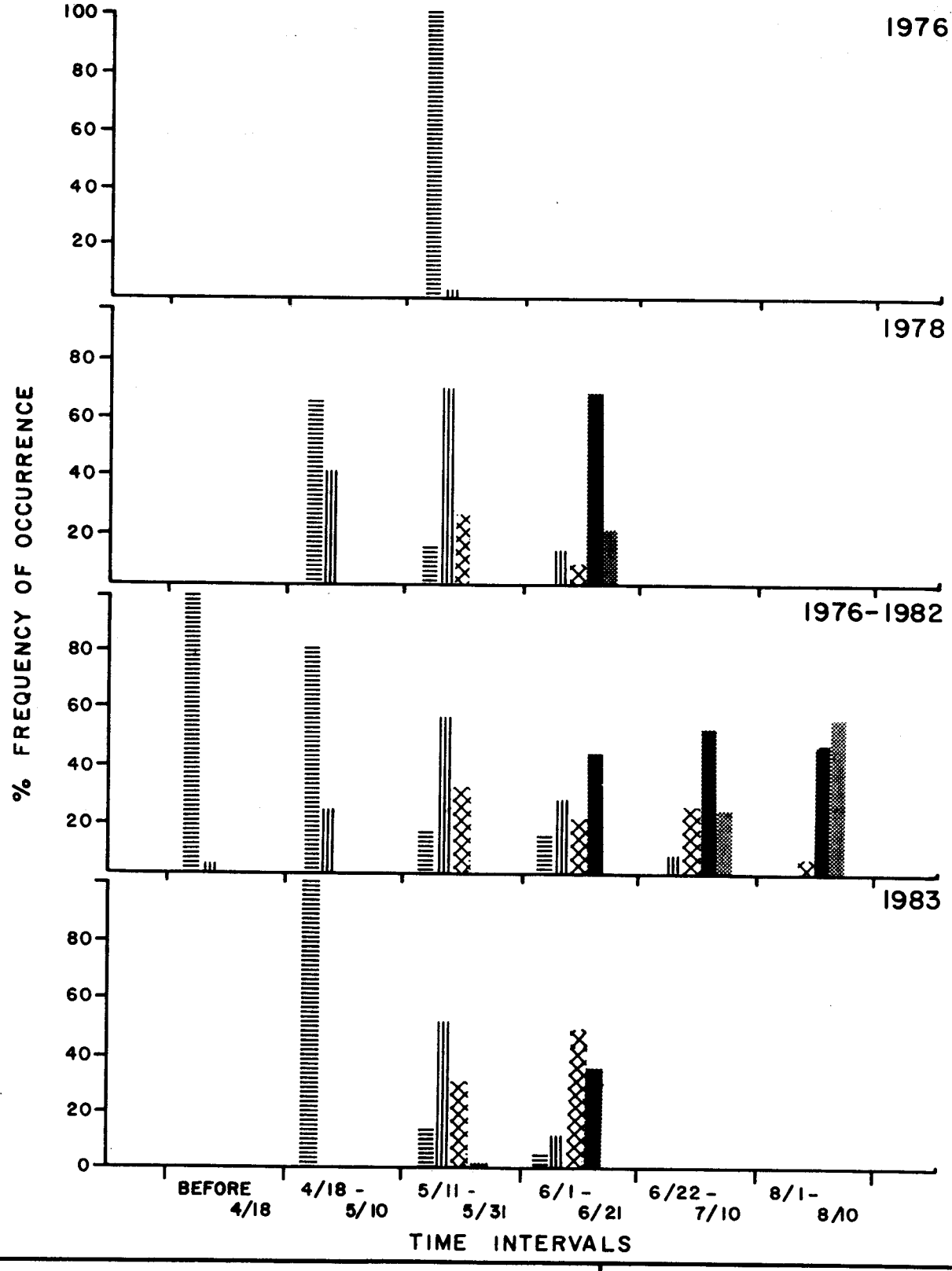
4.2 Interannual Larval Hatch and Development

Although the larval hatch and release was late this year when compared to the average for red king crab in Bristol Bay found by Armstrong, et al. (1983b), it was not the latest recorded. The 1976 release was after 10 May, and the timing of development for 1983 was very similar to the 1978 release (Figure 4.2-1). The 1982 release may also have been similar to 1978 and 1983 in timing; however, sampling was too late last year to be strictly comparable.

The most apparent aspect of Figure 4.2-1 is the highly variable timing between years of the initial hatch release. Physical factors, such as water temperature, are likely the cause of the five plus week difference in timing between releases. This hypothesis finds further support in a recently released U.S. NOAA Weather Service report on this past decade's weather. According to this report, the past ten years, covering the period studied by Armstrong, et al. (1983b) and this investigation, has been one of the most variable decades for weather ever measured, with three of the warmest years and three of the coldest years on record. If water temperature or another physical factor is the cause of the differences in timing, then the variations in timing of larvae release may be due to such variability in weather patterns.

4.3 Post-larval Size and Age Distribution

In the southeastern Bering Sea the time of appearance of the first red king crab juvenile stage varies over four to six weeks after hatching, with peak settlement in early July near Unalaska and mid-August in Bristol Bay (Weber 1967). Juvenile growth progresses from between 2.6 and 3 mm at settlement to an average of 11 mm at 12 months after settlement. Development during this time progresses through eight (Powell



= ZOEA 1

= ZOEA 2

= ZOEA 3

= ZOEA 4

= MEGALOPS

BRISTOL BAY RED KING CRAB

1976, 1978 AND AVERAGE LARVAL STAGE FREQUENCY COMPARED TO THAT IN 1983

VTN

FEBRUARY 1984 | FIGURE 4.2-1

1967) to 11 molts (Weber 1967). The differences in growth rate induced by changes in the early molting frequency data on young crab are great; therefore, it is important to obtain accurate molting frequency data on young crabs.

The September 1983 sampling demonstrated an absense of larvae in the zooplankton samples and a dominance of YOY individuals. This reflects recent (2-4 weeks earlier) mass metamorphosis of larvae into benthic-dwelling juveniles. Although most first post-larvae appear in the southeastern Bering Sea from mid-July through mid-August, minor settlement occurs before and after this time. The few 0+ (4-6 mm) in the April-May and June sampling are presumably individuals that had settled late, in August or September 1982. A late hatching cohort would most likely lead to settlement as cold bottom water temperatures begin and thus growth to 4-6 mm by the following spring might be expected.

Relatively moderate numbers of age 1 and 1+ crabs were found during the April-May and June cruises; somewhat greater numbers of these age groups were found during September, indicating recruitment from the 1982 YOY group. The very low numbers of age 2 and 2+ crabs in the samples may be explained by the highly clumped distribution resulting from podding behavior. Apparently crabs younger than approximately age 2 ($\leq$28 mm) do not stray far from the protection of their settling location. The first year of benthic life is spent in rocky crevices, kelp patches, among colonies of tube worms, and other protective niches. Between the ages of 12 and 24 months, juvenile crabs abandon their numerous hiding places and congregate to form pod communities (Powell and Nickerson 1965; Powell 1974). The small aggregations of the youngest crab often disband and seek refuge in the surrounding substrate. As they age there is a tendency to remain in a pod formation for longer intervals.

Pod formations are analagous to other animal congregations such as herds, flocks and schools. Podding describes the general behavior of young crabs in forming contact aggregations which is believed to provide

protection against predators, as well as to organize the crabs into a coordinated group, so that, acting as a unit rather than as individuals, they can benefit from their coexistence (Powell 1974). The following is an account of a pod observation near Kodiak Island (Powell and Nickerson 1965):

> "On two occasions elongated dome-shaped piles of crabs were observed lying parallel to the beach at depths of four to 35 feet. These piles appear to be numerous pods joined in a line. On February 19, 1961, the first group of an estimated 6,000 crabs averaging 30 mm was observed and described in field notes as a long windrowed pile. A similar observation on April 25, 1962 revealed an estimated 500,000 crabs 34 to 98 mm in carapace length having modes at 61 and 84 mm. One foot from an end of the 12-foot zig zag pile was a pod of approximately 1,000 crabs, giving rise to the idea that spherical pods form elongate piles when they congregate. Thousands of other crabs remained scattered and feeding."

Pods have been observed during every month of the year, and all of them contain both males and females of similar size and of the same age. Most podding crabs are between 2 and 3+ years old (29-73 mm), although the above observation testifies that crabs with a mode of 84 mm were one of the two distinct size classes in a pod.

Few pod-sized crabs (29-73 mm) were collected during the three sampling periods of 1983. During the April-May and June sampling, age 2 and 2+ crabs were rarely found. However, ages 3 and 3+ were more numerous, mainly occurring at deeper stations (stations TB350, TB550, BB557 and PH350) than the previous age group. In September, ages 2, 2+ and 3 were absent and only one age 3+ crab was found. The data collected do not indicate that crabs were sampled while podding. Although each station was briefly sampled, it is expected that if a pod was sampled there would be a high number of similar-sized individuals. Among those stations that yielded pod-size crab both the quantity and the proportion at podding size were low. Presumably the lack of pod-size crab in September is a reflection of the lack of effort in central Bristol Bay, however, it may also be due to their patchy transient nature. Podding has been documented on the North Aleutian Shelf near Akutan and Unalaska

Islands (Powell and Nickerson 1965; Weber 1967). During the year of sampling near Unalaska, several groups of king crabs 29-69 mm were not sampled continuously and were interpreted as being transient.

4.4 Post-larval Distribution and Abundance

The distribution of red king crabs age YOY to three years was generally restricted to the coastal domain of the North Aleutian Shelf and Bristol Bay, the area landward of the 50 m isobath. This area had the lowest bottom salinities ($\leq$26 °/oo), highest bottom water temperatures (>11°C by September) and the largest grained sediments sampled in the study area.

YOY crabs occurred from waters north of Izembek Lagoon (station IL430), northeasterly along the coast and into Togiak Bay in the north. Densities were greatest in the Port Heiden and Kvichak Bay areas. These results agree with settlement areas as projected from previous larval king crab studies. Haynes (1974) reported that under the generally cyclonic (counter-clockwise) water movement in the southeastern Bering Sea, larvae released in the Black Hills-Port Moller area were carried northeastward along the Alaska Peninsula toward the head of Bristol Bay. The pattern of larval distribution described for 1983 showed concentrations of newly released larvae off Port Moller in nearshore (<50 m) waters and also in central Bristol Bay in mid-depth (50-70 m) waters. By June, the greatest concentrations were found roughly parallel to the 50 m isobath from the Port Moller-Port Heiden sampling areas boundary north and west to the edge of the study area. The greatest larval concentration was in the mid-depth (50-70 m) water between Port Moller and Cape Newenham (see Figure 3.2-2).

All YOY juveniles were found on gravel or larger sized substrates. These substrates were similar to those inhabited by early juvenile king crab of lower Cook Inlet and Kodiak Island (Powell, et al. 1974; Sundberg and Clausen 1979). YOY apparently depend on an environment

which provides for adequate food (i.e., hydroids and bryozoans) and protection from predators (see discussion in Armstrong, et al. 1983b). The distribution of such suitable substrates in the study area was extremely patchy and it is believed that settling in areas where such substrates are absent or limited would hasten natural mortality.

The substrates inhabited by juvenile red king crabs during this study also supported a characteristic attached invertebrate fauna, primarily stalked sea squirts (Boltenia ovifera), bryozoans, and colonial tube-dwelling polychaetes in the Kvichak Bay area. Although it appears that a direct relationship exists between the distributions of red king crabs and certain attached epifaunal taxa, the relationships are not yet clearly defined. Samples of Boltenia ovifera, for example, indicated that their greatest concentration was in the 50-70 m deep area of the inner Bristol Bay sampling subarea; no red king crabs younger than age 3+ were found in this area, even though this was the area of greatest pre-settlement larval concentrations during June.

Although YOY in the present study were found in depths of 20-50 m, successful settlement is known to take place in shallower as well as deeper waters. In Kodiak Island waters, young crabs one to 12 months old were commonly found in the littoral zone (Powell and Nickerson 1965). The maximum depth at which post-larval crabs smaller than 16 mm have been captured was 106 m off Kodiak Island (Powell and Nickerson 1965). The Japanese king crab tangle net fishery in the eastern Bering Sea from 1956 to 1959 captured 5,495 juvenile crab from 2 to 33 mm carapace length (INPFC 1960). They were caught 139 to 213 km northwest and seaward of Port Moller, at an average depth of 55 m.

The hypothesis that post-larval survival is related to settlement onto appropriate "refuge" habitat (Armstrong, et al. 1983b) is supported by the apparent distribution of juvenile crabs found in this study. This refuge habitat is thought to consist of gravel or larger-sized substrates inhabited by any of several attached epifaunal invertebrate

species. The attached invertebrate fauna may, in fact, be the most important aspect of the habitat, for very few juvenile crabs were found in samples of bare gravel. Shipboard substrate preference tests were conducted with age 1+ crabs during the June cruise (see Appendix F). While far from conclusive, the tests indicated that in the absence of epifauna, young crabs preferred a medium-sized rock substrate over small rock, gravel or sand. When small "reefs" of natural epifaunal material were placed on the previously bare substrates, the highest percentages of crabs were found on tube worms/sand and mussels/small rock combinations. The erect bryozoan/ medium rock combination attracted the smallest percentage of crabs. Crabs were observed during the experiments feeding directly on the tube worms and scavenging food from the spaces between mussels.

Further studies are needed to test the relationship between post-larval survival and refuge habitat. The successful settlement of young-of-the-year crabs during 1983 was apparently on the habitats described in the Port Heiden and Kvichak Bay sampling areas. These areas are on the edge of the area of apparent maximum larval concentration found during June.

Larval transport by water currents is the apparent mechanism determining the distribution of premetamorphic king crab larvae (Armstrong, et al. 1983b; Haynes 1974; Hebard 1959). It is possible that larvae are transported by near-surface as well as bottom currents, as indicated by the diurnal vertical distribution patterns found during this study (Section 3.2.2). The appearance of young-of-the-year king crabs in the Port Moller-Port Heiden area between June and September is easily explained using the available current data that show a slow counter-clockwise movement along the North Aleutian Shelf (Haynes 1974). More difficult to explain is the occurrence of young-of-the-year crabs in the upper reaches of Kvichak Bay since pelagic larvae were not found in that subarea. No current data are available for Kvichak Bay except the general westward drift of low salinity surface water originating primarily from the Kvichak and Nushagak Rivers.

4.5 Potential Effects of Oil and Gas Development

Theoretical considerations of potential oil and gas development impacts on marine species have been discussed previously for the St. George Basin (Hameedi 1982) and the North Aleutian Shelf (Thorsteinson 1983) in the southeastern Bering Sea. Several workshops held at Asilomar, California (1980) and at Anchorage, Alaska (1981, 1982) considered the impact of oil in this region on commercial crustaceans, notably Tanner crab and red and blue king crab. Largely as a result of these meetings at which biological information on the species was summarized in regards to potential oil impact, shortcomings in available information crucial for oil impact assessment were identified and projects such as the present study were initiated. Consequently, literature dealing with potential hydrocarbon impacts on crab and shrimp of the southeastern Bering Sea has been reviewed several times over recent years (Armstrong, et al. 1981a, 1983a,b; Curl and Manen 1982). These reviews have considered both the physiological/biological sensitivity of crustaceans to hydrocarbons and the ecological vulnerability of selected species. The following discussion is limited to potential impacts of oil spills.

A consensus that red king crab along the NAS and blue king crab around the Pribilof Islands are species of high ecological vulnerability (Armstrong, et al. 1983a) prompted OCSEAP to support research that would better portray the general ecology of these species (e.g., distribution and abundance over different substrate types), and establish links between the population dynamics and year class strength of larvae, juveniles and mature females. As noted by Armstrong, et al. (1983b), the relative interannual variability in temporal and spatial population dynamics of larvae should be considered in terms of: 1) female stocks as the origin of hatch; and 2) young benthic juveniles as the final location of pelagic survivors. This theme has been expanded in the current study and serves as a basis for discussing potential oil impacts to red king crab in the NAS-Bristol Bay region.

The approach taken in this analysis is one that considers major life history stanzas of the species in regards to important biological and ecological traits, and discusses the modes and extent of oil pollution as it may affect these stages. Use of life history stanzas is considered a sound categorical division for comparing and contrasting physiological, reproductive and ecological changes that occur during a life cycle (Wooster 1983). Armstrong, et al. (1983b) have provided a review of oil impact literature and interpreted their data in light of these life history stanzas. The assertions and hypotheses of Armstrong, et al. (1983b) have been modified in accordance with the field data acquired during the present study.

4.5.1 Oil Transport Models and Impact Scenarios

Before relating the biology of red king crab to predictions of oil impact, it is important to first discuss the physical transport of oil both horizontally and/or vertically by currents, winds and biological processes. A brief recount of oil impact scenarios used at OCSEAP synthesis meetings will illustrate the locations and magnitude of oil pollution considered to be representative of possible spills along the NAS and in the St. George Basin. These scenarios will serve as a point of reference in framing estimates of species' vulnerability based on data in this report.

Two models of physical transport processes, water movements and biological interactions and responses to oil in the Bering Sea have been constructed (Leendertse and Liu 1981; Sonntag, et al. 1980). Several models of water transport and circulation have been based on net current directions and velocity (Hebard 1959; Kinder and Schumacher 1981b), and on methane profiles (Cline, et al. 1981).

Hebard (1959) described currents moving to the northwest through Unimak Pass, with a component then moving northeast along the North Aleutian Shelf. Although the direction of the current is highly variable and

to a great extent tidally driven, there is a net movement of 2.0-5.5 cm sec^{-1} eastward and northward into Bristol Bay. Kinder and Schumacher (1981b) and Schumacher and Reed (1983) summarized data for current patterns in the southeastern Bering Sea and showed weak currents of 2-5 cm sec^{-1} along the NAS and 1-5 cm sec^{-1} moving northwest over the St. George Basin (Figure 4.1-3). They stressed that instantaneous flow can be substantially greater than these averages (up to twenty times greater than the long-term vector) and the direction quite variable. Cline, et al. (1981) used methane profiles to calculate current speeds of 7 cm sec^{-1} northeast along the NAS and 5 cm sec^{-1} northwest over the St. George Basin. Both values are in close agreement with current meter readings.

In the area of the present red king crab study, Bristol Bay encompasses two well-defined water masses separated by a frontal system at approximately the 50 m isobath (Figure 4.1-3; Iverson, et al. 1979, Kinder and Schumacher 1981b). Shoreward of the 50 m isobath is the coastal domain where waters are vertically homogeneous and turbulent due to wind and tidal mixing. There is little horizontal mixing across the density gradient of the frontal system, particularly at depth, but surface waters of the coastal domain may deviate from a strict counter clockwise pattern to move northward across the middle shelf domain in summer (L.K. Coachman, Dept. Oceanography, U.W., pers. communication).

The middle shelf domain between 50 and 100 m is characterized as a stratified two-layered system of cold residual water that is heated and mixed to variable depths by radiation and wind in the spring and summer. This water mass is portrayed as an essentially stationary barrier that deflects coastal currents to the northeast toward Kvichak Bay and then west to Cape Newenham.

The physical properties of these water masses in regard to temperature, food supply, and rate and direction of currents are of major importance for assessing their relative value to larval production and survival.

Such information can be used to gauge the movement of crab larvae in currents relative to origins and surface speeds of oil movement. These exercises have been done by Leendertse and Liu (1981) and Sonntag, et al. (1980).

Following hypothetical oil spills or well blowouts in these models, oil is moved by winds and currents, mixed by storms, and transported to the benthos by several processes. It may then impact crab populations by direct exposure, loss of food and over-competition, or accumulation in tissues and gametes. Oil concentrations in the water column and benthic sediments are modeled as a function of the magnitude of an initial oil spill and its duration, time of year, location, and loss of certain oil fractions by processes such as volatilization. Model outputs show the trajectory and extent of oil coverage and concentration at various times after each hypothetical mishap. From data and assumptions on lethal levels, distribution and abundance of animals, sensitive life-history stages and physiological events (e.g., molting of crustaceans), predictions are made of the proportion of a year-class or population killed and the eventual ramifications such losses pose to commercial fisheries.

Scenarios considered by participants of the 1981 Anchorage OCSEAP Workshop included only spills or blowouts that released 50,000 barrels (bbl) which is a quantity far less than might be expected from mishaps involving modern tankers. Oil spill in scenarios used during the North Aleutian Shelf synthesis meeting in Anchorage (March 1982) were even smaller. Spills of 10,000 bbl were modeled by Pelto and Manen (1983) and covered relatively small areas of the NAS (20 km by less than 1 km).

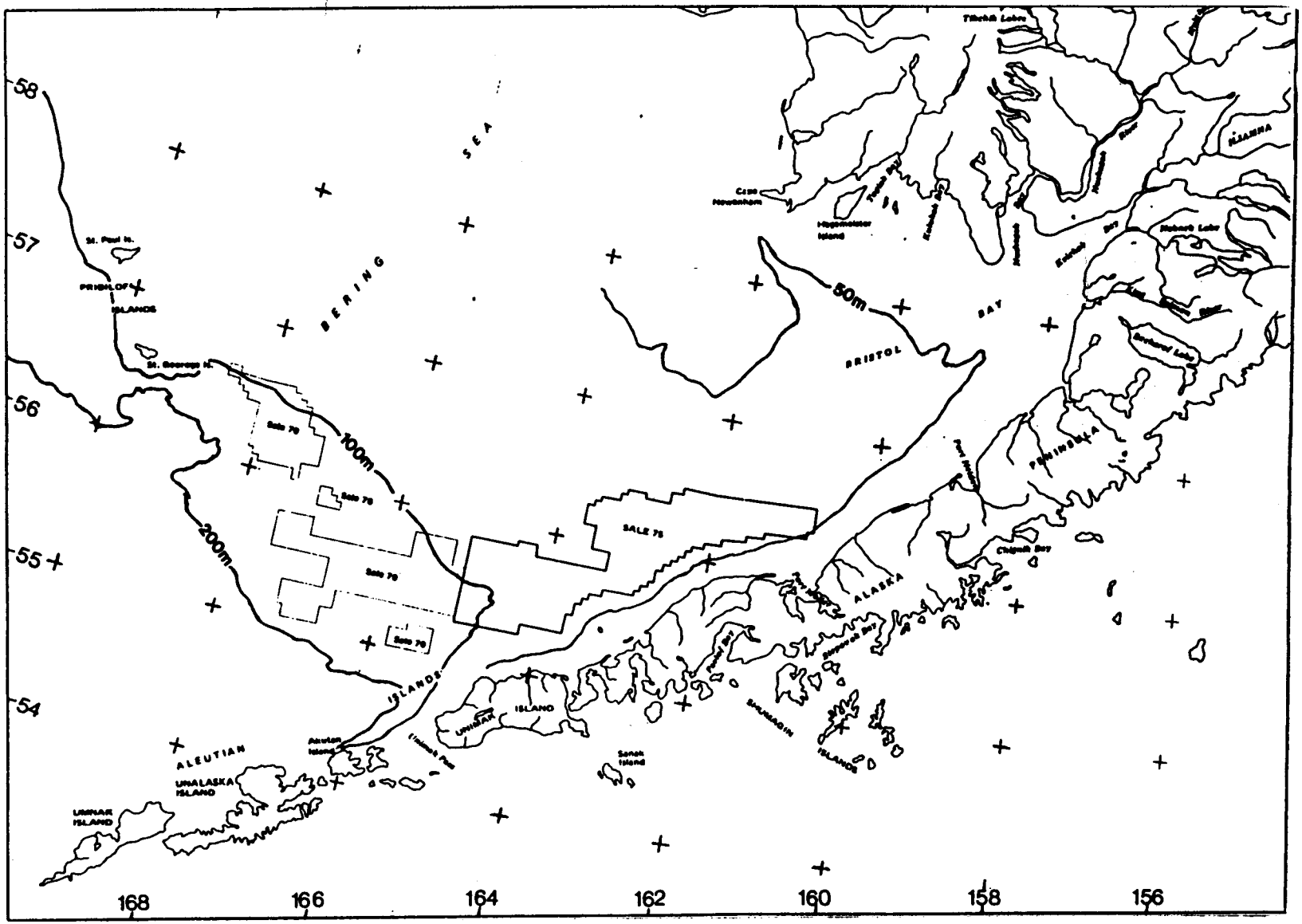
Spill scenarios modeled by the 1980 Asilomar Workshop included both a 100,000 mt (1.11×10^6 bbl) spill over two days and a release of 5,000 mt day^{-1} (55,500 bbl) for 20 days (Sonntag, et al. 1980). After mixing oil to 50 m depth and a loss of 25 percent of the volatile fraction, an area of 7,500 km^2 was polluted at or above 0.2 mg l^{-1} (considered a lethal threshold in that model). If as suggested by Armstrong, et al.

(1983b), the same volume of oil is mixed to 20-30 m and 0.05-0.1 mg l^{-1} is considered toxic to crab larvae, then an area of 15,000 km^2 might be affected. Curl and Manen (1982) predicted that a 50,000 barrel spill in the St. George Basin would be lethal over a 100-300 km^2 area (0.2 mg l^{-1} threshold; mixed to 50 m). In a worst-case scenario, mixing oil less deeply and considering oil concentrations of 0.05-0.1 mg l^{-1} water soluble fraction (WSF) to be toxic, then water over an area of 10,000-15,000 km^2 might contain concentrations toxic to crab larvae following a large spill.

In order to study the direction of surface oil trajectory following oil spills from lease sale areas in the SEBS (Figure 4.5-1), Leendertse and Liu (1981) ran computer simulations based on average wind events in winter and in summer (Figure 4.5-2). During summer and fall, oil from spills in the St. George Basin and along the NAS would be moved by prevailing winds east over the middle shelf and south to the North Aleutian Shelf coast at Unimak Island eastward for 200 km (Figure 4.5-2A). In the winter, oil would be transported northwest off the shelf or towards the Pribilof Islands (Figure 4.5-2B). Most sigificantly, the rate of movement in summer is predicted to be about 8.5 km day^{-1}, much faster than the net current transport of crab larvae along the NAS, which is estimated to be between 1.4 and 3.4 km day^{-1}. Further, surface borne oil can be moved east by winds over the surface of the middle shelf domain to the coastal domain, even though the water masses exchange very little water through advective processes. Easterly movement of oil from the NAS lease sale area in late spring and summer would move hydrocarbons towards major population centers of all red king crab life history stanzas.

4.5.2 Oil Toxicity to Red King Crab Life History Stanzas

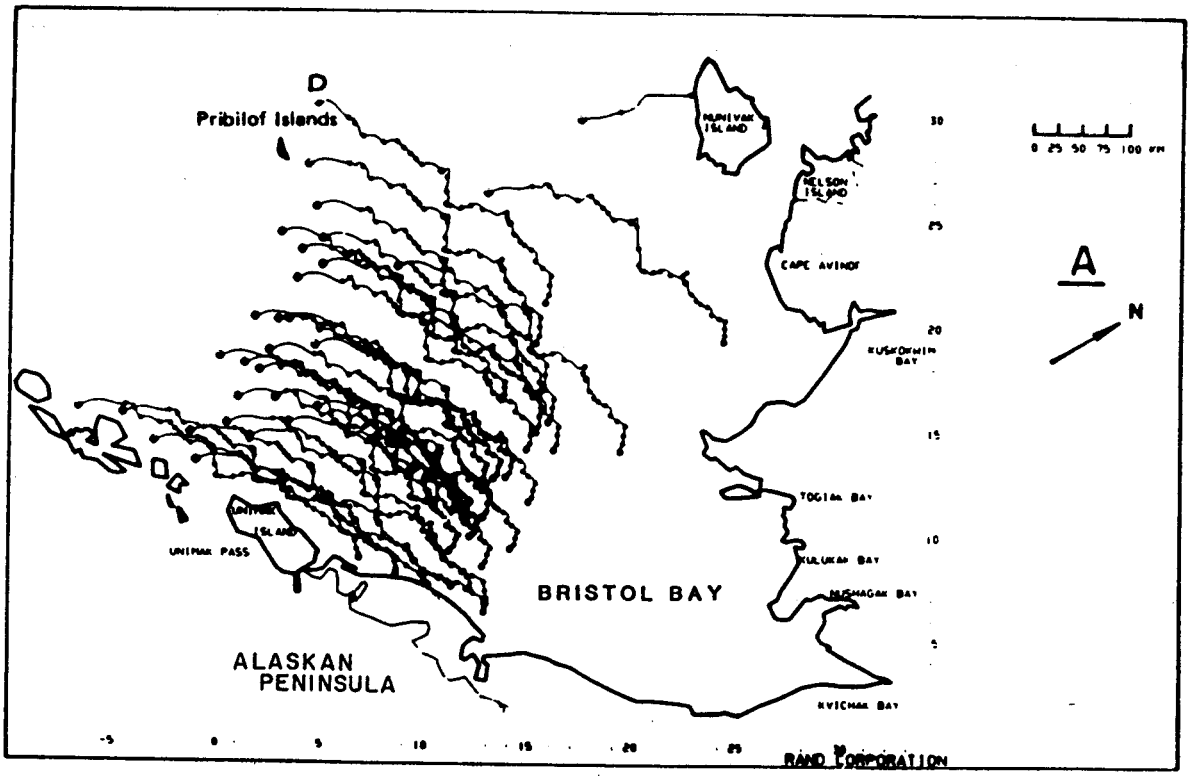
The king crab life history stanzas covered in this analysis are: 1) sexually mature females; 2) developing eggs; 3) pelagic larvae; and 4) young juveniles as 0+ (including young-of-the-year) to 2+ age groups.

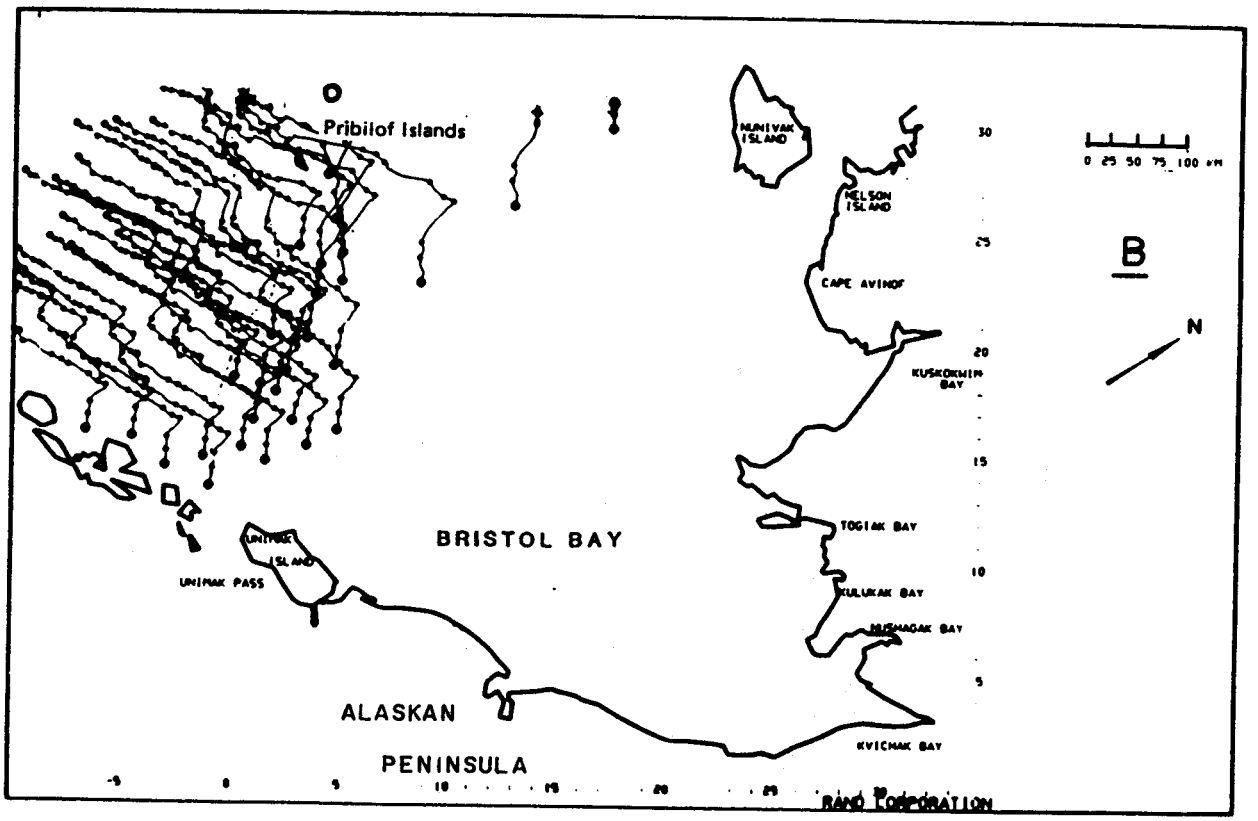


BRISTOL BAY RED KING CRAB

LEASE SALE AREAS IN THE SOUTHEAST BERING SEA

FEBRUARY 1984 | FIGURE 4.6-1





A = SURFACE OIL TRAJECTORIES DURING SUMMER.

B = SURFACE OIL TRAJECTORIES DURING WINTER.

(BOTH FROM LEENDERTSE AND LIU 1981)

BRISTOL BAY
RED KING CRAB

SURFACE OIL TRAJECTORIES IN THE SOUTHEAST BERING SEA

VTN

FEBRUARY 1984 | FIGURE 4.5-2

Other categories such as mature males and subadult juveniles have been adequately discussed in other reviews (Armstrong, et al. 1983b; Hayes 1983).

Sexually Mature Females

The relationship of sexually mature female crab to annual reproductive success and year class strength takes several forms in this analysis. First, it is assumed that some sort of spawner-recruit relationship does exist (e.g., Reeves and Marasco 1980) and that natural female abundance could decline to a point where extraneous perturbations such as oil would significantly exacerbate already low production of larvae. Second, the geographic location of spawning female stocks is of great significance to survival of young-of-the-year juveniles because water conditions in different areas may result in differential survival of larvae. Third, the origin of hatch partially determines the locations of megalopae at the time of metamorphosis and settlement to the benthos; the type of benthic material onto which juveniles settle is critical for initial survival.

Direct Effects on Adults. Oil effects on aquatic organisms may be manifested in several ways (Curl and Manen 1982): 1) rapid mortality resulting from acute exposures to high doses via external contact, inhalation and asphyxiation, or assimilation of hydrocarbon compounds that become toxic at a cellular and biochemical level; 2) bioaccumulation of sublethal amounts that may cause a decline in general vigor and are likely be lethal to the organisms (evidenced in reduced growth, susceptibility to disease, inhibition of feeding); 3) impaired reproduction, reduced broods and viability of progeny; 4) carcinogenic and mutagenic causes of tumors and morphological abnormalities; and 5) uptake of hydrocarbons causing tainting of commercial crab sold as food.

Overt, rapid mortality of adult crabs, including mature females, could be caused by exposure to rather high levels of hydrocarbons (notably the WSF) dissolved in water and via uptake into tissues and accumulation in certain organs. As a second mode of toxicity, water insoluble hydrocarbons mixed to the bottom and covering the benthos could kill crabs by actual coverage of the body and mechanical impairment of respiration and feeding. Toxic levels of WSF have not been well established for adult king crab, although it is known that adult stages are much less sensitive than are larvae and juveniles (Rice, et al. 1979; 1983; Armstrong, et al. 1983a). An approximate range of 96 hr LC_{50} values for adult crab is 4 to 8 mg WSF l^{-1} (Rice, et al. 1979). This is a rather high water concentration and may be found only in the immediate vicinity of a spill. Models of oil transport invariably account for rapid volitalization of a large fraction of the hydrocarbons and dilution of the remaining WSF, so that resultant concentrations are less than 1.0 mg l^{-1} only a few kilometers from a point source (Armstrong, et al. 1983b; Curl and Manen 1982). Since adult crabs are epibenthic, it seems unlikely that sufficiently high levels of oil WSF would affect a large area. Given the distribution of mature females in the SEBS that exceeds an area of 50,000 km^2, it seems unlikely that a majority of the adult populations would be significantly impacted via acute toxicity of the WSF.

Mixing and vertical transport of oil to the benthos might pose an alternative route of exposure of adult females to hydrocarbons. Whether or not a significant portion of the population would be acutely stressed is, again, related to the area affected. Transport models of Sonntag, et al. (1980) and an analysis by Curl and Manen (1982) predict that 5-16 g oil m^{-2} could reach the bottom. The toxicity of this to adults is difficult to gauge, but Armstrong, et al. (1983b) suggested that, over long exposures of several months, such levels would likely impact developing eggs more than adults (see Effects on Reproduction). Since most scenarios for the SEBS have dealt with small spills (e.g., 10,000 bbl spilled off the NAS covered an area of about 8 x 20 km), adult

populations are probably well protected from benthic pollution by virtue of the vast size of the species range.

Ecological Vulnerability of Females. One proviso must be integrated into the topic of acute toxicity. The NAS lease sale area lies adjacent to the coastal domain of the Izembek Lagoon and Port Moller. Spills in this area could be driven by nearshore currents (Leendertse and Liu 1981) and transported northeast into shallow water. A very large spill (in excess of 500,000 bbl) could cover a significant portion of the coastal domain and, in this turbulent, well mixed system, reach the benthos in unknown concentrations. As shown for past years, a large fraction of the mature female population sometimes occurs nearshore and, thus, could be vulnerable to acute oil toxicity. If the event occurred prior to peak egg hatch in early May, then loss of those females and any resultant impact on the population would be exacerbated by loss of a portion of the annual reproductive effort. Redistribution of mature females around the SEBS on an annual basis would change the relative vulnerability of the population as far as exposure in shallow, nearshore water. Data presented in this report show a shift away from the coastline in 1983 compared to distributiuon in 1979/80, for example, and so the spatial vulnerability of mature females relative to nearshore spills would probably be reduced as a consequence.

Effects on Reproduction. The effects of oil need not be manifested in overt mortality to impact the adults and, in turn, younger stages of the species. Sublethal toxicity might perturb the population through a combination of physiological and behavioral processes that regulate reproduction. Oil in water and/or sediments could affect reproduction in several ways: 1) Sediment and infaunal concentrations of hydrocarbons become so high that feeding of crabs is curtailed either by loss of prey (clams, polychaetes, other crustaceans) and/or anorexia. Thus, energetic requirements are not met and gamete production is reduced or inhibited. 2) Hydrocarbons are absorbed and/or ingested with food and deposited in eggs and sperm. At critically high (but as yet unknown) concentrations,

viability of the gametes is impaired and normal development of embryos is arrested, resulting in greatly reduced hatching success. 3) Normal gametes are produced and eggs fertilized and extruded, but sediment hydrocarbons are absorbed directly by the lipid-rich developing embryo and remaining yolk mass. Again, at critically high tissue levels (unknown), development is arrested and the year-class weakened by virtue of poor hatch (see Toxicity to Eggs). 4) Oil WSF adversely affects chemosensory cues used for mating after the females molt, so that copulation is reduced.

The first hypothesis is predicated on the possibility that extensive mortality of epibenthic and infaunal prey would severely restrict feeding by crabs. Scenarios of oil transport to the benthos (summarized by Curl and Manen 1982) predict accumulation of amounts up to 60 g m^{-2} and resultant high mortality. Sonntag et al. (1980) predicted that annual benthic productivity ("benthic food growth rate") would reach zero at sediment oil concentrations of 8 to 16 g oil m^{-2}, well within the range of possible sediment concentrations predicted by participants of the 1981 Anchorage Workshop. In the very large spill scenario of about 500,000 bbl of oil, several thousand square kilometers could be so impacted and food resources of crabs reduced on a large scale. In addition to outright loss of prey, food consumption could be reduced by a sublethal, anorexic response to increasing tissue levels of oil as shown for lobster larvae (Wells and Sprague 1976).

Reduction of food intake by either cause could trigger an energetic imbalance in which metabolic needs account for the largest expenditure of ingested energy and little remains for tissue and gamete production (Edwards 1978). Sub-optimal temperatures might exacerbate the effect of oil on growth and energy budgets of a species as theorized by Warren (1971). Sublethal oil concentrations can act synergistically with sub-optimal temperatures to reduce energy consumption (Edwards 1978), but at the same time increase respiration even at cold temperatures (Laughlin and Neff 1977), thereby further narrowing the scope of growth.

The second hypothesized effect of oil on reproduction is caused by transfer of hydrocarbons ingested and absorbed by adults to gametes. Rapid uptake of petroleum hydrocarbons has been demonstrated in several species of crustaceans (Anderson 1975; Cox, et al. 1976; Tatem 1977). While both adult and larval stages are capable of rapid elimination of hydrocarbons accumulated via the diet, metabolic products appear to be resistant to depuration (Corner, et al. 1976; Lee, et al. 1976; Sanborn and Malins 1977). Residues amounting to 10 percent of the initial level were found in adult copepods which had been exposed for 24 hours (Harris, et al. 1977). Neff, et al. (cited by Varanasi and Malins 1977) found rapid accumulation of naphthalene derivatives by penaeid shrimp that reached tissue levels 100 times greater than those in the exposure water. Highest and most persistent residues were found in the hepatopancreas that directly supplies nutrient materials to the gonads for gametogenesis.

Transfer of naphthalene to eggs was found to occur in the marine polychaete Neanthes arenaceodentata (Rossi and Anderson 1977). Blue crab (Callinectes sapidus) ingesting radiolabeled hydrocarbons assimilated 2 to 10 percent and stored up to 50 percent of this amount in the hepatopancreas, which was the only organ assayed that still contained radioactivity after 25 days of depuration (Lee, et al. 1976). Again, a direct translocation to and biomagnification of hydrocarbons in lipid-rich gametes is possible, although not well studied. Sufficiently high hydrocarbon levels in egg yolk and developing embryos could cause abnormal development.

A final sublethal stress encountered by mature females exposed to oil which could impair copulation and result in a high proportion of infertile egg masses is that related to chemoreception. As previously described, a sexually mature male locates and embraces a female just prior to her molt and they copulate immediately thereafter. Failure to copulate within five days post-ecdysis results in infertile egg masses. Location of a female partner is based on strong pheromone cues that are

detected by chemosensory organs. Pearson, et al. (1980) demonstrated that Dungeness crab can detect hydrocarbons at a level of a few ug l^{-1}. Following an oil spill, water concentrations may exceed 100-200 ug l^{-1} (Hood and Calder 1981), and might impair chemosensory location of females or otherwise alter behavior to reduce breeding within the population.

Developing Eggs

Although larvae are pelagic, the eggs from which they hatch and their prior embryonic development occurs in the benthos and spans up to 11 months for red king crab. Uptake of hydrocarbons by eggs directly from bottom or interstitial water may adversely affect development of embryos. No studies of direct hydrocarbon uptake by crab or shrimp eggs and embryos are available, but transfer of naphthalenes to brooding eggs (high in lipids) was reported to occur in the marine polychaete Neanthes arenaceodentata (Rossi and Anderson 1977), while absorption from sea water occurred (independent of adults) in eggs of the Pacific herring (Eldridge, et al. 1978). The lethal effect such exposure can have on developing embryos was shown by Tatem (1977) who subjected gravid female shrimps (Palaemonetes pugio) to 1.44 mg l^{-1} WSF for 72 hours. One week later control females released an average of 45 larvae each while those exposed to oil released only nine each. Further studies of oil toxicity to developing eggs is warranted in light of possible oil impact to red and blue king crabs that reproduce in relatively shallow, near-shore areas. Since oil degrades slowly in the sediments of very cold arctic waters (Butler and Levy 1978; Curl and Manen 1982; Mayo, et al. 1978), and since female king crabs brood eggs for 11 months, protracted exposure of eggs to hydrocarbons can result from oil spills that reach reproductive grounds.

In oil spill scenarios discussed at North Aleutian Shelf synthesis meeting (Thornsteinson, in press) and in previous discussions in this section, the greatest threat from oil to developing eggs comes in the

nearshore area of the coastal domain, particularly if the annual proportion of spawning females is high in that region. Whether females that hatch eggs within the coastal domain in spring are present there throughout egg maturation is unknown. It can be argued that a nearshore location has the advantage of warmer bottom water as a stimulus to faster development than found in the middle domain. It may directly benefit the female to feed nearshore through the summer and fall if food and temperatures are more conducive to faster growth and ovarian development for the next annual egg mass. If these females do not undergo annual onshore/offshore migrations, then year-round residence in the shallow coastal domain following a large spill could result in a chronic exposure to eggs to hydrocarbons.

Pelagic Larvae

This life history stanza is considered by many to be the most susceptible to oil pollution (Armstrong, et al. 1981b, 1983a,b; Curl and Manen 1982; Rice, et al. 1983). Such high vulnerability may reflect several relationships of larvae to oil that are unique compared to benthic stages. First, larvae are pelagic and as such, are situated in the water column close to spilled oil on the water surface. Second, they have a high frequency of molting which is a physiologically stressful process during which they are more susceptible to pollutant toxicity (Armstrong, et al. 1976). Third, they have a high surface area to volume ratio which may result in faster rates of uptake than occur in larger stages. Further, as developing larvae, they may not have the biochemical/cellular protection such as mixed function oxidases found in larger animals (Malins 1977a,b).

Oil Toxicity. A wealth of information on oil toxicity to marine invertebrates has been made widely available (Malins 1977a; Wolfe 1977). Many investigators have been specifically concerned with sensitivity of larval crustaceans (Bigford 1977; Caldwell, et al. 1977; Cucci and Epifanio 1979; Tatem 1977; Wells and Sprague 1976). Karinen (1981) and Rice, et al. (1983) have reviewed toxicity of oil to Pacific Northwest

and Alaskan species of shrimp and crab including Dungeness crab, king and Tanner crab, and pandalid shrimp. Rice, et al. (1976) and Vanderhorst, et al. (1976) reported that 96 hr LC_{50} values for juvenile and adult pandalid shrimp range from 0.8-11.0 mg l^{-1} WSF. Pandalid larvae, however, are a more sensitive life history stage as evidenced by 96 hr LC_{50} values from 1.0 mg l^{-1} WSF down to 0.3 mg l^{-1} for single aromatic compounds such as naphthalene (Mecklenburg, et al. 1977; Rice, et al. 1976, 1979). Sublethal effects including failure to swim and/or molt inhibition occurred at concentrations from 0.7 to 0.3 mg l^{-1} WSF. A 96 hr exposure of pandalid larvae to 0.6 mg l^{-1} WSF caused a 70 percent reduction in molting from SI to SII (Mecklenburg, et al. 1977). Dungeness crab zoeae were susceptible to WSF as low as 0.22 mg l^{-1} (Caldwell, et al. 1977). Larval king and Tanner crab are equally sensitive to hydrocarbons. Death of Paralithodes camtschatica larvae or failure to swim was caused by WSF of 0.8 to 2.0 mg l^{-1} (Brodersen, et al. 1977; Mecklenburg, et al. 1977), and Chionoecetes bairdi larvae were immobilized by a 96 hr exposure to 1.7 mg l^{-1} WSF (Brodersen, et al. 1977).

Studies with other larval decapods indicate that toxic oil concentrations may be even lower than those discussed above when based on assays of single hydrocarbons, exposures longer than 96 hr, or based on sensitive sublethal criteria. Larval lobster (Homarus americanus) ceased feeding at 0.19 mg l^{-1} WSF and had a 30-day LC_{50} value of 0.14 mg l^{-1} (Wells and Sprague 1976). Specific compounds such as naphthalene are very toxic and caused narcotization followed by death of pandalid shrimp and crab larvae at concentrations of 8-12 ug l^{-1} during exposures of less than 24 hr (Sanborn and Malins 1977). Toxic oil concentrations range as low as 0.15 mg l^{-1} WSF and may be somewhat lower for specific compounds. Moore and Dwyer (1974) give a sublethal range of 0.0011-0.1 mg l^{-1} WSF as stressful to larvae. Wells and Sprague (1976) suggest a multiplier of 0.03 should be applied to LC_{50} concentrations to establish "safe" levels; this would result in acceptable concentrations less than 1 ug l^{-1}. Armstrong, et al. (1983b) suggest that the toxic threshold value of 0.2 mg l^{-1} WSF used in oil spill scenarios be lowered to 0.05 to 0.1 mg l^{-1} in light of this evidence.

Ecological Vulnerability. Armstrong, et al. (1983b) discussed in detail the types and magnitudes of stress that could affect larvae, and also the spatial and temporal vulnerability of this stage. They criticized some assumptions about larval biology used in previous models to predict oil impact (e.g., Sonntag, et al. 1980), and updated biological information obtained through 1983 in order to better portray possible oil stress. Information on larvae obtained during the present study helps to substantiate conclusions made by Armstrong, et al. (1983b) and improves a sense of the relationship between larval settlement and young juvenile distribution nearshore. Yet, the relative importance of nearshore, coastal domain larvae is not so clear given the higher offshore densities found over Bristol Bay in June 1983.

This life history stanza still seems particularly susceptible to oil pollution given physiological, ecological and spatial characteristics of larvae. Data through 1982 indicate that a major portion of the larval population occurs along the 50 m isobath and probably is transported by long-shore currents to the northeast as hypothesized by Hebard (1959), Haynes (1974) and Armstrong, et al. (1983b). Although the frontal system depicted by Kinder and Schumacher (1981a) is not as well studied along the NAS as in upper Bristol Bay, its integrity might be such as to entrain subsurface oil at the front with resultant transport concurrent with larval crab. Cline, et al. (1981) concluded from methane profiles originating from Port Moller that material rarely penetrated more than 20 km offshore and was mostly entrained shoreward of the 50 m front while moving to the northeast, thus substantiating the notion of a strong front in this region. While movement of oil as a surface film by winds results in extensive coverage within brief time periods in the models of Leendertse and Liu (1981) and Pelto and Manen (1983), mixing of oil into the water column along the 50 m isobath might pose a more serious threat to red king crab larvae along the NAS for 10-20 days after a spill.

Larval distribution and abundance in April and June 1983 furnish new information on three points: 1) there is probably considerable

interannual variability in abundance and distribution of larvae; 2) signficant densities of larvae occur seaward of the inner front over the middle shelf domain between 50-70 m; 3) there is evidence that larvae may undergo a diel vertical migration but are not abundant in the upper 10 m.

The scarcity of larvae in 1983 along the entire nearshore perimeter ($\leq$50 m) of Bristol Bay indicates that weak annual production can occur. Densities were 30-fold less between Izembek Lagoon and Cape Seviavin in 1983 than in 1982, a reduction that mirrors NMFS estimates of substantially fewer mature females at the same time. Whether or not the strength of the 1983 benthic juvenile year class is correspondingly weak will not be known for several years. Nonetheless, larvae surviving through the megalope stage metamorphosed to benthic instars at several locations inside 50 m along the NAS, and they were caught in September 1983 (see Figure 3.5-6). This fact further substantiates the importance of nearshore coastal waters to larval production and survival, perhaps even more so in a year of low hatch. A major oil spill in or adjacent to the nearshore coastal domain would significantly threaten a larval year class if, as in 1983, natural production were already low, and oil pollution were to compound zoeal mortality that is probably already high via natural processes. The greatest concern in this equation of larval production versus young-of-the-year juvenile strength, is the magnitude and location of megalope at metamorphosis.

Occurrence of larvae over central Bristol Bay at intermediate densities (relative to nearshore abundance in 1982) between 50 m and 70 m (Figures 3.2-2 and 4.1-1) may confirm earlier observations (Armstrong, et al. 1983b; Haynes 1974) that production occurs in this area. The link between offshore larval cohorts and young-of-the-year nearshore juveniles is still not clear. As previously stated, based on models of prevailing currents and trajectories of transport, larvae from this area would not likely reach nearshore locations along the NAS. If the offshore larvae develop in place and settle to the benthos of central

Bristol Bay, resultant mortality is likely to be so high that the cohort contributes little to the juvenile year class. From this line of thinking, it can be argued that oil pollution and mortality of larvae in the 50-70 m central Bristol Bay region is of little consequence. From a contrary perspective, the offshore cohort could be a vital source of juveniles that settle to Kvichak Bay. Numbers of juveniles and repeating year classes in this area suggest that the far eastern end of Bristol Bay is significant to juvenile recruitment (this point should be given a high priority in future work).

Armstrong, et al. (1983b) criticized models of oil impact on decapod larvae (Curl and Manen 1982; Sonntag, et al. 1980) that mixed oil to a depth of 50 m and argued that larvae would invariably move near (or away from) the surface over a period of several days. Data from the present study suggest such vertical movement might be a regular daily event. The point relative to oil impacts is that a given volume of oil could be more toxic to a population near the surface if spread rapidly in a horizontal plane and mixed to a depth of, say 20 m. Behavior of the larvae would repeatedly bring them in contact with this layer containing higher pollutant concentrations.

A further ecological consideration raised by Armstrong, et al. (1983b) is whether hatching is synchronized along the NAS and, in turn, whether one or several cohorts are produced annually. They criticized earlier assumptions about timing of hatch used by Sonntag, et al. (1980) to model oil impact at the critical point of the larval stanza. Rather than a protracted hatch over the three months of April, May and June (20%, 60% and 20% per month of yearly total), data from 1982 and 1983 indicate that, within a wide geographic area (e.g., Unimak Island to Cape Seniavin), the larval year class is hatched over a short period of 2-3 weeks. Since hatching seems to be a well-synchronized event, a major oil spill that affects a significant proportion of a larval year-class would not be mitigated by a later hatch of larvae after oil disperses below toxic levels. For example, first stage king crab zoeae

that are killed by oil north of Unimak Island in late April could not be replaced by other first stage zoeae hatched later in the same area (although they may be replaced by larvae also hatched in April and subsequently transported to the affected area).

An exception to this statement, is the observation that offshore larvae in the 50-70 m central Bristol Bay area were a cohort which may have hatched about three weeks later than those nearshore. Again, it is not known if this population adds to nearshore juvenile recruitment and in so doing, could mitigate the loss of nearshore larvae to oil pollution.

Young Juveniles

An important but poorly studied life history stanza in the southeastern Bering Sea is newly settled juveniles up to two years old. Their susceptibility to oil pollution may be very high, in part, because of highly restricted distribution in critical but scarce habitat. Very young juvenile king crabs (less than two years old) in the Kodiak region prefer rocky, cobble habitat that affords shelter from predators (Feder 1978;, Jewett and Powell 1981). Very little habitat of this type exists along the NAS (Michel, et al. 1982) and young-of-the-year (0+) juveniles that settle on open bottom are probably vulnerable to heavy predation. Thus, any habitat that offers protection to young crabs is critical to benthic survival. During an intensive search for 0+ and 1+ juvenile king crabs along the NAS in June, August and October 1982, the only specimens of this size/age category were taken around Amak Island off Izembek Lagoon (W. Pearson, Battelle Northwest, pers. comm.)

It was the apparent scarcity of 0+ and 1+ juveniles during the 1982 cruises that led OCSEAP to fund this more systematic and broadscale survey in 1983. During all three cruises conducted during the present study, juveniles were patchily distributed and were associated with rather specific substrates that apparently afford shelter (Section 3.4). Areas off Port Moller, Cape Seniavin, Port Heiden, and in Kvichak and

Togiak Bays where young juveniles were caught, are all in water less than 50 m. The centers of juvenile abundance are fairly far to the northeast of the NAS lease sale area and beyond the predicted reach of oil pollution in scenarios of the NAS synthesis workshop (Armstrong, et al. 1983a). However, the paucity of young juveniles between Unimak Island and Port Moller may reflect the shift of females away from this area and, thus, reduced larval hatch compared to historic levels.

The question of spatial vulnerability of young juveniles is difficult to gauge without a sense of final lease sale sites and how close to important juvenile centers oil development might be located. A more meaningful analysis of this question should simultaneously consider habitat requirements of the juveniles. Based on 1983 data, the following conclusions can be drawn: 1) 0+ to 1+ juveniles are most abundant in water less than 50 m within the coastal domain; 2) they are most common on a substrate that offers refuge from predators as well as food (e.g., small cobble, shell hash, living biological material); 3) not all areas have the same number of co-existing juvenile year classes which suggests that the extent of annual larval dispersal and subsequent juvenile settlement is variable; 4) there are areas of relatively high juvenile abundance in eastern and northern Bristol Bay where no larvae were found in 1983, and 5) the relationships of such settlement areas to larval production and transport is unknown.

Given the apparently patchy and limited habitat of young juveniles, its location in the mainstream of nearshore currents, and shallow depths, it seems possible that oil from a large spill could reach juvenile locations around Port Moller and Cape Seniavin and be mixed to the bottom; whether toxicity would ensue is arguable. Heavy oiling of the benthos to the extent discussed by Curl and Manen (1982) and Sonntag, et al. (1980), at about 8-16 g m^{-2}, could be acutely toxic as a coating or as high WSF concentration at the sediment surface. Such heavy benthic contamination would be limited to a much smaller area than covered by surface oil, and likely would not affect a significant portion of the entire NAS or Bristol Bay juvenile population.

Long-term, sublethal effects may also not pose a great threat except in the immediate vicinity of a spill. Experiments conducted in 1982-1983 at the Auke Bay NMFS lab studied the survival and growth of young juvenile king crab fed oiled food (mussels) or kept on oiled sediment. In neither experiment did juveniles seem to be adversely affected based on preliminary analysis of data (J. Garrett, S.D. Rice, C. Broderson, NMFS Auke Bay Lab, pers. communication). In another experiment designed to study sublethal effects of oil in water (WSF) to crab, energetic criteria were used to compare relative scopes for growth (Warren 1971) between treatments. At high but sublethal WSF consentrations, juvenile crab had reduced feeding rates and therefore consumed less (T. Shirley, Univ. Alaska Juneau, pers. communication). This situation, if prolonged, would inhibit growth and survival, but the former results indicate that juvenile crab may be fairly resistant to oil exposure via food and sediments.

Although longevity of oil in sediments is great, it is not known whether there is a constant leaching of the WSF in toxic quantities into overlying water. Given a tremendous capacity by the system to dilute toxicants emanating from a point-source, it seems unlikely that oil at toxic levels would chronically affect a benthic community much beyond the confines of the immediate polluted area. An estimate of adverse effect might be reduced to a calculation of the proportion of habitat polluted relative to the total occupied by the species during any life-history stanza.

SECTION 5.0

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APPENDIX A:

MEAN LARVAL RED KING CRAB DENSITIES BY STAGE, CRUISE AND SUBAREA

APPENDIX A

MEAN LARVAL RED KING CRAB DENSITIES BY STAGE, CRUISE AND SUBAREA [a]

	STAGE 1	STAGE 2	STAGE 3	STAGE 4	STAGE 5
CRUISE 83-1 (APRIL-MAY)					
IZEMBEK	0.81	0.00	0.00	0.00	0.00
PORT MOLLER	5.12	0.10	0.00	0.00	0.00
PORT HEIDEN	0.65	0.00	0.00	0.00	0.00
KVICHAK BAY	0.00	0.00	0.00	0.00	0.00
TOGIAK BAY	0.03	0.00	0.00	0.00	0.00
OUTER BRISTOL BAY	0.39	0.00	0.00	0.00	0.00
CRUISE 83-2 (MAY)					
IZEMBEK	0.09	4.24	0.12	0.00	0.00
PORT MOLLER	6.85	50.71	10.23	0.80	0.00
CRUISE 83-3 (JUNE)					
IZEMBEK	0.05	0.21	0.20	0.11	0.00
PORT MOLLER	0.05	0.41	0.96	1.09	0.00
PORT HEIDEN	0.00	0.08	0.28	0.75	0.00
KVICHAK BAY	0.00	0.30	1.20	0.13	0.00
TOGIAK BAY	0.52	0.74	0.70	0.17	0.00
OUTER BRISTOL BAY	0.19	2.12	13.26	11.74	0.00
CRUISE 83-5 (SEPTEMBER)					
IZEMBEK	0.00	0.00	0.00	0.00	0.00
PORT MOLLER	0.00	0.00	0.00	0.00	0.00
PORT HEIDEN	0.00	0.00	0.00	0.00	0.00
KVICHAK BAY	0.00	0.00	0.00	0.00	0.00
TOGIAK BAY	0.00	0.00	0.00	0.00	0.00
OUTER BRISTOL BAY	0.00	0.00	0.00	0.00	0.00

(a) Means are geometric.

APPENDIX B:

TRAWL GEAR TYPES USED BY CRUISE AND STATION

APPENDIX B

TRAWL GEAR TYPES USED BY CRUISE AND STATION

Station	Cruise 83-1	83-3	83-5	Station	Cruise 83-1	83-3	83-5
BB190	T			PM360			
BB199	T2			PM370	T	T	T
BB250	T2			PM440		T	
BB270	T,R			PM540		R	
BB299	T2	T		PM620	R	T2	T
BB340	T			PM630		T	
BB370	R			PM650	R	T2	T
BB390	T			PM660			
BB440				PM670	T	T2	T
BB450	T	T		PM730	R2	T2	T4
BB480	T	T		PM735		R	
BB557	T	T		PM740		R2	
BB555		T		PM745		T,R	
BB560		T		PM750		R2	
BB665		T		PM820	R2	T	T
BB670		T		PM830	R	T	R
BB760	T	T,R	T	PM850	R	T	T
BB770	T	T	T	PM870			
IL130	T	T		PM920	T	T	T
IL150	T	T	T	PM930	R	T	T
IL160	T	T		PM950	R	T	T
IL220		R		PM970			
IL230		T	R	PM010			T3
IL260		R	T	PH120			T
IL270		T		PH130	R	T	T
IL320	T			PH150	T	T	T
IL330	T,R			PH220	R	T,R	R
IL350				PH230	R2	T,R	T
IL370	T,R			PH250	R	T,R	T
IL420	R	R3	R	PH320	T	T,R	T
IL430	R	R	R	PH330	T	T	
IL440	R	T	T	PH350	T	T,R	T
I1470	R	T	T	TB130		T	
PM150		T		TB150	T	T	
PM320	T	T	T	TB216			T
PM330	T	T	T	TB220	R	T	
PM350	T5	T	T	TB230	R	T	

APPENDIX B

(continued)

Station	Cruise 83-1	83-3	83-5
TB250	T	T,R	T
TB329	T2	T,R2	T
TB320	R2	T2,R	T
TB330	T	T	T
TB350	T	T	T
TB429	R2	T	T
TB430	T	R	
TB431	R	T	T
TB450	R	T	T
TB520	T	T	
TB540	R	T	T
TB550	R2	T	
KB150	R	T	R
KB250	R	T	T
KB240	R	T	T
KB2*9	R	T	
KB2*8		R	T
KB2*7		R2	
KB2*6		R	
KB2*5		R	
KB2*4	R6	R	R7
KB2*3		R	
KB2*2		R8	
KB2*1			R
KB2*0	R	R	
KB330		R	
KB320	R	R	
Total	T-45	T-68	T-44
	R-45	R-42	R-15
Stations:	T-38	T-63	T-39
	R-35	R-29	R-9
Total	70	82	48

(a) Key: T = Trynet, 1 sample
R = Rockdredge, 1 sample

APPENDIX C:

TRAWL/DREDGE NOTES

APPENDIX C

TRAWL/DREDGE NOTES

Station	Haul Number	Remarks
Cruise 83-3 (June):		
BB299	01	Macoma sp. and whelk shell debris, parchment-like worm tubes. Hermit crabs in whelk shells. A C. bairdi female was infested with parasites under abdominal flap.
IL160	02	Sand dollars, sea stars, flatfish, shrimp, broken bivalves. Plenty of Cyanea.
IL150	03	Sand dollars, many Asterias amurensis, rock sole, yellowfin sole, some shell debris, fish bones. One P. camtschatica carapace, 115 mm wide by 108 mm long; clean bright shell. One large cod with very full gut; contents in advanced stage of digestion, mostly mysid or euphausiid; remains of one fish, possibly sandlance.
IL130	04	Large catch of sole, sculpins, with sand dollars, Asterias, clams. Very clean haul. Rock sole guts (4) and yellowfin sole guts contained small heart urchin tests and solitary ascidians (olive pit look-alikes). One yellow Irish lord examined for gut content: sandlance and euphausids.
IL220	05	Rock dredge contained black, coarse sand; bivalves (Astarte) and sand dollars very abundant. Drift algae and bryozoans also in haul. NOTE: the catch recorded represents the material retained in plastic fish baskets after washing; some of the very small bivalves were lost.
IL230	06	Trynet haul contained an abundance of sponge, bryozoans and gastropod shells, with associated hard-bottom fauna.
IL260	07	Rock dredge haul filled completely with gravel, fine to coarse. Bag was probably filled after first 4 minutes, as evidenced by dramatic change in wire angle. Haul included sea stars, some sand dollars, polychaetes, sandlance and hermit crabs.

APPENDIX C

(continued)

Station	Haul Number	Remarks
IL270	08	Trynet haul contained sponge (hermit crab sponge), small amount of shell debris. Both Tanner crab species, one hair crab, several flatfish species.
IL470	09	Trynet: starfish and flatfish abundant.
IL440	10	Same as Haul 09.
IL430	11	Cobble and gravel.
IL420	12	Rock dredge: barnacles (B. nubilus), jingles, gastropod shell.
	13	Rock dredge: black cobble-gravel.
	14	Same as Haul 12.
		(All of these three hauls had abundant hermit crabs, rock and other crabs.)
PM320	15	Color echo-sounder shows lots of targets in shallow (16-18 m), nearshore water. Trynet haul contained yellowfin and rock sole, pollock, cod, sculpins, sandfish, small halibut (6) and a few flathead sole. Many Asterias, some Crangonids and sea anemones.
PM330	16	Short trawl (2 min.) contained Asterias, yellowfin sole, rock sole, one longhead dab, one small halibut, some pollock and hermit crabs.
PM350	17	Trynet haul contained Asterias (62 lbs.), Evasterias (1), crangonids, pagurids and flathead sole.
PM370	18	Trynet haul contained Spisula clams and shell debris, small sand dollars, crangonids, yellowfin and rock sole, Levasterias, Asterias and Tanner crabs (opilio).
PM670	19	Trynet came aboard dripping with sea onions (Boltenia) from the footrope and chains, and a load of same in the bag. Also abundant were golden, leafy bryozoan. Levasterias and some Tanner and red king crabs (few). The usual compliment of yellowfin, rock sole and other flatfish were present.

APPENDIX C

(continued)

Station	Haul Number	Remarks
PM650	20	The trynet haul was dominated by Asterias, large brown anemones (30 lbs.), two red king crabs and the usual soles.
PM730	21	Trynet haul contained Asterias (185 lbs.), yellowfin and rock sole, few hermit crabs and one juvenile red king crab.
PM620	22	Yellowfin sole once again dominated the try net catch (100+ lbs.), with Asterias also abundant. Razor clams (7), hermit crabs and rock sole were few; one red king crab juvenile.
PM820	23	Trynet haul contained starry flounder, Asterias, mussels (being eaten by stars), rock sole and Argis (Crangonidae).
PM830	24	Trynet haul dominated by rock and yellowfin sole; a few starry flounder, Asterias, young Pacific cod and walleye pollock, and shell debris (Spisula).
PM850	25	Trynet haul contained Asterias, yellowfin sole, rock sole, Boltenia and a couple of longhead dab.
BB770	26	Very large haul. Trynet full of Boltenia (57.5 lbs.), sponge (61 lbs.), sand dollars (and epifaunal green slime), bryozoans, ascidea, red king crabs (3-4 year olds), and the usual yellowfin and rock sole.
PM950	27	Trynet contained a big skate, some large cod, stars, sea onions, and soles.
PM930	28	Trynet haul contained two juvenile red king crab, many sea onions (Boltenia), bryozoans, sea stars (38 lbs.), soles, lots of amphipods and one halibut.
PM920	29	Sea stars and flatfish once again dominated the trynet haul, with the appearance of juvenile yellowfin sole. A high diversity of fish species was noted by the scientific staff.

APPENDIX C

(continued)

Station	Haul Number	Remarks
PH130	30	A 7-minute trynet tow was dominated by sea stars and flat fish, mostly yellowfin sole and rock sole. Lower diversity than last haul.
PH150	31	No field notes.
PH220	32	Large and small yellowfin sole in this trynet haul; only small rock sole present. Small plaice and dab, sea stars, Crangon and threaded sculpin.
PH220	33	A rock dredge tow at the same station as Haul 32 came up with no substrate material, a few sea stars and some small flatfish. Must be a sand bottom (?).
PH230	34	Rock dredge haul came up with a bag one-third full of gravel. Fauna consisted of lots of Corophium amphipod tube clumps, erect bryozoans, Crossaster and Asterias, small decorator crabs very abundant, some hermit crabs. Two 6 mm red king crabs were found, one inside an empty Spisula shell, one in the gravel. Gravel was sluice sorted.
PH230	35	Trynet tow in the same area contained a diversity of organisms, including: Evasterias, a few Crossaster and Leptasterias. Corophium masses, tube worms, Balanus, yellowfin sole, small rock sole, numerous Sclerocrangon, numerous Oregonia, lots of Asterias, sponge, soft coral and others.
PH250	36	Trynet contained erect bryozoa, large Hyas lyratus, large holothuroidians, Asterias and some soles.
PH250	37	Rock dredge came up with coarse sand, Asterias, tellin clams, sea glob (Aplidium sp.), Sclerocrangon. Not a quantitative sample.
BB760	38	Rock dredge contained a very small volume of material. Boltenia ovifera, fine gravel and shell debris, basket stars, hermit crabs (P. ochotensis), and some small Hippolytid shrimp.

APPENDIX C

(continued)

Station	Haul Number	Remarks
BB760	39	No field notes.
BB665	40	Trynet: many Boltenia ovifera, Asterias; eight red king crabs (4-5 year olds), five Tanner crabs (bairdi and opilio), yellowfin and rock sole, longhead dabs and Crangon dalli.
TB550	41	Trynet haul with lots of sea onions (Boltenia ovifera), a load of large Asterias, a few small Asterias, one Tanner crab, 28 red king crabs (4-5 year olds), rock and yellowfin sole.
KB250	42	No field notes.
PH370	43	Rock dredge: sand/gravel, broken shell, Asterias, some Boltenia, amphipods, hermit crabs and Crangon.
PH350	44	Trynet haul: lots of sponge, Boltenia (56 lbs.), Asterias (119 lbs.), Evasterias, a high diversity of decapod shrimp (10 spp.), lots of crabs (Oregonia, Hyas, Tellmessus), snails, hermits, bivalves, yellowfin and rock sole.
PH330	45	A small catch in the trynet, many small Asterias, some rock and yellowfin sole.
PH320	46	Trynet: small catch of barnacles, yellowfin and rocksole, Asterias.
PH320	47	Rock dredge: gravel, sand and silt. Asterias and Crangon dalli.
KB150	48	Trynet, small catch. Yellowfin and rock sole.
KB240	49	No field data.
KB320	50	Trynet lost, doors and all.

APPENDIX C

(continued)

Station	Haul Number	Remarks
KB320	51	Rock dredge haul full of gravel and rock sole. Lots of urchins, some Tellmessus, Asterias, Henricia, Crossaster, Sclerocrangon and Crangon.
KB2*9	52	Trynet haul contained several boulders (up to 150 lbs.), one red king crab (30-40 mm), Asterias (predominantly small stars less than 20 mm dia.), threaded sculpin and many small flatfish (including three halibut).
KB2*0	53	Rock dredge contained cobble, gravel and a boulder mixed with coarse sand. Thousands of Eupentacta sp., a small cucumber, and hundreds of Pagurus beringanus. A few Crossaster, Henricia, Clinocardium and Frustula.
KB2*2	54	Rock dredge haul: rock (largest 12"x 10"x 6") and cobble (1 to 6"). Small Balanus on rocks, some Leptasterias polaris, Henricia, numerous Calliastoma, some urchins, sponge, Crangonids.
KB2*2	55	Rock dredge: small amount of 2-4" cobble with Sclerocrangon, P. beringanus, tube worms (sand) in small clumps.
KB2*2	56	Rock dredge haul: small catch; cobble. Some urchins, Calliostoma, Leptasterias, Neptunea ventricosa.
KB2*2	57	Rock dredge: 2-6" rock with Balanus, pebble tube worm, seven red king crab (10-40 mm), Crossaster, Henricia, Leptasterias, Pagurus beringanus, lobed ascidian, brightbelly sculpin.
KB2*2	59	Two red king crab. Similar to Haul 57, sponge and Margarites snail.
KB2*2	60	Rock dredge, rocky as previous hauls, no red king crabs, tube worms, several urchins.
KB2*2	61	Rock dredge, gravel to 2" rock. Five red king crabs, more barnacles than before (a subjective estimate), hermit crabs, some stars, very few tube worms. Generally less small grained material. One large clump of tundra grass, decomposing. Brightbelly sculpin, small clams.

APPENDIX C

(continued)

Station	Haul Number	Remarks
KB2*4	62	Rock dredge, small (1-2") to large (10-15") rock. Very abundant tubiculous polychaetes, two red king crabs, urchins, Sclerocrangon, Crossaster, Henricia, threaded sculpin, gastropods and hermits.
KB2*3	63	Rock dredge: gravel to small stones, a few rocks. Abundant Mytilus binding stones together. One Asterias and one Evasterias, hermits, crangonids, a few urchins, small sponge, cockle, some erect bryozoans, moon snail (Natica clausa) and egg masses.
KB2*5	64	Rock dredge. Gravel and stone, abundant mussels, larger individuals than at KB2*3, some stars, hermits and crangonids.
KB2*6	65	Rock dredge. Eight red king crabs in rock up to 2", with some larger rock. Urchins, Crossaster, Levasterias, tube worm masses, large barnacles, Hyas, Sclerocrangon, gunnel.
KB2*7	66	Rock dredge, 1-3" rocks with gravel and coarse sand. No king crabs; urchins and hermits were dominante, with Asterias, Crossaster, Leptasterias, Margarites, few Hyas, tube worms and Sclerocrangon.
KB2*7	67	Rock dredge: coarse sand and gravel with large rocks (2-8"). Urchins and tube worms abundant, with usual rock fauna, as above, present. No king crabs.
KB2*8	68	Rock dredge: medium to coarse sand and gravel, some large rocks to 8". No king crabs. Usual rock fauna.
KB330	69	No field notes.
TB450	70	No field notes.
TB430	72	Trynet: small haul, mainly yellowfin sole.
TB429	73	Trynet: large catch, 300 lbs. of yellowfin sole, some Asterias and some P. ochotensis.

APPENDIX C

(continued)

Station	Haul Number	Remarks
TB329	74	Trynet: another very large catch, this one dominated by humpy shrimp, pricklebacks, crangonids, some yellowfin sole, threaded sculpins, small pollock, many large barnacle shells.
TB329	75	Rock dredge: silty-clay-sandy-gravel. Very little biota, some Asterias, a few anemones, crangonids. No fish.
TB329	76	Rock dredge: same as Haul 73, sample dumped.
TB320	78	Rock dredge contained fine to coarse sand, gravel and small rock. Pagurus beringanus, Crangon, Asterias, amphipods, cumaceans. All animals were small and very few in number (1-6).
TB320	79	Trynet haul contained yellowfin sole, rock sole, capelin, Crangon and hexagrammids.
TB320	80	No field notes.
TB330	81	No field notes.
TB450	82	Trynet haul contained Hyas coarctatus, three red king crabs, a large cod, yellowfin sole, longhead dabs, Pandalus goniurus, Crangon dalli and Boltenia.
TB350	83	Trynet haul contained lots of yellowfin sole, some rock sole (many small), seven red king crabs, lots of finger sponge, flathead sole (one large, rest small) and large plaice.
BB557	84	Trynet haul contained 23 red king crab (>60 mm), many Boltenia and an assemblage of yellowfin sole and Asterias. One large male Tanner crab.
TB250	85	Trynet haul contained predominantly yellowfin sole, rock sole, Asterias, a few pollock and sculpins, yellow sponge debris, Pacific cod and a few Crangonids.

APPENDIX C

(continued)

Station	Haul Number	Remarks
TB250	86	The rock dredge at this station collected very little. Shell debris was the predominant substrate. Animals included Asterias, yellow sponge, bivalves, amphipods, small sand dollars, many very tiny gastropod shells with hermit crabs in residence, some gastropods, some crangonids, two Neptunea heros and some black gravel.
TB230	87	Trynet haul contained a medium-sized catch of shell debris with attached red sea anemones, and sipunculids, rock and yellowfin sole, Asterias, and smaller numbers of plaice, dabs, pollock, cod, sculpins and poachers.
TB220	88	No field notes.
TB130	89	Trynet haul off Cape Newenham on a mud bottom yielded lots of Crangon dalli and Pandalus goniurus. Many capelin were caught, the majority of these were in very bad condition and partly eaten (many breeding males were in the catch: do they die after spawning and become food for the shrimp?). Yellowfin sole and small pollock and cod were present.
TB150	90	Trynet haul contained small yellowfin sole and rock sole, dabs, threaded sculpin.
BB450	91	Trynet haul contained large yellowfin sole, large pollock, one bearing female red king crab.
BB555	92	Trynet haul was fairly small, dominated by juvenile rock and yellowfin sole, three C. bairdi, one red king crab, and some crangonids. A few sand dollars, Asterias, pollock, dabs and flathead sole were present.
BB670	93	No field notes.
BB560	94	No field notes.

APPENDIX C

(continued)

Station	Haul Number	Remarks
- - - - - - - -		THE REMAINING HAULS WERE QUALITATIVE ONLY - - - - - - -
PM670	95	Trynet haul contained one Tanner crab (C. bairdi), many Boltenia ovifera and yellowfin sole. A few rock soles and P. ochotensis were present. Also, a few sand dollars and small poachers, sponge and one Leptasterias.
PM650	96	Trynet haul contained Evasterias, yellowfin and rock sole, lots of anemones, some poachers, one large plain sculpin, small cod, Crangon dalli, a large skate, one female red king crab, and pollock.
PM740	97	Rock dredge haul contained shell debris, lots of small bivalves, gastropods, Pagurus ochotensis, yellowfin sole and C. dalli.
PM740	98	Rock dredge haul contained items similar to Haul 92 with shell debris, small sand dollars, cockles, very little to no organic debris, no bryozoans. The sand dollars appeared very clean with no green algae. The shell debris was mainly Tellin shell.
PM735	99	Rock dredge haul filled with coarse sand/fine gravel. One red king crab (6 mm), quite a few hermit crabs, Elassochirus tennuamanis, and about 10 Asterias.
PM630	100	Trynet haul with flatfish, Asterias. Many juvenile rock sole.
PM730	101	Trynet haul contained the ususal yellowfin and rock sole, Asterias and one red king crab.
PM620	102	No field notes.
PM750	103	Rock dredge contained Asterias, Pagurus ochotensis, P. stevensae, Cyclocardia sp. (rough cockle), Crangon dalli, Margarites (gastropod), sand dollars and shell debris. (This haul was with a 4:1 scope and at 1+ to 2 knots.)

APPENDIX C

(continued)

Station	Haul Number	Remarks
PM750	104	Rock dredge contained Asterias, one Lethasterias nanimensis and very little else, no debris. (This haul was with a 5:1 scope at 1 knot.)
PM745	105	Rock dredge contained very little: some shells, bivalves, Asterias.
PM745	106	Trynet: no catch, not on bottom.
PM540	107	Rock dredge contained fine sand and shell debris, small bivalves and gastropods. (This haul was in a small canyon heading toward the mouth of Port Moller.)
PM440	108	Trynet contained yellowfin and rock sole, including 50 mm rock sole, Asterias, Myoxocephalus jack, others.
PM250	109	Trynet haul contained flatfish, cod, Asterias, with halibut, starry skate, small pollock, sandlance, poachers, Pagurus ochotensis, crangonids. Rock sole were predominant.
PM150	110	Trynet haul contained lots of Asterias with urchins, rock and yellowfin sole and crangonids. Common in the haul were: Sclerocrangon, pollock, Pacific cod, ribbed sculpin, Oregonia gracilis, poachers, a few Lethasterias, Evasterius, anemones, bivalves and shells, Hyas lyratus and some pagurids. Many, many small Asterias were present.
BB480	111	No field notes.
		MonArk Trynet Stations, Port Moller
1		1244-1249 hours, 3:1 scope, 7 fathoms. Yellowfin sole, Asterias, Crangon dalli, one halibut, sand dollars, small dabs and rock sole.
2		1259-1309 hours, 3:1 scope, 6 fathoms. Yellowfin sole, sea stars, sand dollars, sand lance, poachers, rock sole, crangonids, three halibut.

APPENDIX C

(continued)

Station	Haul Number	Remarks
3		1328-1338 hours, 3:1 scope, 5 fathoms. Yellowfin sole, C. dalli, sandlance, sand dollars, rock sole, halibut, cod, plaice, dabs.
4		1353-1403 hours, 3:1 scope, 4 to 3 fathoms. Many small flatfish, same as #3, no halibut.
5		1408-1418 hours, 5:1 scope, 2 fathoms. Many small plaice, yellowfin sole, dabs, some rock sole, cod, Bering poacher, sandlances, sturgeon poacher, some algae.
6		1422-1432 hours, 4:1 scope, 5 fathoms. Similar to #5, with five small halibut.
7		1440-1450 hours, 3:1 scope, 5 fathoms. Two small halibut, large rock sole, yellowfin sole, C. dalli, sand dollars, dabs, plaice.
8		1515-1523 hours, 3:1 scope, 7 fathoms. One starry flounder, one halibut, yellowfin and rock sole, Asterias, sand dollars, plaice, dabs, sea weed.

APPENDIX C

(continued)

Station	Haul Number	Remarks
Cruise 83-5 (September):		
IL150	01	Trynet. No substrate retrieved. Small catch of Asterias amurensis and rock sole.
IL260	02	Trynet. No substrate. Asterias, rock sole, yellowfin sole, a few hair and Tanner crab.
IL230	03	Rock dredge. Shell fragments, barnacle covered rocks, many small sea stars and crabs.
IL470	04	Trynet. No substrate. Star fish and flatfish.
IL440	05	Trynet. Total catch rock sole and Asterias.
IL430	06	Rock dredge. Shell fragments and a few large rocks. Brittlestars.
IL420	07	Rock dredge. Shell fragments, jingle shells, some pea gravel. Sponges.
IL320	08	Trynet. Some large rocks, mud, yellowfin sole and Asterias.
IL330	09	Trynet. No substrate. Flatfish and sea stars.
IL350	10	Trynet. Same as above.
IL370	11	Trynet. Large amount of clam shell debris. Flatfish, large sea stars, a few red king and Tanner crabs.
PM670	12	Trynet. No substrate. Flatfish, some sea stars, Boltenia ovifera.
PM650	13	Trynet. No substrate. Mostly flatfish and sea stars.
PM620	14	Trynet. Same as above.
PM730	15	Trynet. Some mud. Flatfish and sea stars.

APPENDIX C

(continued)

Station	Haul Number	Remarks
PM850	16	Trynet. No substrate. Boltenia, kelp fragments, flatfish and sea stars.
PM830	17	Rock dredge. Small black gravel, mussels.
PM820	18	Trynet. Rocks. Small catch of flatfish, cod and small sea stars.
PM930	19	Trynet. Flatfish and sea stars.
PM920	20	Trynet. Same as above.
PM950	21	Trynet. Flatfish and sea stars.
PM150	22	Trynet. Shell debris. Flatfish and sea stars.
PM130	23	Trynet. Sand. Clams, flatfish, sea stars.
PM230	24	Trynet. Small stones. Red tree coral, tube worms, red king crab (small) found in bryozoans, flatfish, sea stars.
PH250	25	Trynet. No substrate. Red tree coral, decorator crab, flatfish, sea stars.
PH350	26	Trynet. No substrate. Boltenia, bryozoans, flatfish, a few sea stars.
PH120	27	Trynet. Flatfish, a few sea stars, bryozoans.
PH220	28	Rock dredge. No substrate.
PH320	29	Trynet. Sand. Small numbers of flatfish and sea stars.
KB150	30	Rock dredge. Shell, gravel. Flatfish, sea stars.
KB250	31	Trynet. Boltenia, bryozoa, flatfish and sea stars.
TB450	32	Trynet. Flatfish and sea stars.
TB350	33	Trynet. Boltenia, flatfish and sea stars.

APPENDIX C

(continued)

Station	Haul Number	Remarks
TB250	34	Trynet. Same as above.
TB330	35	Trynet. Flatfish including one halibut and sea stars.
TB320	36	Rock dredge. Pea gravel, black sand. A few flatfish and sea stars.
TB216	37	Trynet. Sea stars and a few flatfish.
TB329	38	Rock dredge. Mud, stones. A few sea stars and shrimp.
TB329	39	Trynet. No substrate. Many humpy shrimp, a few flatfish.
TB429	40	Trynet. Many yellowfin sole, sea stars, shrimp.
TB431	41	Trynet. Flatfish and sea stars.
TB540	42	Trynet. Boltenia, flatfish, sea stars.
KB240	43	Trynet. Flatfish and sea stars.
KB2*8	44	Trynet. Numerous small flatfish and sea stars.
KB2*1	45	Rock dredge. Rocks. Sea stars, shrimp.
KB2*4	46	Rock dredge. Cobble.
KB2*4	47	Rock dredge. Cobble. Polychaete tubes and first instar red king crabs, sea urchin, Pagurus beringanus.
KB2*4	48	Rock dredge. Cobble and rock. Polychaete tubes, first instar red king crabs, sea urchins, P. beringanus.
KB2*4	49	Rock dredge. Rocks (10-30 cm dia.). Some polychaete tubes, sea urchins, red king crabs.
KB2*4	50	Rock dredge. Rocks. Same as above.

APPENDIX C

(continued)

Station	Haul Number	Remarks
KB2*4	51	Rock dredge. Rocks. Same as above.
KB2*4	52	Rock dredge. Rocks. Same as above.
BB760	53	Trynet. Basket stars, sand dollars, flatfish, Boltenia.
BB770	54	Trynet. Huge haul of sand dollars, small flatfishes, red king crabs, Tanner crabs.
PM010	55	Trynet (MonArk launch). One large rock, sea stars, sea urchin.
PM010	56	Trynet. Large rocks. Red king crab, sea stars, sea urchins.
PM010	57	Trynet. Black sand. Shrimp, some fish.

APPENDIX D:

GUT CONTENT ANALYSIS FIELD NOTES

APPENDIX D

GUT CONTENT ANALYSIS FIELD NOTES

Station	Haul Number	Fish Species	Size (mm)	Gut Contents
Cruise 83-3 (June):				
IL150	03	Pacific cod	large	Euphausiids, 1 sandlance(?), gorp
IL130	04	Rock sole		Small, yellow heart urchin tests; solitary ascidians
		Yellowfin sole		Same as above
		Yellow Irish lord	large	Euphausiids and sandlance
PM320	15	Plain sculpin	-	1 yellowfin sole, 1 crangonid
		Plain sculpin	-	1 small flatfish, gorp. (roundworms)
		Plain sculpin	-	Well-digested fish remains
		Sandfish	201	140 mm walleye pollock
		Pacific cod	300	Black pebbles, crustaceans
		Pacific cod	215	Crangonids, pebbles (full gut)
		Pacific cod	215	Euphausiids (full gut)
		Pacific cod	140	Euphausiids (full gut)
		Pacific cod	140	Euphausiids (full gut)
		Pacific cod	140	Empty
		Walleye pollock	500	Pollock (100 mm), crangonids
		Walleye pollock	130	Euphausiids
		Walleye pollock	120	Euphausiids
		Walleye pollock	120	Euphausiids
		Rock sole	230	1 sand dollar, crustaceans (euphausiids), fish remains (semi-full stomach)
		Rock sole	370	Crustaceans (almost empty)
		Rock sole	300	Euphausiids (full)

APPENDIX D

(continued)

Station	Haul Number	Fish Species	Size (mm)	Gut Contents
		Yellowfin sole	230	Brown ascidian (?) (full)
		Yellowfin sole	200	Euphausiids (full)
PM370	18	Rock sole	410	Spisula siphons, about 1 cm diameter
		Yellowfin sole	300	Whole Spisula, up to 3 cm long
		Yellowfin sole	-	Bivalves (Spisula?) 1-2 mm long
		Flathead sole	300	1 moon snail, 1 hermit crab
PM670	19	Rock sole		Clams, whole and broken
PM650	20	Plain sculpin	400+	Empty
		Plain sculpin	400+	Fish flesh, one Crangon
PM730/ PM620	21/22	Alaska plaice		Empty
		Alaska plaice		Empty
		Alaska plaice	250	Clam siphons (Siliqua?)
		Longhead dab	120	Gorp, polychaetes(?), grit/ dirt
		Yellowfin sole	140-280	All with evidence of clams, broken and whole shells
PM820	23	Starry flounder		Mytilus
PM950	27	Pacific cod	760	3 flatfish, one sea onion (Boltenia ovifera), euphausiids and gorp
		Pacific cod	530	Euphausiids, 3 rocks
		Pacific cod	630	Fish flesh, a 370 mm long vertebral column, euphausiids, king crab leg, rock, clam
		Aleutian skate		Sandlance, crangonids
PM930	28	Halibut	430	2 sandlance, 1 flatfish

APPENDIX D

(continued)

Station	Haul Number	Fish Species	Size (mm)	Gut Contents
PM920	29	Yellowfin sole	100	Brittle star rays, clam siphon tips
PH220	32	Walleye pollock	470	Euphausiids
TB450	78	Pacific cod (several)		Large pagurid claws, squid shells(?), polychaetes, euphausiids, sipunculids(?)
Cruise 83-5 (September):				
PM650	13	Plain sculpin	457	One jellyfish
PM920	20	Pacific cod	455	Sea onion, fish flesh, rocks, shells
PH120	27	Pacific cod	254	Empty
		Yellowfin sole	356	Empty
		Rock sole	250	Empty
		Plain sculpin	455	Empty
PH350	26	Yellowfin sole	356	Two Oregonia gracilis
		Pacific cod	483	Gorp, gravel
KB250	31	Yellowfin sole	315	Empty
		Yellowfin sole	175	Crustacean parts
		Rock sole	380	Bivalve shell fragments, sand, gorp
		Rock sole	250	One euphausiid, polychaetes, gammarid, amphipods, sand
TB330	35	Halibut	-	Pagurus ochotensis, Eramacrus isenbeckii
		Yellowfin sole	310	One sandlance, one holothurian

APPENDIX D

(continued)

Station	Haul Number	Fish Species	Size (mm)	Gut Contents
		Yellowfin sole	290	Empty
		Rock sole	370	Empty
TB431	41	Plain sculpin	350	Six flatfishes, one crab (Telmesis), three Gymnocanthus, gravel, gorp
TB429	40	Pacific cod	550	Full gut was 1/3 rocks (up to 25 mm diameter); crab parts (Atelecyclid); two very digested fish (flatfish?)

APPENDIX E:

MULTIPLE LINEAR REGRESSION MODELS BY RED KING CRAB AGE AND CRUISE

APPENDIX E

MULTIPLE LINEAR REGRESSION MODELS BY RED KING CRAB AGE AND CRUISE[a]

Number of Variables in Model	r^2	Variable
DEPENDENT VARIABLE: YOUNG-OF-THE-YEAR CRAB		
Cruise 83-1 (April-May) (n=31):		
1	0.0074	Shrimps
1	0.0088	Sea onion
1	0.0205	Depth
1	0.2851	Bryozoan
1	0.7144	Sea star
2	0.7178	Sea star, salinity
2	0.7182	Bryozoan, sea star
2	0.7241	Sea star, sponge
2	0.7294	Roundfishes, sea star
2	0.7298	Sea star, gravel
3	0.7338	Sea star, sea urchin, gravel
3	0.7378	Roundfishes, sea star, depth
3	0.7385	Roundfishes, sea star, salinity
3	0.7419	Roundfishes, sea star, sponge
3	0.7524	Roundfishes, sea star, gravel
4	0.7535	Flatfishes, roundfishes, sea star, gravel
4	0.7537	Roundfishes, sea star, worms, gravel
4	0.7548	Bryozoan, roundfishes, sea star, gravel
4	0.7562	Roundfishes, sea star, sponge, gravel
4	0.7563	Roundfishes, sea star, sea urchin, gravel
5	0.7577	Roundfishes, sea star, sponge, depth, gravel
5	0.7579	Bryozoan, roundfishes, sea star, sponge, gravel
5	0.7579	Roundfishes, sea star, sea urchin, worms, gravel
5	0.7586	Bryozoan, roundfishes, sea star, sea urchin, gravel
5	0.7661	Roundfishes, sea star, sea urchin, sponge, gravel
Cruise 83-3 (June) (n=47):		
1	0.0125	Depth
1	0.0281	Roundfishes
1	0.0338	Flatfishes
1	0.0578	Bryozoan
1	0.4859	Sea urchin

APPENDIX E

(continued)

Number of Variables in Model	r^2	Variable
2	0.4987	Sea urchin, gravel
2	0.5011	Sea urchin, sponge
2	0.5031	Roundfishes, sea urchin
2	0.5036	Flatfishes, sea urchin
2	0.5185	Bryozoan, sea urchin
3	0.5263	Flatfishes, roundfishes, sea urchin
3	0.5308	Bryozoan, flatfishes, sea urchin
3	0.5339	Bryozoan, sea urchin, gravel
3	0.5361	Bryozoan, sea urchin, sponge
3	0.5390	Bryozoan, roundfishes, sea urchin
4	0.5460	Bryozoan, flatfishes, sea urchin, gravel
4	0.5474	Bryozoan, sea urchin, sponge, gravel
4	0.5491	Bryozoan, flatfishes, sea urchin, sponge
4	0.5556	Bryozoan, roundfishes, sea urchin, sponge
4	0.5559	Bryozoan, flatfishes, roundfishes, sea urchin
5	0.5602	Bryozoan, flatfishes, sea urchin, sponge, gravel
5	0.5603	Bryozoan, roundfishes, sea urchin, sponge, salinity
5	0.5628	Bryozoan, roundfishes, sea urchin, shrimps, sponge
5	0.5633	Bryozoan, flatfishes, round fishes, sea urchin, shrimps
5	0.5733	Bryozoan, flatfishes, roundfishes, sea urchin, worms
Cruise 83-5 (September) (n=36):		
1	0.0712	Depth
1	0.3709	Gravel
1	0.7418	Worms
1	0.8211	Salinity
1	0.9982	Sea urchin
2	0.9982	Roundfishes, sea urchin
2	0.9982	Sea star, sea urchin
2	0.9982	Bryozoan, sea urchin
2	0.9985	Sea urchin, gravel
2	0.9995	Sea urchin, shrimps

APPENDIX E

(continued)

Number of Variables in Model	r^2	Variable
3	0.9995	Sea urchin, shrimps, salinity
3	0.9995	Sea urchin, shrimps, worms
3	0.9995	Flatfishes, sea urchin, shrimps
3	0.9996	Sea star, sea urchin, shrimps
3	0.9996	Bryozoan, sea urchin, shrimps
4	0.9996	Bryozoan, sea urchin, shrimps, salinity
4	0.9996	Bryozoan, flatfishes, sea urchin, shrimps
4	0.9996	Bryozoan, sea urchin, shrimps, worms
4	0.9997	Bryozoan, sea star, sea urchin, shrimps
4	0.9997	Flatfishes, sea star, sea urchin, shrimps
5	0.9997	Flatfishes, sea star, sea urchin, shrimps, worms
5	0.9997	Flatfishes, sea onion, sea star, sea urchin, shrimps
5	0.9997	Flatfishes, roundfishes, sea star, sea urchin, shrimps
5	0.9997	Flatfishes, sea star, sea urchin, shrimps, depth
5	0.9998	Bryozoan, flatfishes, sea star, sea urchin, shrimps
DEPENDENT VARIABLE: 1-2 AGE CRAB		
Cruise 83-1 (April-May) (n=31):		
1	0.0540	Depth
1	0.1978	Salinity
1	0.3135	Shrimps
1	0.3442	Gravel
1	0.9530	Sea urchin
2	0.9538	Sea star, sea urchin
2	0.9540	Sea urchin, sponge
2	0.9584	Sea urchin, gravel
2	0.9680	Sea urchin, shrimps
2	0.9753	Sea urchin, salinity
3	0.9757	Sea star, sea urchin, salinity
3	0.9760	Roundfishes, sea urchin, salinity

APPENDIX E

(continued)

Number of Variables in Model	r^2	Variable
Cruise 83-5 (September) (n=36): (continued)		
3	0.9995	Sea urchin, shrimps, salinity
3	0.9995	Sea urchin, shrimps, worms
3	0.9995	Flatfishes, sea urchin, shrimps
3	0.9996	Sea star, sea urchin, shrimps
3	0.9996	Bryozoan, sea urchin, shrimps
4	0.9996	Bryozoan, sea urchin, shrimps, salinity
4	0.9996	Bryozoan, flatfishes, sea urchin, shrimps
4	0.9996	Bryozoan, sea urchin, shrimps, worms
4	0.9997	Bryozoan, sea star, sea urchin, shrimps
4	0.9997	Flatfishes, sea star, sea urchin, shrimps
5	0.9997	Flatfishes, sea star, sea urchin, shrimps, worms
5	0.9997	Flatfishes, sea onion, sea star, sea urchin, shrimps
5	0.9997	Flatfishes, roundfishes, sea star, sea urchin, shrimps
5	0.9997	Flatfishes, sea star, sea urchin, shrimps, depth
5	0.9998	Bryozoan, flatfishes, sea star, sea urchin, shrimps
DEPENDENT VARIABLE: 1-2 AGE CRAB		
Cruise 83-1 (April-May) (n=31):		
1	0.0540	Depth
1	0.1978	Salinity
1	0.3135	Shrimps
1	0.3442	Gravel
1	0.9530	Sea urchin
2	0.9538	Sea star, sea urchin
2	0.9540	Sea urchin, sponge
2	0.9584	Sea urchin, gravel
2	0.9680	Sea urchin, shrimps
2	0.9753	Sea urchin, salinity
3	0.9757	Sea star, sea urchin, salinity
3	0.9760	Roundfishes, sea urchin, salinity

APPENDIX E

(continued)

Number of Variables in Model	r^2	Variable
3	0.9762	Sea urchin, shrimps, salinity
3	0.9684	Sea onion, sea urchin, salinity
3	0.9815	Sea urchin, depth, salinity
4	0.9818	Sea urchin, sponge, depth, salinity
4	0.9819	Bryozoan, sea urchin, depth, salinity
4	0.9824	Sea urchin, dkepth, salinity, gravel
4	0.9824	Sea urchin, shrimps, depth, salinity
4	0.9826	Sea onion, sea urchin, depth, salinity
5	0.9829	Bryozoan, sea urchin, depth, salinity, gravel
5	0.9831	Bryozoan, sea onion, sea urchin, depth, salinity
5	0.9833	Sea onion, sea urchin, shrimps, depth, salinity
5	0.9835	Sea onion, sea urchin, depth, salinity, gravel
5	0.9844	Sea urchin, shrimps, depth, salinity, gravel
Cruise 83-3 (June) (n=47):		
1	0.0039	Bryozoan
1	0.0046	Sea star
1	0.0051	Gravel
1	0.0077	Flatfishes
1	0.0259	Depth
2	0.0348	Roundfishes, depth
2	0.0385	Depth, salinity
2	0.0395	Depth, temperature
2	0.0451	Flatfishes, depth
2	0.0480	Depth, gravel
3	0.0541	Flatfishes, sea star, depth
3	0.0581	Depth, salinity, gravel
3	0.0591	Depth, temperature, gravel
3	0.0600	Sea star, depth, gravel
3	0.0726	Flatfishes, depth, gravel
4	0.0755	Flatfishes, depth, temperature, gravel
4	0.0772	Sea star, depth, salinity, gravel
4	0.0822	Flatfishes, sea urchin, depth, gravel
4	0.0825	Bryozoan, flatfishes, depth, gravel
4	0.0864	Flatfishes, sea star, depth, gravel

APPENDIX E

(continued)

Number of Variables in Model	r^2	Variable
5	0.0911	Bryozoan, flatfishes, sea urchin, depth, gravel
5	0.9815	Flatfishes, sea star, depth, temperature, gravel
5	0.0926	Flatfishes, sea star, depth, salinity, gravel
5	0.0962	Bryozoan, flatfishes, sea star, depth, gravel
5	0.0980	Flatfishes, sea star, sea urchin, depth, gravel
Cruise 83-5 (September) (n=36):		
1	0.0563	Temperature
1	0.0768	Salinity
1	0.1082	Sea urchin
1	0.5498	Worms
2	0.5536	Shrimps, worms
2	0.5597	Sponge, worms
2	0.5859	Worms, gravel
2	0.7611	Worms, salinity
2	0.9239	Sea urchin, worms
3	0.9255	Roundfishes, sea urchin, worms
3	0.9260	Sea urchin, worms, temperature
3	0.9265	Bryozoan, sea urchin, worms
3	0.9308	Sea urchin, worms, gravel
3	0.9308	Sea urchin, worms, depth
4	0.9325	Roundfishes, sea urchin, worms, gravel
4	0.9329	Bryozoan, sea urchin worms, depth
4	0.9335	Bryozoan, sea urchin worms, gravel
4	0.9335	Sea urchin, worms, depth, gravel
4	0.9364	Sea urchin, sponge, worms, gravel
5	0.9373	Sea urchin, sponge, worms, salinity, gravel
5	0.9374	Sea urchin, sponge, worms, temperature, gravel
5	0.9386	Sea urchin, sponge, worms, depth, gravel
5	0.9388	Bryozoan, sea urchin, sponge, worms, gravel
5	0.9426	Sea urchin, shrimps, sponge, worms, gravel

APPENDIX E

(continued)

Number of Variables in Model	r^2	Variable
DEPENDENT VARIABLE: 2+ and 3 AGE CRAB		
Cruise 83-1 (April-May) (n=31):		
1	0.0397	Flatfishes
1	0.0793	Salinity
1	0.1510	Gravel
1	0.1692	Sponge
1	0.5699	Sea urchin
2	0.5814	Sea urchin, shrimps
2	0.5905	Sea urchin, gravel
2	0.6063	Sea urchin, salinity
2	0.6123	Sea urchin, temperature
2	0.6324	Sea star, sea urchin
3	0.6514	Flatfishes, sea urchin, temperature
3	0.6527	Sea star, sea urchin, shrimps
3	0.6638	Sea star, sea urchin, salinity
3	0.6682	Sea star, sea urchin, temperature
3	0.6701	Bryozoan, sea star, sea urchin
4	0.6923	Bryozoan, sea star, sea urchin, shrimps
4	0.6974	Sea star, sea urchin, salinity, temperature
4	0.7038	Bryozoan, sea star, sea urchin, salinity
4	0.7076	Flatfishes, sea star, sea urchin, temperature
4	0.7085	Bryozoan, sea star, sea urchin, temperature
5	0.7284	Flatfishes, sea star, sea urchin, temp.. gravel
5	0.7298	Bryozoan, sea star, sea urchin, depth, temp.
5	0.7362	Flatfishes, sea star, sea urchin, salinity, temp.
5	0.7399	Bryozoan, sea star, sea urchin, salinity, temp.
5	0.7469	Bryozoan, flatfishes, sea star, sea urchin, temp.
Cruise 83-3 (June) (n=47):		
1	0.0206	Temperature
1	0.0248	Salinity
1	0.0538	Sponge
1	0.0691	Roundfishes
1	0.1352	Sea star

APPENDIX E

(continued)

Number of Variables in Model	r^2	Variable
2	0.1468	Sea star, temperature
2	0.1568	Sea star, depth
2	0.1638	Roundfishes, shrimps
2	0.1919	Roundfishes, sea star
2	0.1926	Sea star, sponge
3	0.2121	Roundfishes, sea star, temperature
3	0.2310	Roundfishes, sea star, depth
3	0.2424	Roundfishes, sea star, shrimps
3	0.2460	Roundfishes, sea star, gravel
3	0.2513	Roundfishes, sea star, sponge
4	0.2711	Roundfishes, sea star, sponge, depth
4	0.2783	Roundfishes, sea star, shrimps, gravel
4	0.2788	Roundfishes, sea star, shrimps, depth
4	0.2897	Roundfishes, sea star, sponge, gravel
4	0.2942	Roundfishes, sea star, shrimps, sponge
5	0.3011	Roundfishes, sea star, sea urchin, sponge, gravel
5	0.3076	Roundfishes, sea star, shrimps, sponge, temp.
5	0.3083	Roundfishes, sea star, sea urchin, shrimps, sponge
5	0.3132	Roundfishes, sea star, shrimps, sponge, depth
5	0.3190	Roundfishes, sea star, shrimps, sponge, gravel

Cruise 83-5 (September) (n=36):

No data

DEPENDENT VARIABLE: 3+ AGE CRAB

Cruise 83-1 (April-May) (n=31):

1	0.0473	Flatfishes
1	0.0507	Roundfishes
1	0.0750	Gravel
1	0.2416	Sponge
1	0.4224	Sea urchin

APPENDIX E

(continued)

Number of Variables in Model	r^2	Variable
2	0.4540	Sea urchin, shrimps
2	0.4640	Sea urchin, gravel
2	0.4826	Sea urchin, depth
2	0.5031	Sea urchin, salinity
2	0.5157	Roundfishes, sea urchin
3	0.5339	Roundfishes, sea urchin, shrimps
3	0.5357	Roundifshes, sea urchin, temperature
3	0.5427	Roundfishes, sea urchin, gravel
3	0.5461	Roundfishes, sea urchin, sponge
3	0.5645	Roundfishes, sea urchin, salinity
4	0.5743	Roundfishes, sea star, sea urchin, salinity
4	0.5755	Roundfishes, sea urchin, sponge, salinity
4	0.5755	Flatfishes, roundfishes, sea urchin, temperature
4	0.5782	Roundfishes, sea urchin, salinity, temperature
4	0.5806	Flatfishes, roundfishes, sea urchin, salinity
5	0.5917	Flatfishes, roundfishes, sea urchin, worms, temp.
5	0.5926	Roundfishes, sea urchin, sponge, temp., gravel
5	0.6042	Flatfishes, roundfishes, sea urchin, sponge, temp.
5	0.6067	Flatfishes, roundfishes, sea urchin, temperature, gravel
5	0.6149	Flatfishes, roundfishes, sea urchin, salinity, temperature
Cruise 83-3 (June) (n=47):		
1	0.0111	Gravel
1	0.0380	Salinity
1	0.0477	Depth
1	0.1091	Sea onion
1	0.1289	Sponge
2	0.1409	Flatfishes, sponge
2	0.1444	Sponge, salinity
2	0.1463	Sponge, depth
2	0.1479	Sea urchin, sponge
2	0.1655	Sea onion, sponge

APPENDIX E

(continued)

Number of Variables in Model	r^2	Variable
3	0.1735	Sea onion, sponge, depth
3	0.1764	Flatfishes, sponge, salinity
3	0.1776	Sea onion, sponge, salinity
3	0.1783	Sea onion, sea urchin, sponge
3	0.1794	Flatfishes, sea onion, sponge
4	0.1923	Sea onion, sea urchin, sponge, salinity
4	0.1933	Flatfishes, sea onion, sponge, temperature
4	0.1953	Flatfishes, sea urchin, sponge, salinity
4	0.1955	Flatfishes, sea onion, sponge, depth
4	0.2103	Flatfishes, sea onion, sponge, salinity
5	0.2113	Flatfishes, sea onion, sea star, sponge, salinity
5	0.2121	Bryozoa, flatfishes, sea onion, sponge, salinity
5	0.2127	Flatfishes, roundfishes, sea onion, sponge, salinity
5	0.2143	Flatfishes, sea onion, sponge, depth, salinity
5	0.2230	Flatfishes, sea onion, sea urchin, sponge, salinity
Cruise 83-5 (September) (n=36):		
1	0.0302	Bryozoa
1	0.0330	Roundfishes
1	0.2081	Depth
1	0.2901	Temperature
1	0.3873	Sea onion
2	0.3922	Sea onion, gravel
2	0.3948	Roundfishes, sea onion
2	0.3973	Bryozoan, sea onion
2	0.4113	Sea onion, depth
2	0.5714	Sea onion, temperature
3	0.5771	Sea onion, sea star, temperature
3	0.5772	Sea onion, sea urchin, temperature
3	0.5789	Sea onion, worms, temperature
3	0.5806	Sea onion, salinity, temperature
3	0.5844	Bryozoa, sea onion, temperature

APPENDIX E

(continued)

Number of Variables in Model	r^2	Variable
4	0.5919	Bryozoan, sea onion, sea star, temperature
4	0.5939	Bryozoan, sea onion, worms, temperature
4	0.5945	Flatfishes, sea onion, sea star, temperature
4	0.5948	Bryozoan, sea onion, salinity, temperature
4	0.5984	Flatfishes, roundfishes, sea onion, temperature
5	0.6084	Flatfishes, roundfishes, sea onion, worms, temp.
5	0.6115	Flatfishes, roundfishes, sea onion, salinity, temperature
5	0.6164	Flatfishes, roundfishes, sea onion, sea star, temperature
5	0.6199	Bryozoan, flatfishes, sea onion, sea star, temp.
5	0.6212	Bryozoan, flatfishes, roundfishes, sea onion, temperature

(a) Key: See Section 2.4 for multiple linear regression model methodology

APPENDIX F:

JUVENILE RED KING CRAB SUBSTRATE PREFERENCE TESTS

APPENDIX F

JUVENILE RED KING CRAB SUBSTRATE PREFERENCE TESTS

The following tests were conducted aboard the NOAA ship Miller Freeman during the June cruise (83-3). The objective was to test for substrate preference in juvenile red king crabs.

Materials

The materials used included a large fiberglass aquarium (approximately 1 m x 1m x 1m) supplied with running sea water. The aquarium was kept in a room with subdued light and covered with black plastic and wooden boards to keep out light. Crab counts were made with the use of a red-lense flashlight. Six age 1+ red king crabs were used for the tests. The carapace length and sex were determined for five of these crabs: male, 22 mm; male, 20 mm; male, 20 mm; female, 22.5 mm; and female, 16.5 mm.

Methods

Before each test, crabs were kept separated in water-filled glass containers for several hours.

Test 1: Bare Substrates. Each quarter of the aquarium bottom was covered with one substrate type, as indicated in Figure F1. At the beginning of the test, six crabs were placed on the substrates in the positions in Figure F1. The locations of crabs were observed and plotted every 15 minutes for two hours during the first run, and approximately every 30 minutes for three and one half hours during the second run. The crabs were left in the aquarium for the 16 hours between runs. At the end of the test, the total number of crab observations tallied per quadrat were summed (Table F1) (one half crab was tallied for each of two quadrats where border were stradled by a single crab).

Test 2: Substrate and Epifaunal "Reefs". Test 2 involved the placement of an epifaunal "reef" in the center of each bottom quadrat. The reef materials included erect bryozoans attached to rocks, tube worm colonies, mussels and large barnacles. Reef positions are shown in Figure F2. Crabs were held in glass containers as for Test 1, and placed in the aquarium positions indicated in Figure F2. Crab locations were plotted six times during a six-hour period. Crab position tallies are presented in Table F2.

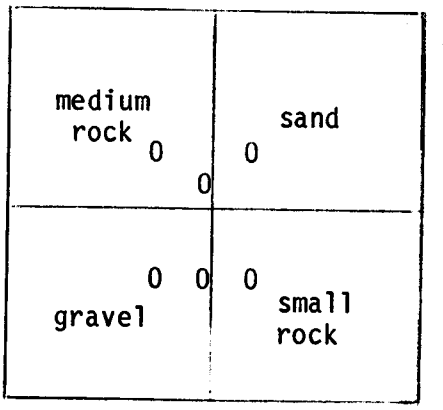

Figure F1. Substrates Used in Test 1.

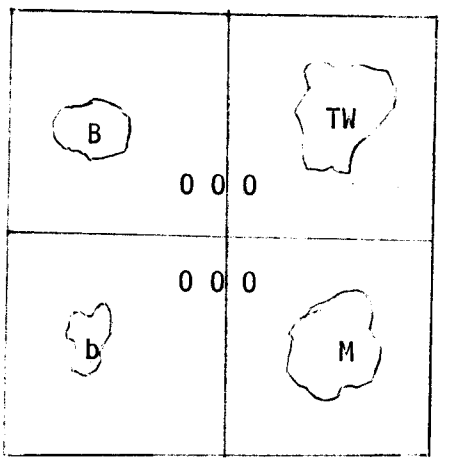

Figure F2. "Reef" Materials Used in Test 2. Substrates Are the Same as in Figure F1.

Results and Discussion

Test 1: The greatest percentage of crabs, 55 percent, was found on the medium rock substrate; the lowest percentage, 10 percent, was found on gravel. Although far from conclusive, this simple test indicates a marked preference for the largest-grained substrate.

Test 2: The greatest percentage of crabs, 40 percent, was found in the quadrat with tube worms, followed by mussels, then barnacles, then bryozoans. Crabs were observed in contact with the "reef" materials only on the tube worms. The results indicate that the epifauna present in the quadrats may have been more important to the test animals than the actual bare substrate.

General Comments

A number of variables could not be accounted for in these tests. Feeding crabs (i.e., hunger) could have been a major factor in Test 2 results. The crabs were left in the aquarium after Test 2 for observation; some were seen feeding on tube worms and scavenging for food between the mussels.

TABLE F1

RESULTS OF TEST 1

	Medium Rock	Sand	Small Rock	Gravel
Number of crabs	49.5	15.5	16	9
Percent of total	55	17	18	10

TABLE F2

RESULTS OF TEST 2

	Medium Rock	Sand	Small Rock	Gravel
Number of crabs	2.5	14.5	11.5	7.5
Percent of total	7	40	32	21

DISTRIBUTION AND ABUNDANCE OF DECAPOD CRUSTACEAN LARVAE IN THE SOUTHEASTERN BERING SEA WITH EMPHASIS ON COMMERCIAL SPECIES

by

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Final Report
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1.0 GENERAL INTRODUCTION

1.1 Justification of the Study

The southeastern Bering Sea is characterized by rich water column productivity of both phytoplankton and zooplankton (McRoy and Goering 1974; Goering and Iverson 1978; Goering and McRoy 1981, Cooney 1981) which, in turn, supports an extensive and productive benthic community over much of the shelf (Feder and Jewett 1981; McDonald et al. 1981; Jewett and Feder 1981). Some of the most abundant epifaunal organisms quantified in these studies are several species of crab that constitute lucrative invertebrate fisheries for the United States (Otto 1981). Distribution of these species, particularly gravid females and sensitive larvae and juveniles, in relation to areas of future oil and gas development of the St. George Basin and North Aleutian Shelf (NAS), make them particularly vulnerable to oil mishaps that could have ultimate repercussions on the general benthic community and commercial fishery (Curl and Manen 1982; Armstrong et al. 1983).

Minerals Management Service (MMS) has established six outer continental shelf planning units in the Bering Sea. Three of these units have been through tract selection stages and include the St. George Basin and the North Aleutian Shelf, which together encompass virtually all of the southeastern Bering Sea crab fishering grounds. Two synthesis meetings have been held to consider the impact of Outer Continental Shelf (OCS) oil and gas development on biota and habitats in both units in order to aid in development of management plans that mitigate perturbations on resources. Proceedings of the St. George Basin meeting have been

published prior to an anticipated lease sale in mid-1983 (Hameedi 1982), and reports of the NAS meeting are in review and expected by summer 1983. Data and interpretations from the present study on decapod larvae were included in proceedings from both meetings (Curl and Manen 1982; Armstrong et al. 1983), and served to extend knowledge on the biology and ecology of commercial crabs that was used to predict vulnerability of the species.

Crabs in the southeastern Bering Sea constitute one of the most valuable crustacean fisheries in the world. Two principle groups, king crab (Paralithodes camtschatica and P. platypus) and Tanner crab (Chionoecetes bairdi and C. opilio) comprised 35.4% and 23%, respectively, of total U.S. crab landings in 1980. Their respective dollar values were 60% and 11.7% of total ex-vessel U.S. crab revenues of $291,350,000 (NOAA 1981; Pacific Packers 1981; Sections 3.0 and 4.0 of this report give extensive literature reviews of general biology and fishery information on king and Tanner crab). Since the beginning of this project in January 1981, commercial fishing has suffered two years of depressed landings in 1981 and 1982, particularly of red king crab. Landings declined from 131 x 10^6 lb in 1980 to about 35 x 10^6 in 1981 (INPFC 1982), and the fishery was closed at about 3.5 x 10^6 in 1982 (M. Hayes, NMFS, Seattle, pers. communication). Such severe reductions in landings are in accord with NMFS predictions of decreased abundance (5-fold decrease from 1979 to 82: Otto et al. 1982), and reflect a substantial, but unexplained, variation in success of year-classes.

Larval stages are generally considered more sensitive to environmental stresses than adults or juveniles of aquatic species (Anger et al. 1981; Bakun et al. 1982; May 1974; Vernberg and Vernberg 1972). Studies of larval crab and shrimp biology in the southeastern Bering Sea are timely for insights behind the vagaries of adult abundance that might be traced to relative success of pelagic larval year-classes. An important consideration for predictions of impact is whether oil mishaps could further diminish populations already reduced by natural stresses on their larvae.

Forthcoming development of petroleum and gas reserves in the reproductive and fishing grounds of commercially important Crustacea led to the study outlined in this report. While extensive literature exists on the distribution and abundance of juvenile and adult decapod Crustacea in the southeastern Bering Sea (Jewett and Feder 1981; Otto 1981a; provided by NMFS as part of the commercial fisheries survey; Somerton 1981), little data on the general ecology, distribution, and abundance of their pelagic larvae are published. Larvae are considered extremely susceptible to oil pollution because:

1. This life-history stage is pelagic, usually in the upper 20 m of the water column and, for some species and stages, largely in the neuston (e.g., Smyth 1980). Given the tendency of the various molecular fractions of petroleum to either dissolve or form colloids and particles in water and disperse as a surface film or sink slowly (Shaw 1977; McAuliffe 1977), crustacean larvae are more likely to be exposed to oil on a broader scale than are their benthic parents.

2. Larval crustaceans are more sensitive to any group of pollutants (including oil) than are juvenile or adult stages (Armstrong et al. 1976; Johnson 1977).

3. Larvae grow rapidly in the water column and molt up to five times in three to four months, whereas adults molt only once annually. Molting is the physiological event in crustacean life cycles most sensitive to ambient perturbations such as oil pollution. During an oil mishap, larvae will be exposed for a greater portion of their abbreviated molt cycle than will adults.

4. Recruitment of legal crabs to a fishery may be largely dependent on the larval survival of a given year-class (McKelvey et al. 1980; Somerton 1981). Annual variations of high or low abundance indicate differential mortality caused by physical and biological factors that vary in intensity and effect year to year (Incze 1983). Extensive oil pollution in critical seasons could increase larval mortality in years when natural causes are relatively benign, or act synergistically with severe natural events to decimate larval cohorts and, in turn, curtail the fishery years later.

1.2 The Data Base

Zooplankton samples sorted for this study of larval decapod distribution and abundance have come from several collections made in different years and areas with varying degrees of temporal/spatial thoroughness and continuity (Section 2.0, Methods and Materials, gives details of the data base). Only in the years 1980 and 1981 (and to a limited

extent in 1982) did we have the opportunity to plan systematic collections related to hypotheses of species biology. Even in those years our program was a small, opportunistic portion of larger missions that limited that scope of work accomplished. Samples from years 1976-1979 came from several ichthyoplankton and zooplankton surveys that were, in cases, extremely helpful and relevant to our decapod study. But some collections were meager or far removed from areas of principal king and Tanner crab distribution and, consequently, only partially contributed to analyses of annual and regional differences in larval population dynamics.

The majority of collections were made during May and June of each year. The study suffered somewhat from lack of thorough collections in April to characterize time and area of hatch (more so for king crab), and also from few samples through July and August to better fix the period of metamorphosis to the benthos. Spatial representation was best over the middle, and outer shelf where the PROBES study was conducted for several years (see Section 2.0), and thus both species of Tanner crab and pandalid shrimp are the taxa where larval biology is best documented (Sections 4.0 and 6.0, respectively). Since very few samples were taken near the Pribilof Islands, nearshore along the North Aleutian Shelf and also in Bristol Bay from 1976 to 1981, a somewhat incomplete picture of both blue and red king crab larval ecology and biology has emerged, although collections in 1982 nearshore along the NAS have improved knowledge of the latter species (Section 3.0).

Despite these shortcomings, the sum of data presented in this report is the most comprehensive study of larval decapods in the south-

eastern Bering Sea to date and, for many taxa, over their entire range from the Bering Sea through the Gulf of Alaska and farther south. In reviewing the literature on shrimp and crabs, we were struck by the paucity of studies on the population dynamics and general ecology of larval decapod stages along the west coast of the United States and Canada. Investigations such as Lough's (1976) along Oregon that focus on decapod larvae are rare (see literature reviews in Section 3.0-7.0). Rather, such larval stages are studied in laboratories while field investigations tend to deal more with juvenile and adult populations. Zooplankton investigations tend to focus on holoplanktonic taxa such as copepods without much attention given meroplanktonic groups. Yet factors such as species distribution, ranges and fluctuations in abundance of benthic adult populations may largely be explained by responses and survival of pelagic larvae (Bakun et al. 1982; Incze 1983; Young and Hazlett 1978). A notable exception in the pattern of few, comprehensive studies of larval crab populations are those done over the last several years on the eastern U.S. coast (Grant 1977; Johnson 1982, McConaugh et al. in press; Smyth 1980), which have greatly increased knowledge of estuarine and nearshore larval crab biology. Such information increases the accuracy of environmental impact predictions stemming from numerous projects in that region.

1.3 Format of this Report

This contract was established to provide information on larval decapods to federal agencies considering ramifications of oil and gas develop- and to aid them in devising management policy to mitigate possible impacts.

The sections of this report describe firstly the general methods and materials used in the program (Section 2.0). Next are several sections (3.0-7.0) that review pertinent literature on the biology and fishery (if applicable) of major decapod groups and then present results of this study. The commercial king and Tanner crabs are discussed in Sections 3.0 and 4.0, respectively, followed by other crabs (5.0), shrimp (6.0) and hermit crabs (7.0). While the latter three groups are not commercially important (an exception is the horsehair crab, Erimacrus isenbeckii), they may be of major ecological importance as predators and prey within benthic communities and must not be overlooked in predictions of oil impact.

Data on larval distribution and abundance, relationships to benthic adult stocks, molt frequency, annual variations in physiological and biological factors, etc., are considered in light of possible oil impacts in Section 8.0. Literature on oil toxicity to Crustacea is reviewed and previous models of oil impact are studied and criticized as a preface to discussion of decapod species/taxa vulnerability to oil in the southeastern Bering Sea. Data gaps are identified and future research on decapods in that area is suggested in the conclusion.

2.0 MATERIALS AND METHODS

2.1 Sample Sources and Station Locations

Zooplankton samples used for enumeration of decapod larvae were obtained from several sources. Four series of samples were retrieved from storage and loaned to us by the principal investigators of earlier zooplankton studies conducted in the southeastern Bering Sea under OCSEAP support. These samples had not been examined previously for decapod larvae. In addition to these past samples, participation in the 1980 and 1981 PROBES cruises enabled purposeful sampling for this study. In addition to our own sampling, a large number of depth-stratified samples were shared by the PROBES zooplankton working group, and samples were collected by National Marine Fisheries Services (NMFS) personnel during two cruises in 1981. Table 2.1 lists cruise and station information for the zooplankton samples analyzed in this study. The locations of sampling stations for each year and cruise are illustrated in Figures 2.1-2.18 at the end of this Chapter. Specific information regarding the location of stations as well as the sampling gear used and all results are available through the National Oceanograph Data Center, Washington, D.C. under project title "Decapod Larvae," File Type 124 (zooplankton data).

A study of distribution and abundance of red king crab larvae along the North Aleutian Shelf was supported by NMFS and OCSEAP in 1982 and findings are briefly presented in this report for comparative purposes. Station locations are shown in Figs. 2.19 and 2.20 for collections made during June 16-29 and August 3-10, respectively, that totalled 131 samples (Table 2.1).

Table 2.1. Dates and sources of zooplankton samples searched for decapod larvae in this study.

Year	Temporal coverage of zooplankton samples	Cruise	Cruise sponsor*	Vessel	No. of stations	No. of stations
1976	26 April-31 May	MF-76A	OCSEAP	Miller Freeman	27	30
1977	16 April-17 May	RP-4-MF-77B	OCSEAP	Miller Freeman	80	112
1978	11 Feb-16 March	MF-78-1	OCSEAP	Miller Freeman	21	29
	11 April-29 June	TT-131	PROBES	T. G. Thompson	186	225
1979	1-27 June	3MF-70	OCSEAP	Miller Freeman	32	36
1980	6 April-8 June	TT-149	PROBES	T. G. Thompson	68	317
	4-5 October	AX-9	PROBES	Alpha Helix	4	21
1981	16 April-20 July	TT-159	PROBES	T. G. Thompson	165	610
	14-31 May	RP-4-DI-81A	NMFS	Discoverer	16	16
	24 May-20 July	AL/811	NMFS	Alaska	23	23
TOTAL					622	1,419
1982**	6-29 June		OCSEAP/	Miller Freeman		83
	3-10 August		NMFS	Miller Freeman		48

*OCSEAP, within National Oceanic and Atmospheric Administration. OCSEAP samples 1976-1979 collected under contract by National Marine Fisheries Service.
PROBES: National Science Foundation (Processes and Resources of the Bering Sea Shelf)

**Only samples through 1981 were supported on this contract. 1982 samples were collected with NMFS support and OCSEAP logistics.

However, the data are not included in File Type 124, "Decapod Larvae" as of this writing.

2.2 Sample Collection

Zooplankton samples were collected with Bongo nets on a 60 cm (diameter) Bongo frame, a MOCNESS (Multiple Opening/Closing Nets and Environmental Sampling System, Wiebe et al. 1976), a NORPAC net (Motoda et al. 1957) and an MTD net (Motoda, 1969). The mesh size on the nets deployed with each piece of gear varied, but all were fine enough to retain even the smallest of the decapod larvae of this region.*

During OCSEAP and NMFS cruises in 1976-1979, Bongo frames were deployed with one 333 μm and one 505 μm mesh net attached. The samples analyzed in this study depended exclusively upon availability and included collections from both mesh sizes. Bongo nets used during the 1978 PROBES cruise were 333 μm during Leg I and 505 μm during Legs II-IV (the investigators resorted to the larger mesh to reduce net clogging). A 505 μm net was used during the 1980-1982 PROBES and NMFS cruises. The NORPAC and MTD nets used both 333 and 505 μm mesh, and the MOCNESS was equipped with 149 μm mesh nets

Flow meters attached in front of the opening of Bongo, NORPAC, and MTD nets and near the top of the MOCNESS were used to estimate the volume of water filtered by each net. Bongo tows were made using standard

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*The smallest larvae were stage I zoeae (SI) of the Brachyuran family Pinnotheridae: minimum dimension of smallest individual collected with 149 μm nets was approximately 1.5 mm. The largest mesh used was 550 μm.

techniques which attempt to equally sample all depths involved in the tow (Smith and Richardson, 1977). The MTD and MOCNESS nets had discrete flow data for each depth interval sampled. The only samples for which flow data were not available are those from PROBES 1978; the average flow (250 m^3) computed for other processed zooplankton data from that cruise was used. Since every effort was made to keep those tows uniform, the error introduced by this estimation is probably small compared to real differences in decapod abundance.

The depth of sampling varied with the gear and cruise objectives. The depth of Bongo tows from OCSEAP and NMFS cruises generally reflected changes in the depth of water at various stations, whereas PROBES Bongo tows usually sampled only the upper 60 m of water, even at the deeper stations. MOCNESS was operated to sample the following depth intervals: 1200-600, 600-300, 300-120, 120-80, 80-60, 60-40, 40-20 and 20-0 m (sometimes 20-10 and 10-0 m). These depth intervals were modified slightly or deleted as station depth or equipment malfunction dictated. The MTD net used to collect samples examined in this study was deployed at fixed depths (e.g., 10 m, 30 m, etc.) rather than hauled obliquely through larger depth intervals.

Samples were preserved in 3-5% formalin:seawater.

2.3 Sample Processing

Initial zooplankton samples obtained for this study varied from 20% (our share of the MOCNESS samples) to 100% (most Bongo samples) of the original tow. This sample was then either examined entirely or was subsampled before removal of decapod larvae. The decision of whether or

not to subsample depended on the size of the sample and required some subjective judgment. The general rules governing this decision follow:

1. Subsampling was done only if the settled volume of zooplankton in a clean sample exceeded approximately 0.15 l. The desired settled volume of a clean sample from which decapod larvae would be removed was approximately half the above, or 75 ml. A Folsom plankton splitter was used to split samples.

2. Subsampling was not done if the original sample contained a large volume of gelatinous zooplankton or aggregating phytoplankton (e.g., palmelloid form of Phaeocyctis poucheti) which interfered with the subsampling (splitting) process.

3. Subsampling was not done if the original sample contained a large number of large organisms (euphausiids, chaetognaths, etc.) but relatively few smaller animals.

4. A sample was not subdivided into a fraction containing less than 1/80 (MOCNESS) or 1/16 (Bongo) of the original tow.

The above guidelines were followed to ensure that subsampling yielded representative samples of the plankton. The adequacy of this approach was checked on several occasions with samples representing a variety of plankton conditions. These results are reported in the Data Sensitivity and Accuracy section that follows.

In all cases where at least one split was possible, one of the final pair of samples was archived for possible future needs, including

verification of results or examination of subsampling error. Decapod larvae were removed from the remaining subsample for identification. Occasionally, a subsample yielded hundreds of decapod larvae of a genus. When such numbers were found, these larvae were further sub-sampled using a small plankton splitter before taxonomic work was begun.

2.4 Taxonomy

Once removed from the raw plankton sample, decapod larvae were stored in a 95% ethanol, 2% glycerol solution until they could be identified and counted. The principal objective of this program was enumeration of the larvae of the commercially important king and Tanner crabs, as well as general categories to include all "other" crab and shrimp larvae. However, in the process of distinguishing king and Tanner crab larvae from other Anomura and Brachyura, several additional identifications are made simultaneously. The result is that, with a little extra effort, all other Anomurans and Brachyurans could be identified to some finer taxonomic level within these two sections. The enumeration of larvae of the Korean horse-hair crab, for which there is a developing fishery, was one advantage of this extra effort. Among the shrimp, identification to family can ordinarily be accomplished without much difficulty, so this was routinely done. This has the advantage of separating out the pandalid shrimp (Family Pandalidae) for which there was once, and may be again, a commercial fishery. Identification of the pandalids was done to species level.

A hierarchical list of taxonomic levels identified from our zooplankton samples is provided in Table 2.2. References for the identifi-

Table 2.2. List of taxonomic levels of decapod crustacean larvae identified in this study.

Order Decapoda
- Suborder Reptantia
  - Section Brachyura
    - Family Majidae
      - Subfamily Oregoniinae
        - *Chionoecetes* spp.
        - *C. bairdi*
        - *C. opilio*
        - Non-*Chionoecetes* Oregoniinae (Includes *Hyas* spp. and *Oregonia* spp.)
      - Subfamily Acanthonychinae and/or Pisinae
    - Family Atelecyclidae
      - *Erimacrus isenbeckii*
      - *Telmessus cheiragonus*
    - Family Cancridae
    - Family Pinnotheridae
  - Section Anomura
    - Family Lithodidae
      - *Paralithodes camtschatica*
      - *P. platypus*
      - Non-*Paralithodes* Lithodidae
    - Family Paguridae
      - *Pagurus* spp.
- Suborder Natantia
  - Section Penaeidea
    - Family Penaeidae
      - *Penaeus* spp.
  - Section Caridea
    - Family Pandalidae
      - *Pandalus borealis*
      - *P. tridens*
      - *P. hypsinotus*
      - *P. stenolepis*
      - *Pandalopsis dispar*
    - Family Crangonidae
      - *Crangon* spp.
      - *Argis dentata*
    - Family Hippolytidae
    - Family Pasiphaeidae
      - *Pasiphaea* spp.

cation of these larvae and the various larval stages are included in the text sections for each major larval group.

2.5 Data Reporting

The larvae of commercial decapod crustaceans are the focus of this report; they include the larval stages (zoeae and megalopae) of king crab (*Paralithodes camtschatica*, *P. platypus*), Tanner crab (*Chionoecetes bairdi*, *C. opilio*), korean horse-hair crab (*Erimacrus isenbeckii*), and pandalid shrimp (*Pandalus borealis*). In most cases, larvae of all other taxonomic divisions enumerated in our laboratory work are discussed in general categories as the larvae of "other anomuran crabs," "other brachyuran crabs" and "other shrimp." The pagurid crabs (Anomura: Paguridae), though of no direct commercial value, have received special attention because of the abundance and widespread distribution of their larvae in the study area.

Larval abundance is reported throughout most of this text as estimated number of larvae per 100 m^2 sea surface area (number/100 m^2). This provides a common unit of measure by which the abundance of various larvae can be compared and summed, regardless of differences in their vertical distribution in the water column. The larvae of some taxa are more concentrated in some depth intervals than others, and this may change for the various developmental stages. Vertical distribution patterns and mean densities of larvae (numbers per 1000 m^3) are described for most of the major taxonomic groups. These data are used in the interpretation of potential oil impacts.

In our annual report (Armstrong et al. 1981), all larval abundance data were reported in units of numbers/1000 m^3. This volumetric basis for representing mean abundance was abandoned because it did not include larvae below 60 m depth (although the error introduced by this omission was small) and because it was not an accurate reflection of how larvae are distributed in the ocean. The units presently used (number/100 m^2 of sea surface) include all larvae sampled and provide no misconception about "uniform distribution." Estimates of abundance from the annual report can be compared with the data provided here in the following way. In virtually all cases the majority of larvae were found above 60 m (Tanner crab mainly in the upper 20 m), so this was considered a lower limit for calculations of numbers/1000 m^3. The surface area of a 1000 m^3 volume extending to 60 m depth is about 16.7 m^2. To convert the volumetric estimates of abundance to units of numbers/100 m^2, a multiplication factor of 5.99 is used (100 ÷ 16.7 = 5.988). For sampling in depths less than 60 m this multiplier changes. For example, density values for larvae caught in 40 m of water will be only four times greater in units of 100 m^2 than 1000 m^3. However, few samples reported in the 1981 annual report were integrated over water columns of less than 60 m depth.

2.6 Data Sensitivity and Accuracy

The volume (or mass) of plankton retained by the comparatively large mesh of the Bongo nets was frequently much smaller than that retained by the finer mesh nets used on MOCNESS. Yet the estimated volume of water sampled by nets of the two devices (according to the flow

meters) was often similar (generally 200-300 m^3). It was determined above that all decapod larvae would be retained by any of the mesh sizes employed for the samples, so that the nets, in theory, should serve equally well for estimating the density of decapod larvae at various stations. However, at least three factors affect the estimates we make: (1) systematic differences in the degree of subsampling dictated by corresponding differences in the volume of plankton retained by each net per volume of water filtered; (2) inherent differences in net clogging related to net porosity and (3) differences in the location of the flow metering device.

When the volume of water filtered by a MOCNESS and a Bongo are approximately the same but there are large numbers of small organisms retained by MOCNESS and not by the larger mesh Bongo nets, the former will be sub-sampled to a greater extent than the latter. When the net plankton samples from MOCNESS and the Bongo are approximately the same size and, consequently, subject to the same sub-sampling, it is frequently because the former has sampled less water than the latter. It is only when small plankton (in the intermediate size range 150-333 μm or 150-505 μm) are rare that the volumes of water filtered and the number of sub-sampling splits can be the same for both MOCNESS and Bongo samples. Since the latter condition does not usually prevail, the representative volume of water actually examined in MOCNESS sub-samples is almost always smaller than that examined from Bongo samples. This has the effect of decreasing the lower level of detection, or numerical sensitivity, of the MOCNESS samples relative to the Bongo.

Bongo samples were usually split no further than 1/8, and were never split to less than 1/16, of the original sample. Such splits place the lower level of detection in sub-samples at about 8-16 animals of each taxon per 200-300 m^3 average tow, assuming perfectly uniform distribution of the larvae in the splitting process. Early in the season, the zooplankton community is not well developed, so splits were usually not necessary. Under these conditions the entire sample is examined and the probable lower level of detection for reporting becomes about 1 in 250 m^3 (assuming an average tow), or roughly 5 per 1000 m^3 or 30 per 100 m^2.

MOCNESS nets filtered about three times more water per meter of depth than the Bongo tows (200-300 m^3 per 20 m depth interval for MOCNESS compared with 200-300 m^3 per 60 m for Bongo nets). However, our share of PROBES MOCNESS samples was 20% of the original (the splits were done on board ship), so we always examined plankton from a smaller volume of water with MOCNESS samples than Bongo samples. Theoretically, MOCNESS samples should be less capable of detecting low larval abundance than Bongo samples. In addition, the finer mesh of the MOCNESS nets usually necessitated more sub-sampling, but not early in the season (April and early May) at early stages in the development of the zooplankton community.

Since MOCNESS nets had a finer mesh, they were more prone to net clogging than the larger mesh Bongo nets. Clogging may be caused by phytoplankton as well as zooplankton, and reduces the actual amount of seawater filtered. The analytical problem created by this condition is compounded by the location of the flow-metering device. Unlike the

Bongo frame, the MOCNESS frame cannot accommodate a flowmeter positioned in front of the net opening (because of the sliding nets and the way the frame is handled on deck). Instead, the flowmeter sits atop the frame, where it is insensitive to actual changes in flow into the net. The MOCNESS theoretically over-estimates the volume of water filtered, and our calculations should routinely underestimate the density of decapod larvae present. This problem is not even internally consistent within a station, since phytoplankton and other zooplankton are not uniformly distributed with depth and may affect only some of the nets used. The 0-20 and 20-40 m nets are usually subject to more clogging than the deeper ones, so that calculations of abundance in the upper 40 m should be underestimated relative to calculations for deeper samples.

While these potential difficulties should be remembered in interpreting plankton data, they do not appear to have presented a major problem in this study. This may have been due to differences in the calibration and/or performance of the flow meters. Incze (1983) compared estimates of abundance of Chionoecetes larvae made with MOCNESS and Bongo nets deployed at the same stations and found no consistent bias in the estimates. Rather, small-scale patchiness in abundance was sufficient to mask differences in the accuracy of flow estimation based on a comparison of coefficients of variation. In this study, all gear were considered to provide similar estimates of abundance.

2.7 Vertical Distribution Patterns

Discrete depth interval samples collected by MOCNESS were used to examine patterns of vertical (depth) distribution of abundant decapod

larvae. A computer program was used to generate listings of all MOCNESS stations where larvae of a particular taxon were found. For each depth interval (0-20, 20-40, 40-60, 60-80, and >80 m) at each station, the estimated abundance of larvae (number/1000 m^3), the number of larvae actually counted for the estimate, and the size of the sub-sample providing this count were listed. Stations with estimates of larval abundance based on too few specimens and/or on very small sub-samples were not considered. Although no strict criteria could be developed for making this decision, it was generally not difficult to decide by inspection whether the data were sufficient for adequately describing a vertical distribution pattern. For each station with sufficient data, the vertical distribution of larvae was determined by calculating the proportion of all larvae collected at each depth interval. This was done for each year of MOCNESS samples (1980 and 1981), and, sometimes, for individual larval stages. For some taxa, diurnal patterns were also examined.

2.8 Geographic Division of the Study Area

The study area was divided into twelve sub-areas, or strata (Fig. 2.21), for estimating mean larval abundance. The divisions were based on regional hydrographic structure, faunal distribution patterns and the availability of sampling data. A breakdown of the southeastern Bering Sea into strata facilitated comparisons of timing and abundance of certain taxa between areas and years. This approach worked best with Tanner crab and pandalid shrimp larvae, but also facilitated a summary of general larval distributions for taxa that were less common or were poorly sampled, such as king crab and Korean hair crab. Estimates of

abundance within strata were made by averaging data from all stations sampled within certain time intervals (usually one month; see Incze 1983 for details). For illustrating patterns of larval abundance, however, individual station data were used. Further subdivisions of strata were made for descriptive and statistical purposes in the case of Tanner crab larvae (Section 4.0).

Figs. 2.1 - 2.18. Station locations for zooplankton samples examined for decapod larvae and reported here. Sponsoring agency/ programs, year, cruise number, and dates as follows (NOAA 1976 through 1979 = OCSEAP program; NOAA 1981 = NMFS program):

2.1. NOAA 1976. Cruise MF-76A, 26 April - 31 May. Three stations west of 172°W not shown.

2.2. NOAA 1977. Cruise RP-4-MF-77B, 16-30 April.

2.3. NOAA 1977. Cruise RP-4-MF-77B, 1-17 May.

2.4. NOAA 1978. Cruise MF 78-1, 11 February - 16 March. Six stations west of 172°W not shown.

2.5. NOAA 1979. Cruise 3 MF-79, 1-27 June.

2.6. PROBES 1978. Cruise TT 131 (University of Washington), Leg 1 11-28 April.

2.7. PROBES 1978. Cruise TT 131 (University of Washington), Leg 3 27 May - 11 June.

2.8. PROBES 1978. Cruise TT 131 (University of Washington), Leg 4 17-29 June.

2.9. PROBES 1980. Cruise TT 149 (University of Washington), Leg 2 6-21 April.

2.10. PROBES 1980. Cruise TT 149 (University of Washington), Leg 3 27 April - 18 May.

2.11. PROBES 1980. Cruise TT 149 (University of Washington), Leg 4 22 May - 8 June. PROBES A-line shown.

2.12. PROBES 1980. Cruise AX 9 (University of Alaska) Samples collected 4 and 5 October.

2.13. PROBES 1981. Cruise TT 159, Leg 1, 17-26 April

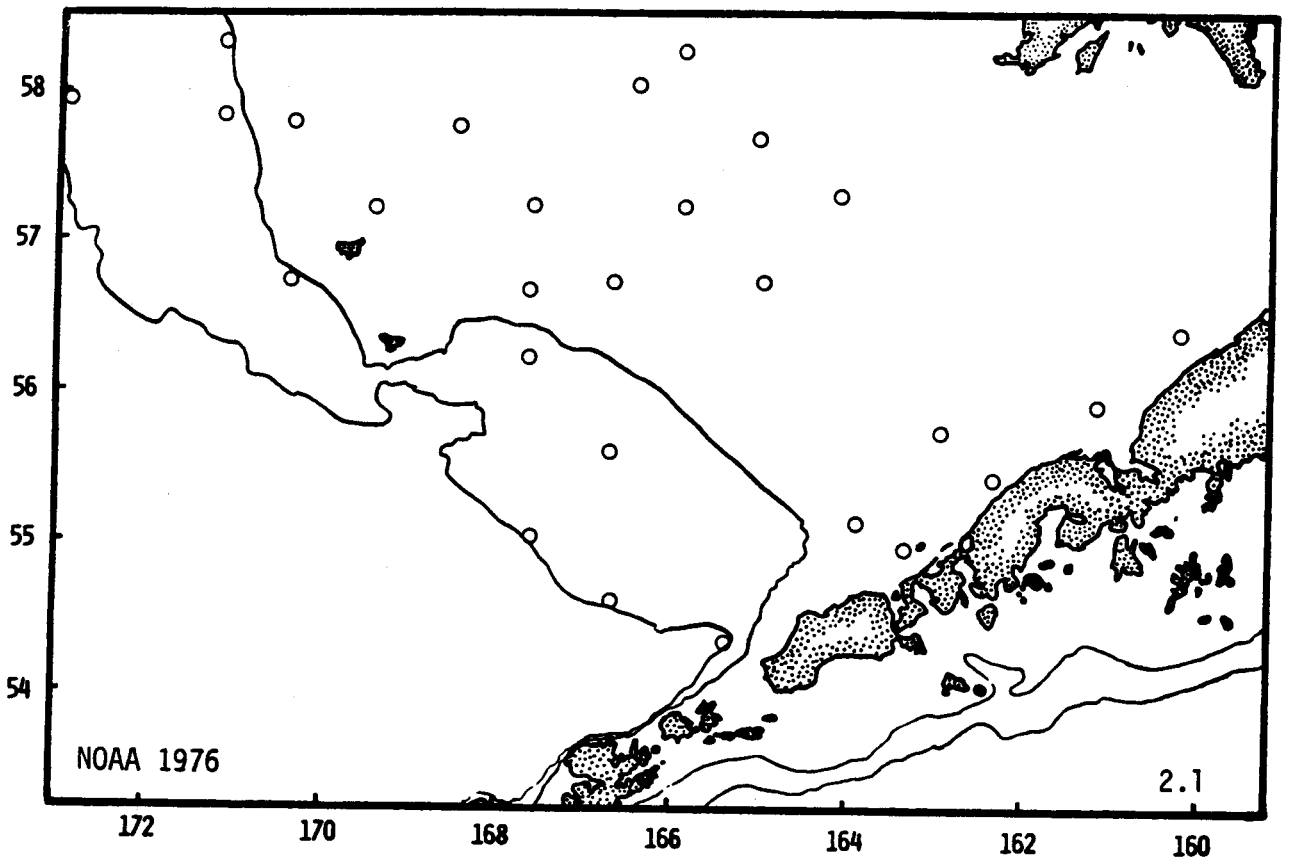
2.14. PROBES 1981. Cruise TT 159, Leg 2, 2-25 May

2.15. PROBES 1981. Cruise TT 159, Leg 3, 31 May - 20 June

2.16. PROBES 1981. Cruise TT 159, Leg 4, 27 June - 19 July

2.17. NOAA 1981A. Cruise RP4-D1-81A, 14-31 May

2.18. NOAA 1981B. Cruise AL/811, 24 May - 20 July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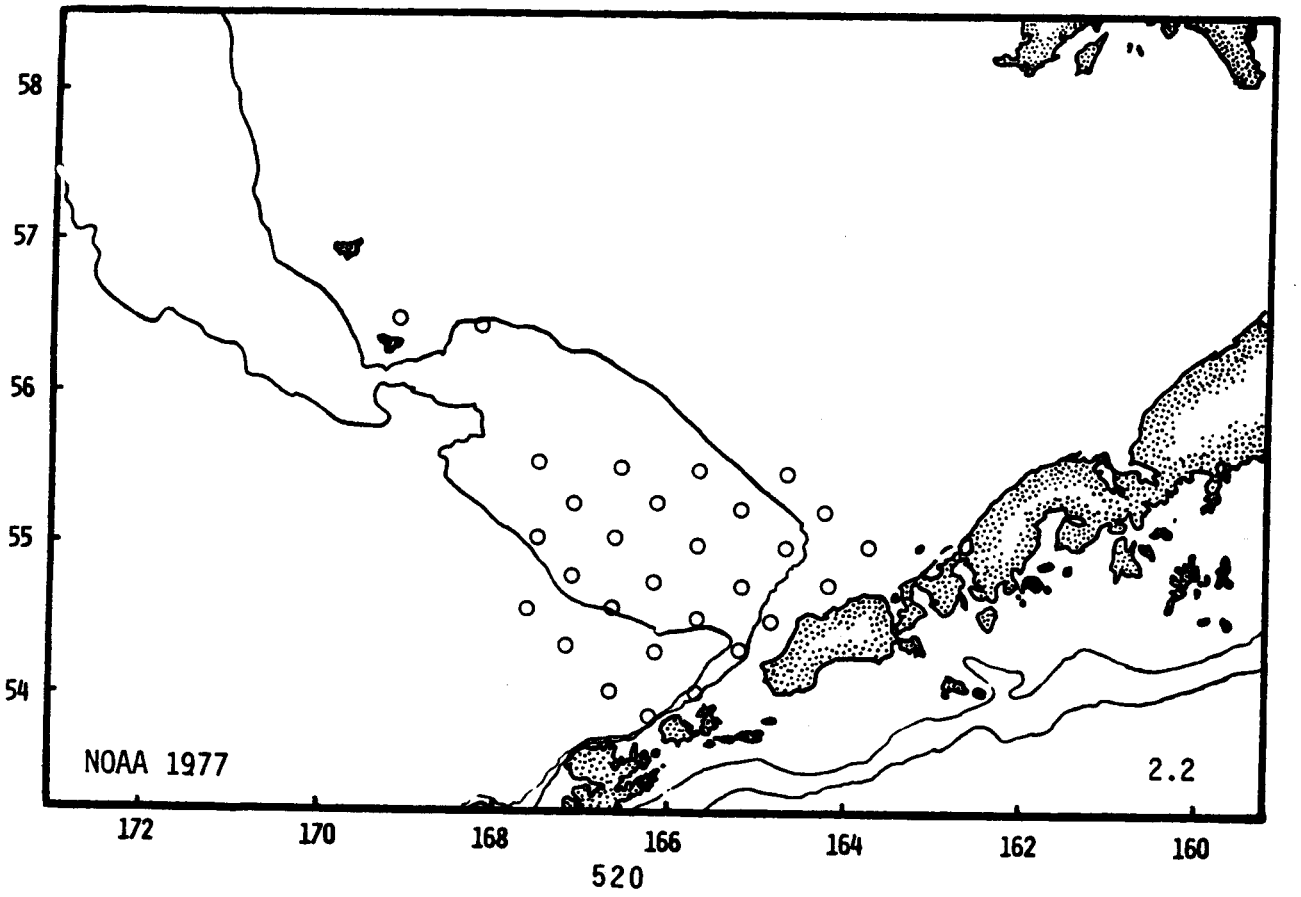
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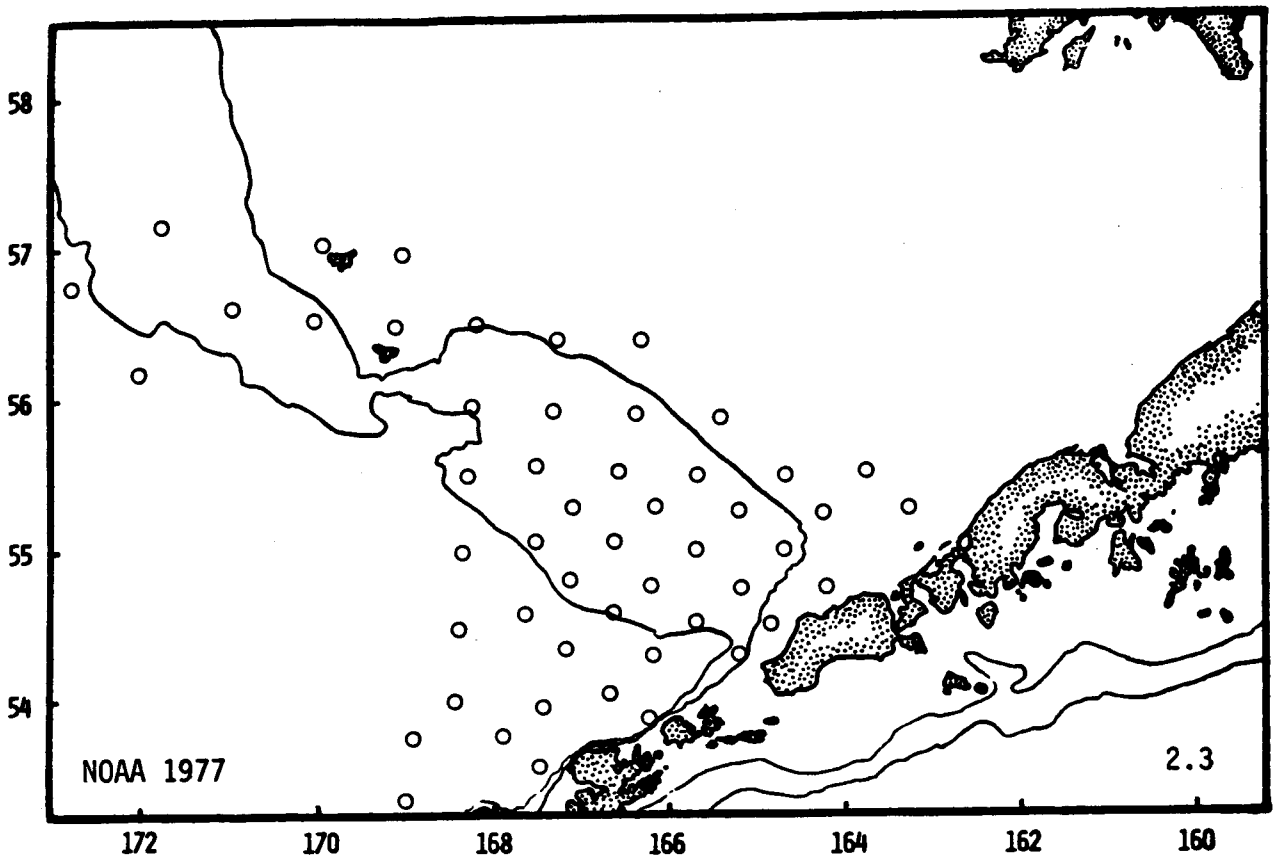
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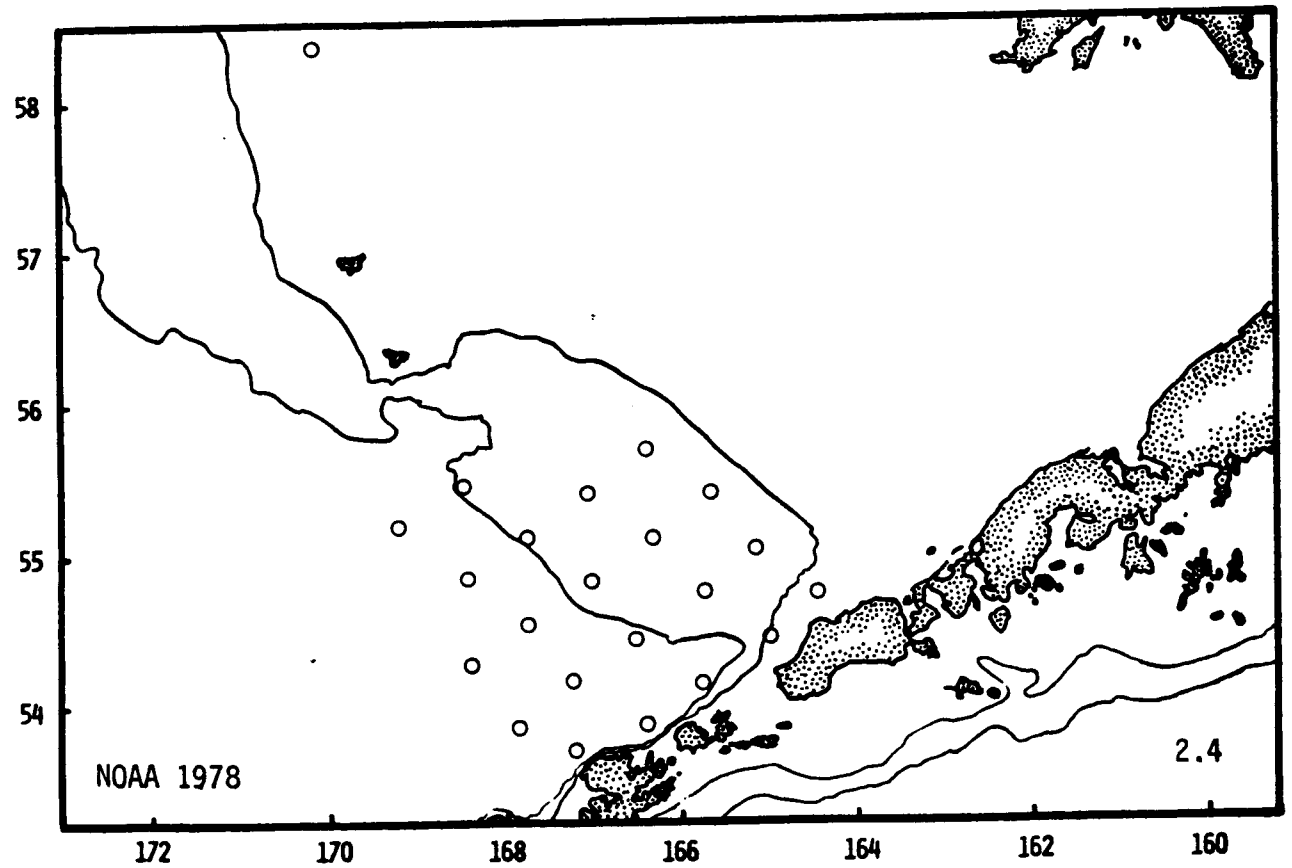
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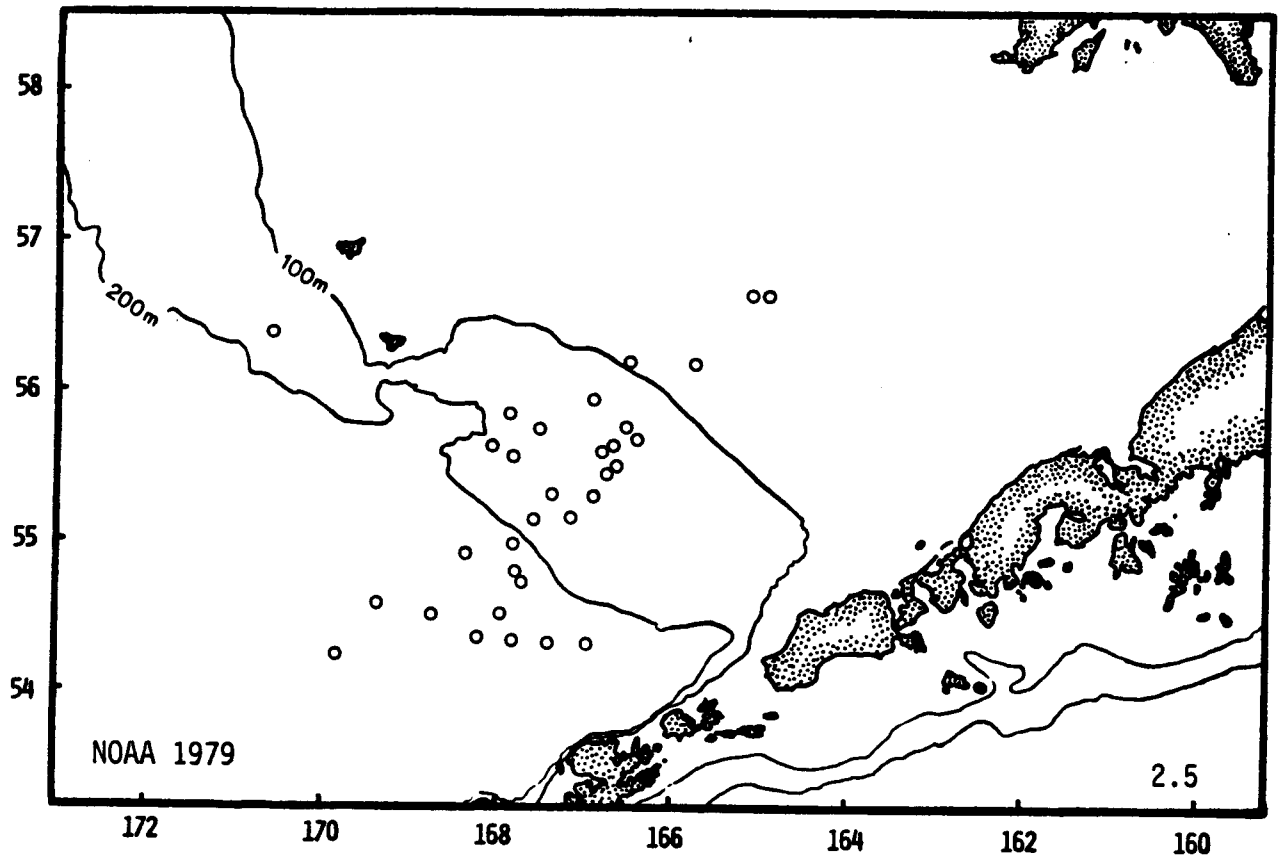
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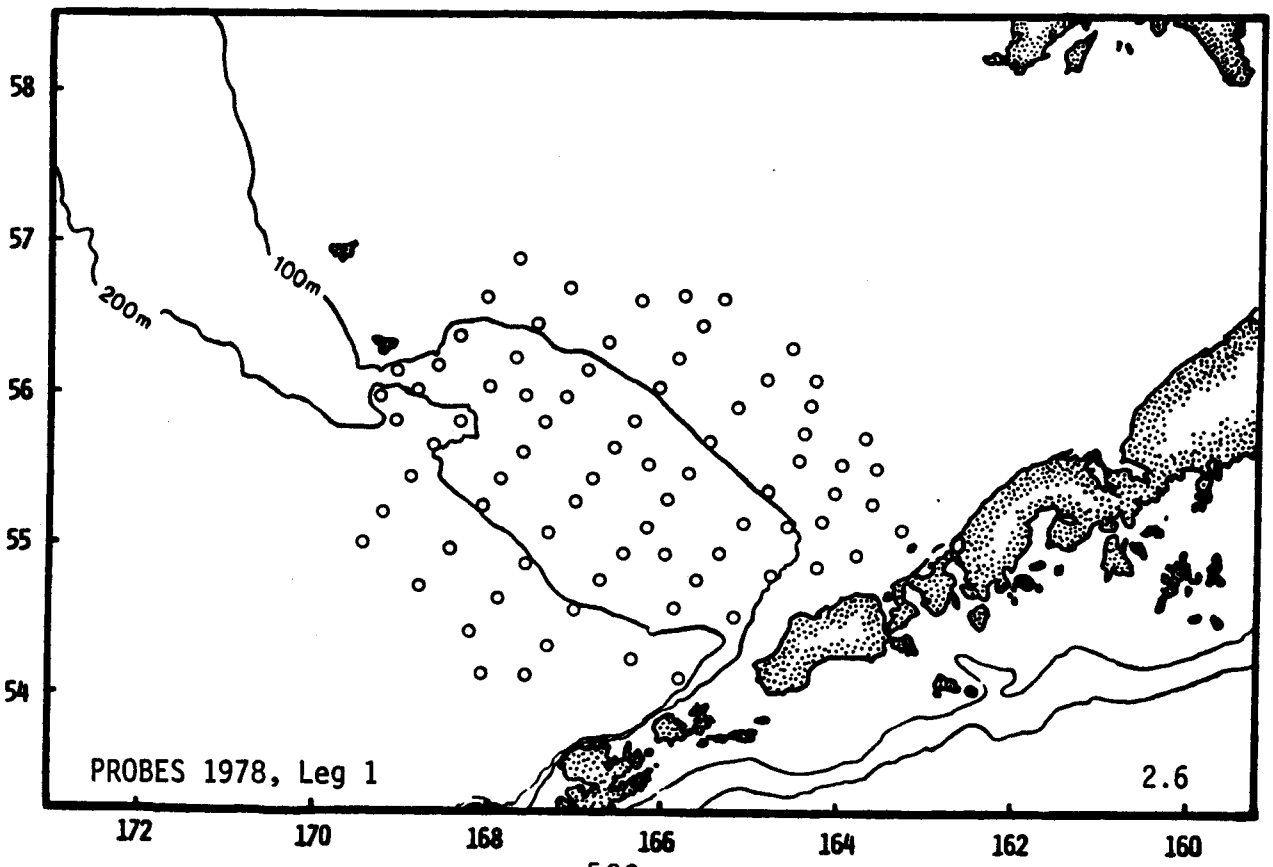
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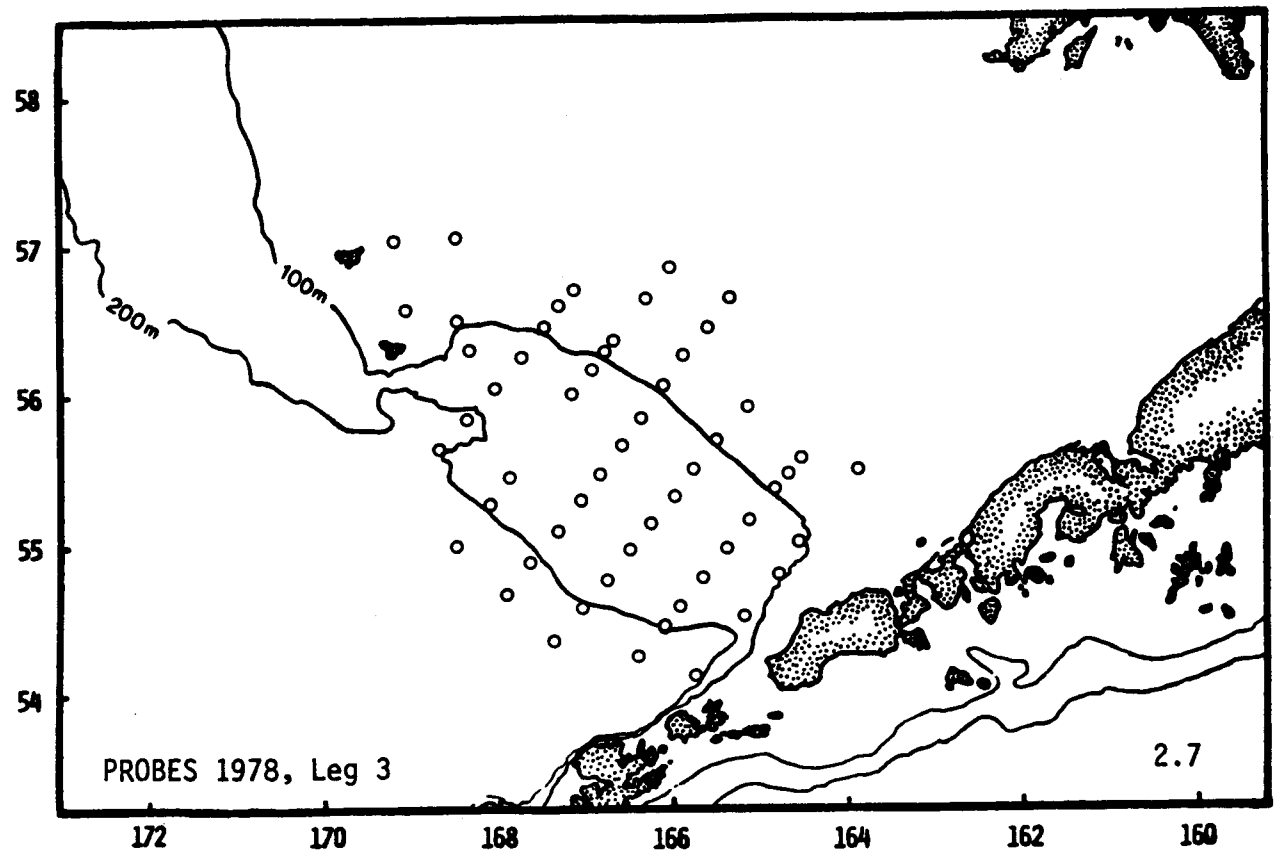
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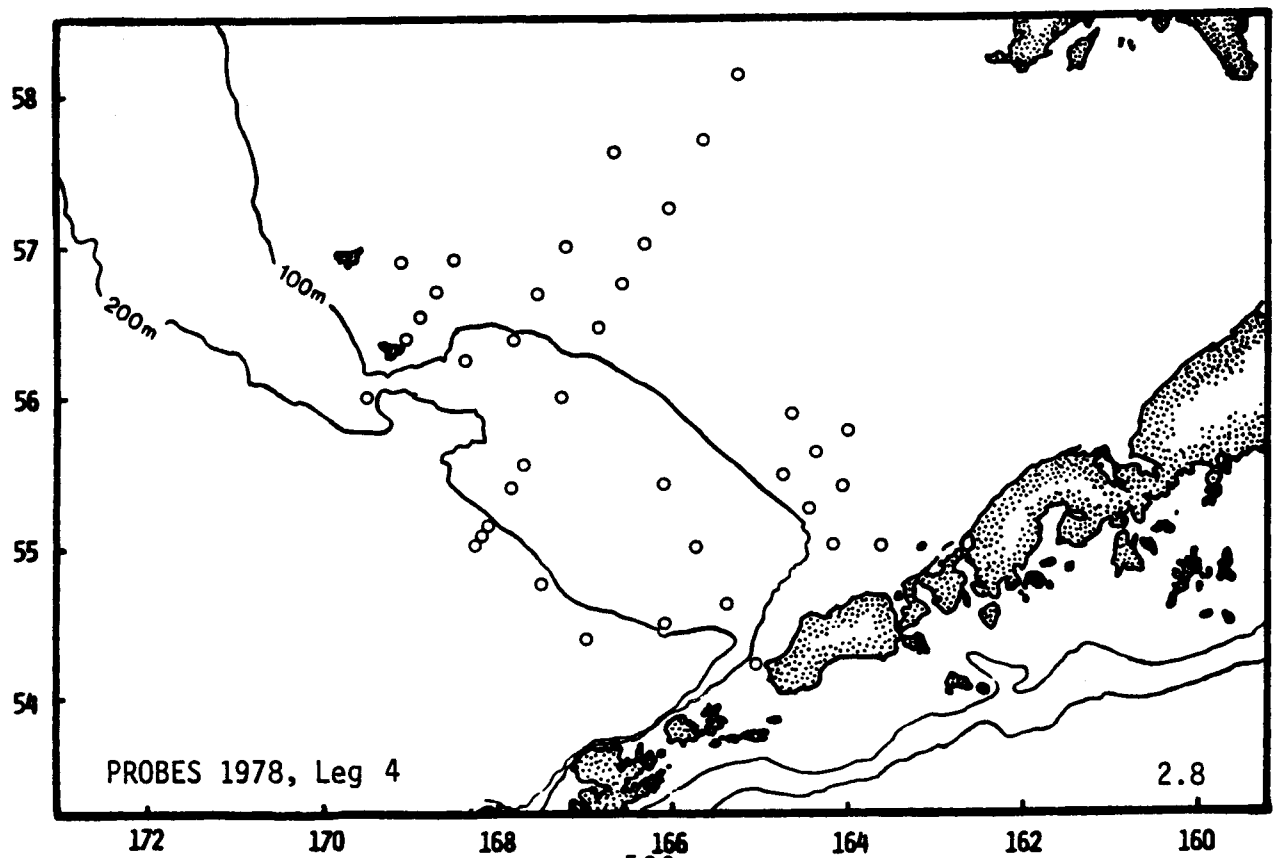
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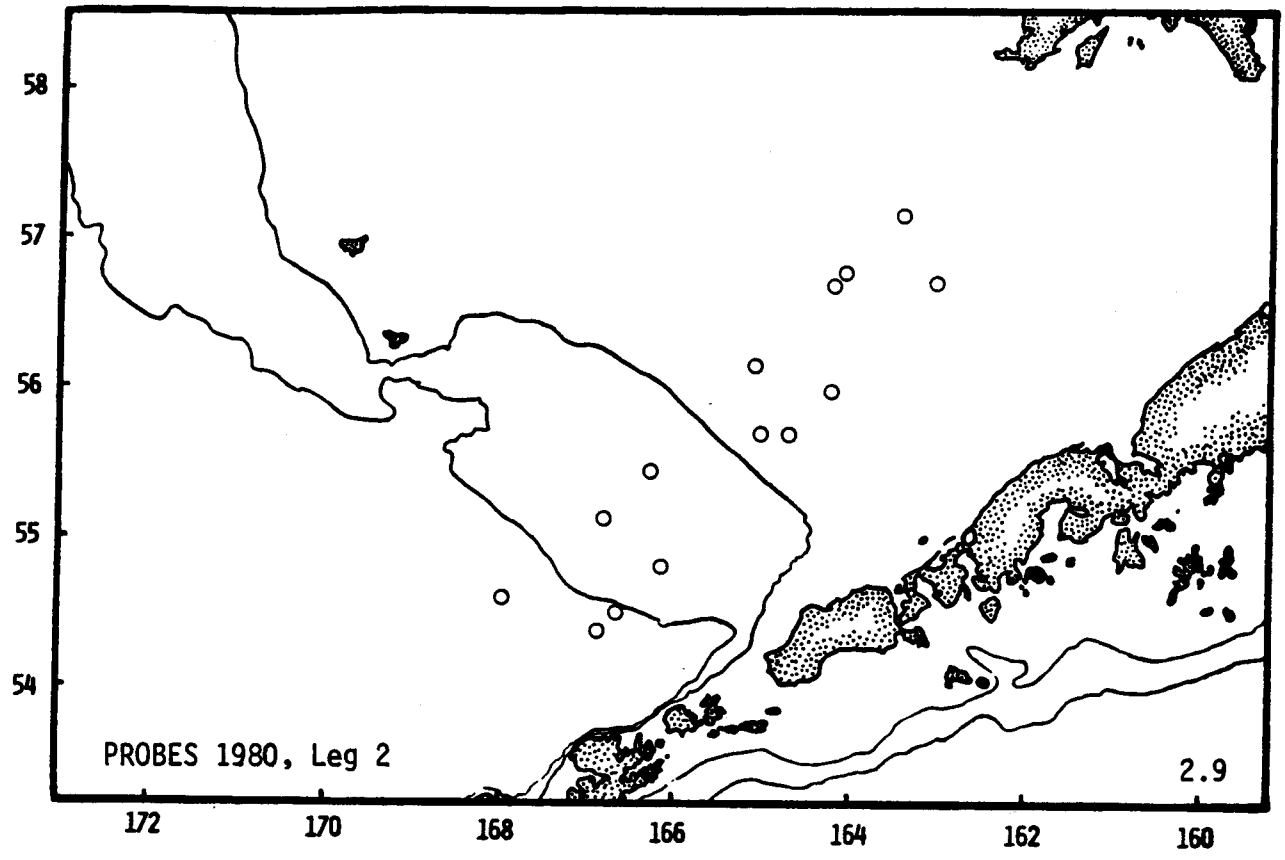
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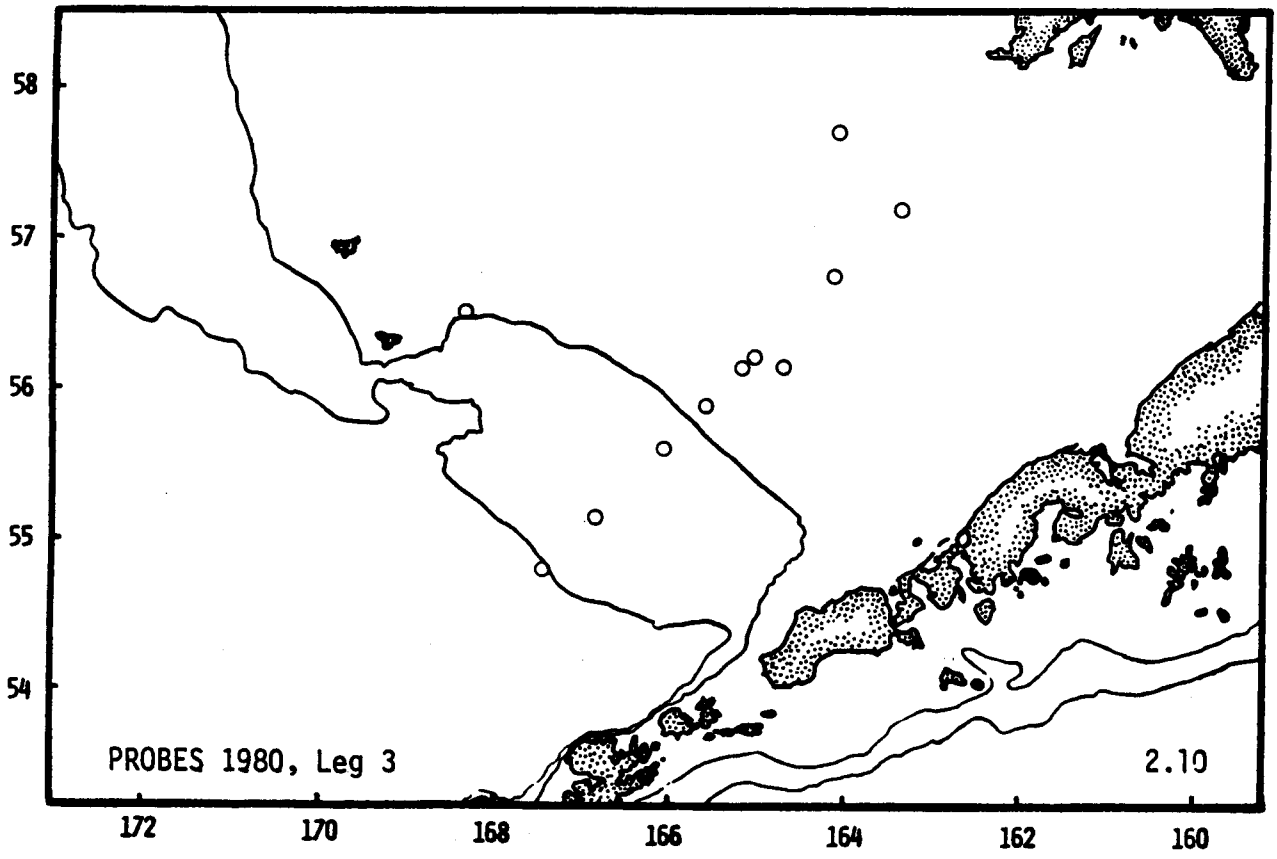
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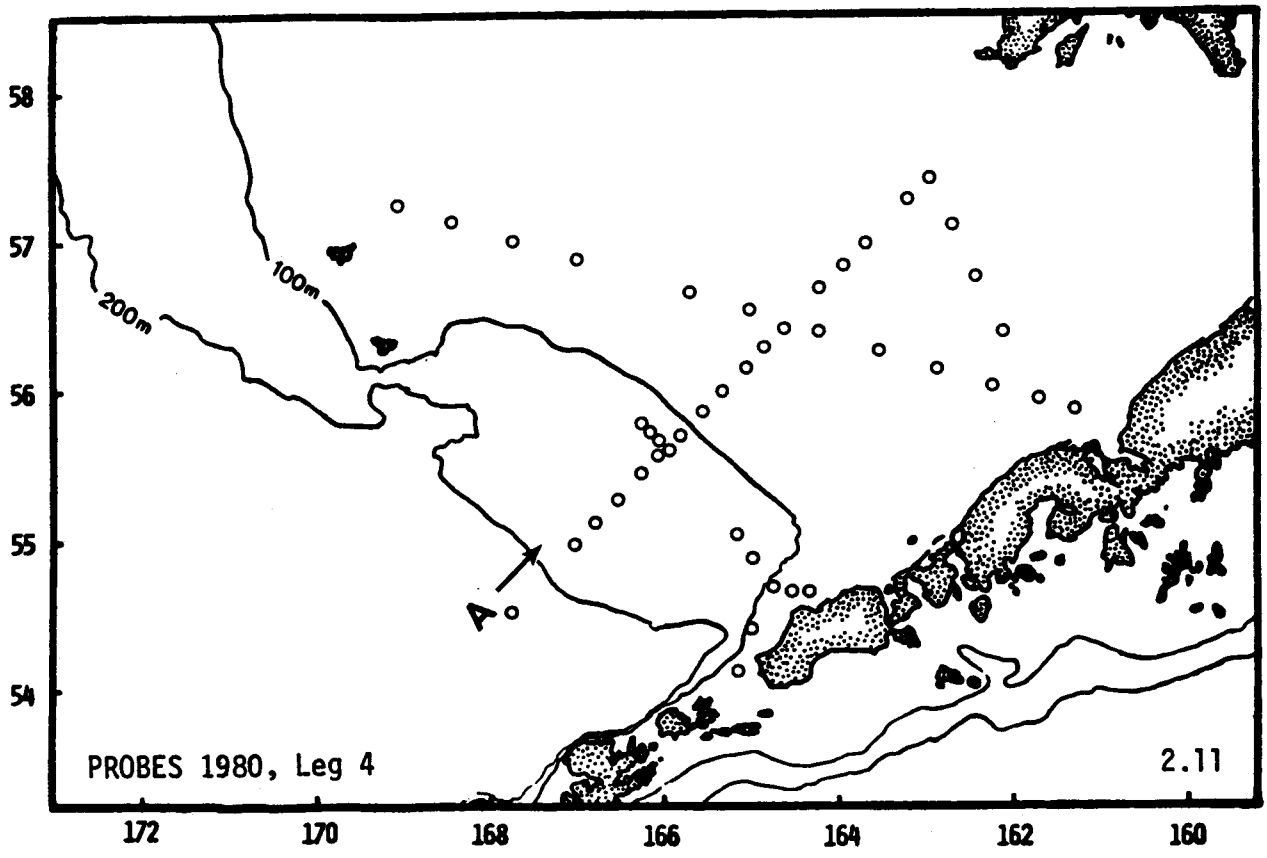
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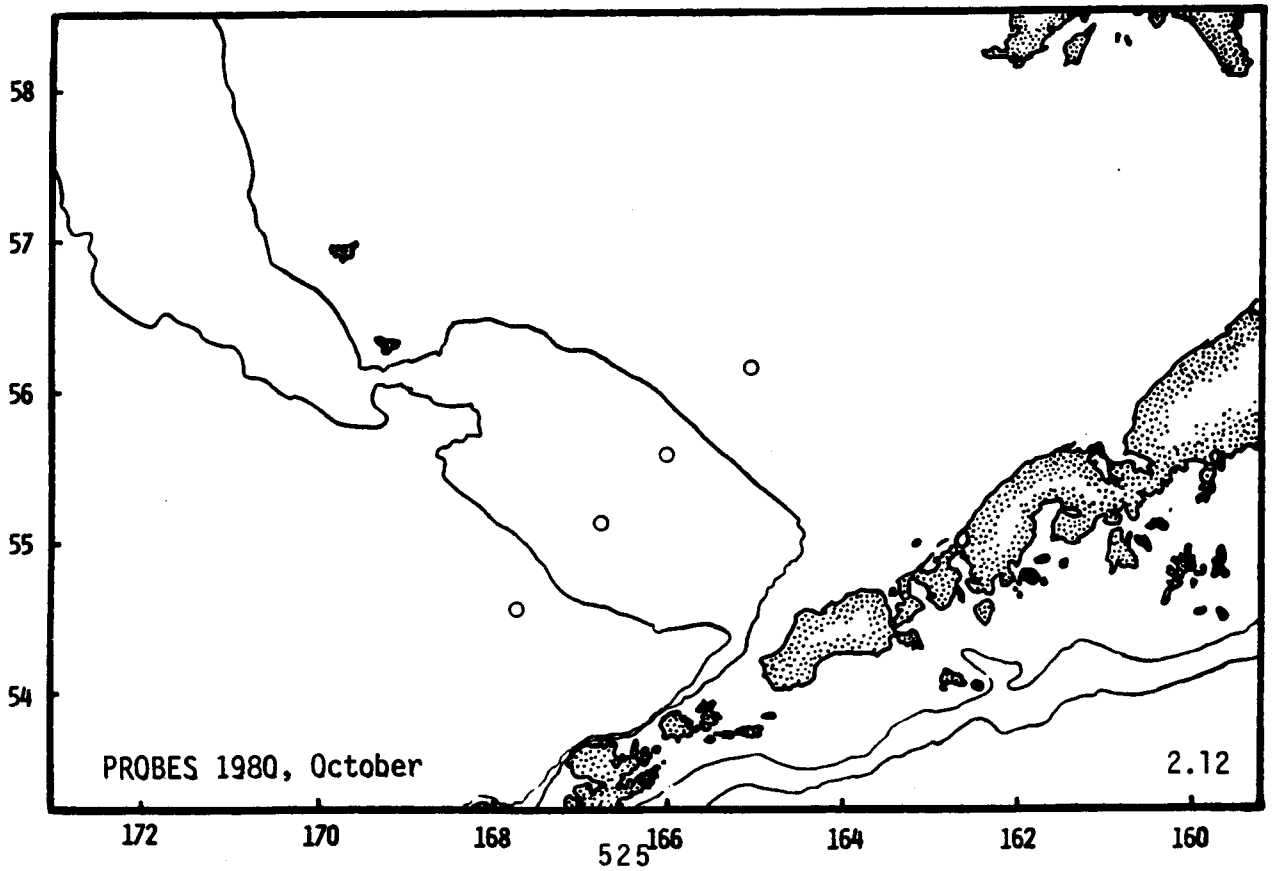
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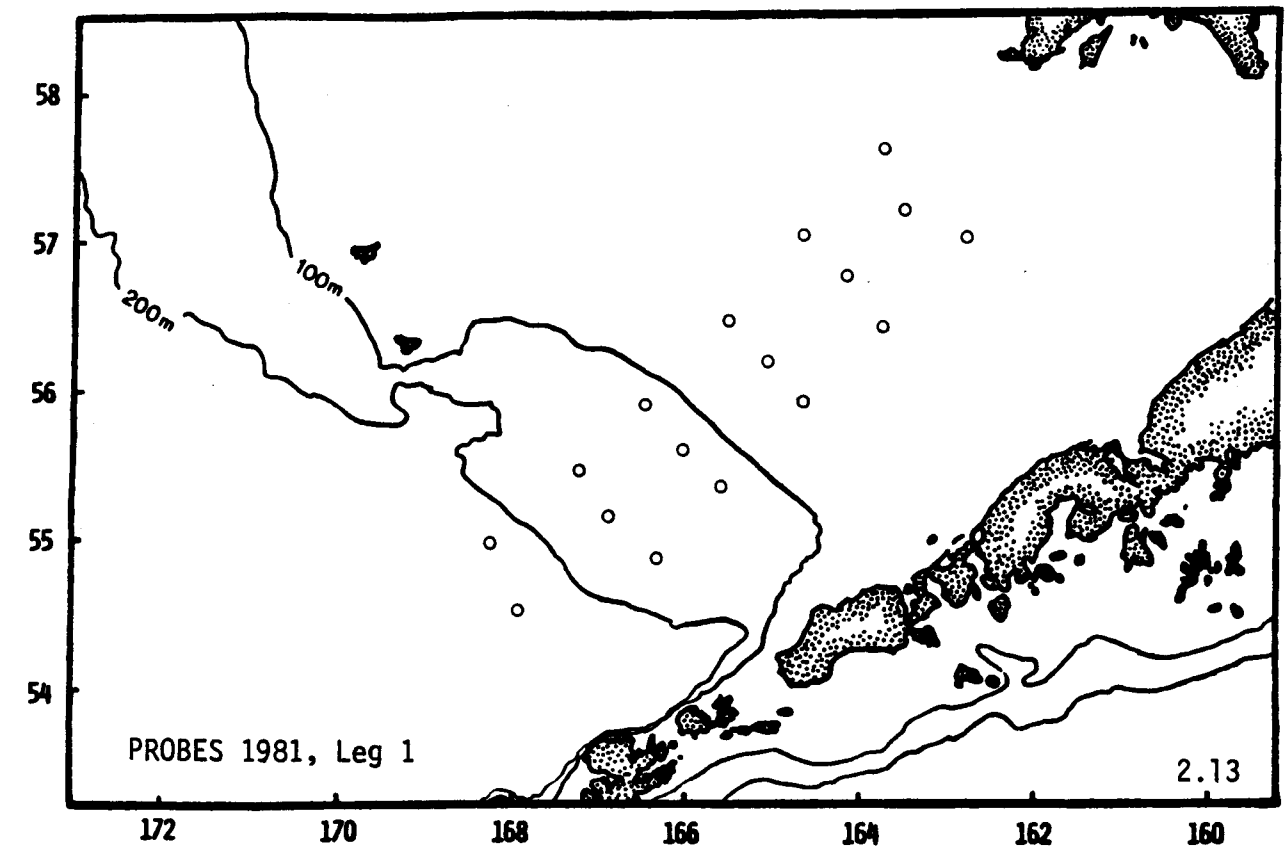
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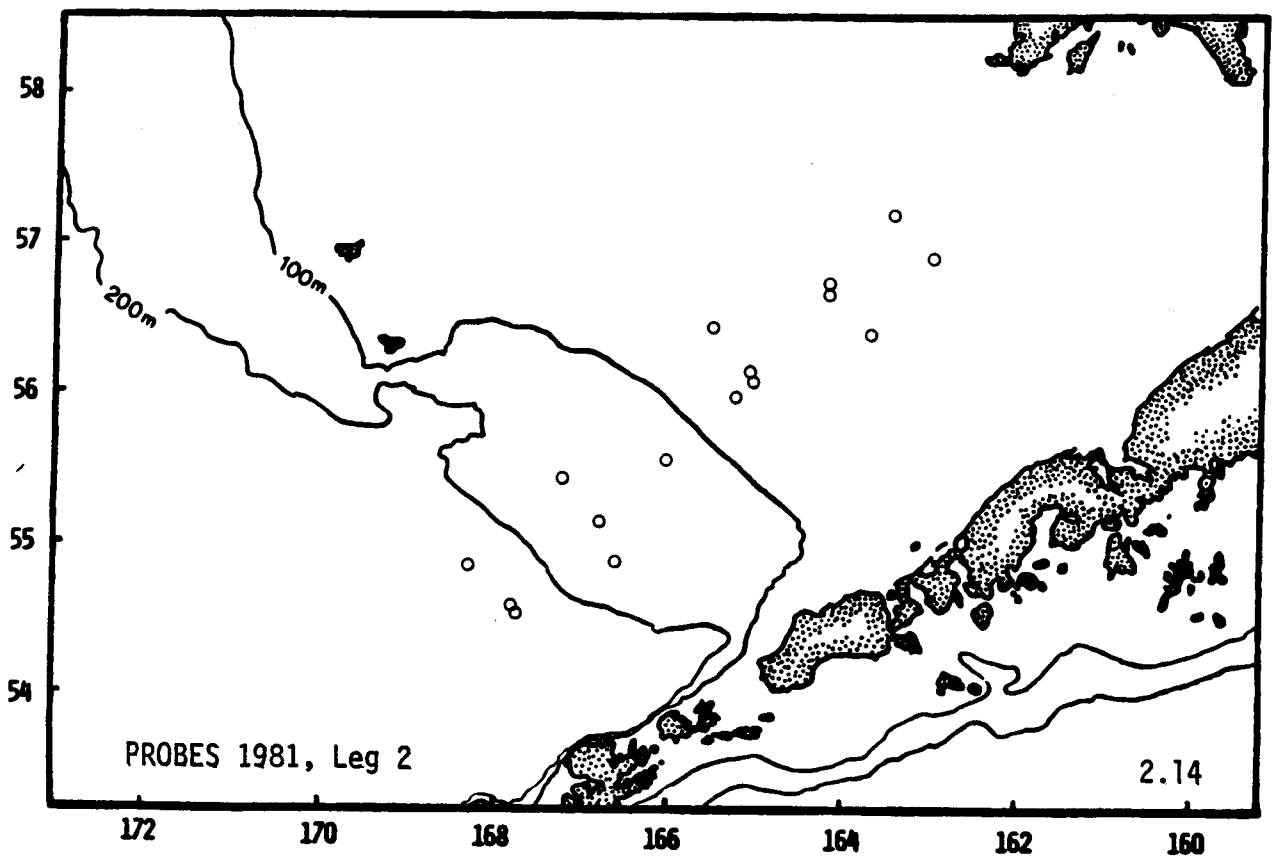
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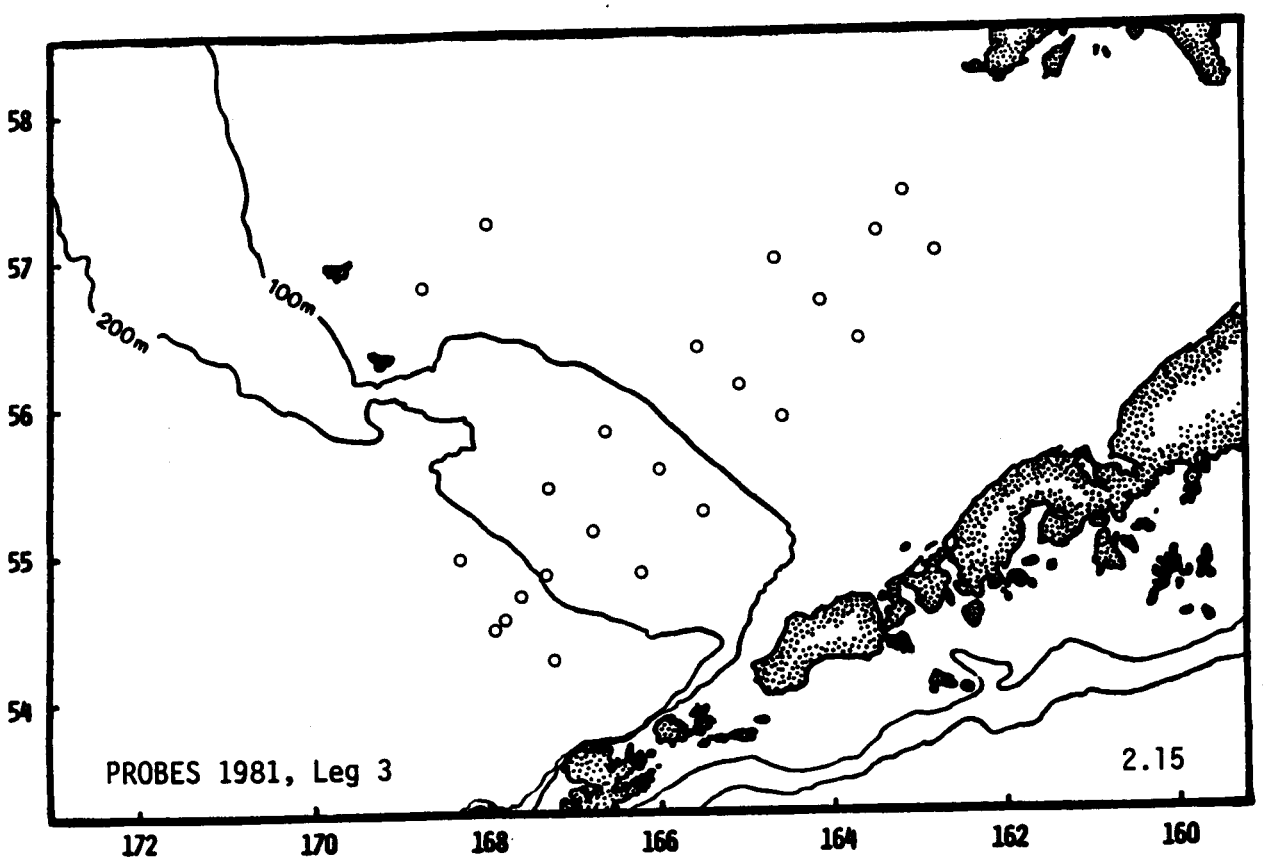
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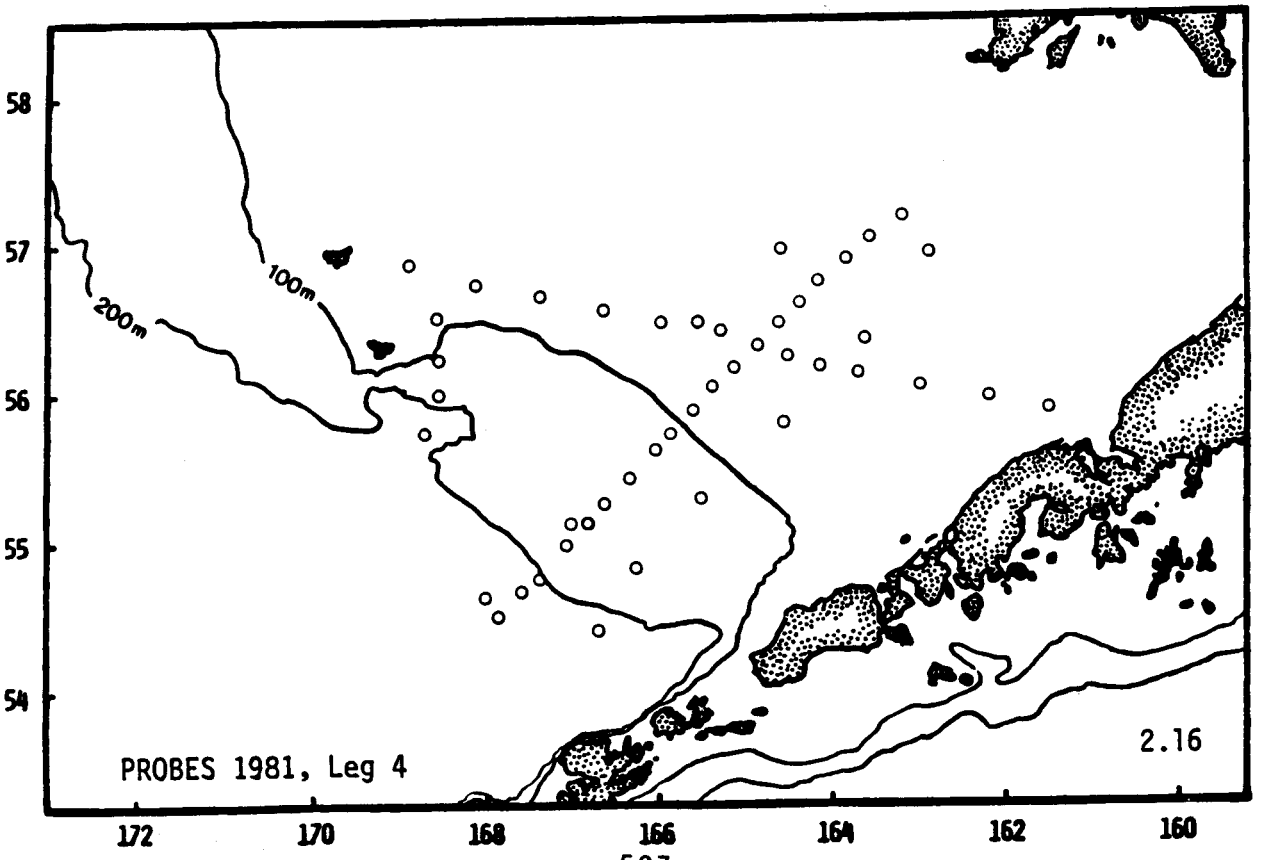
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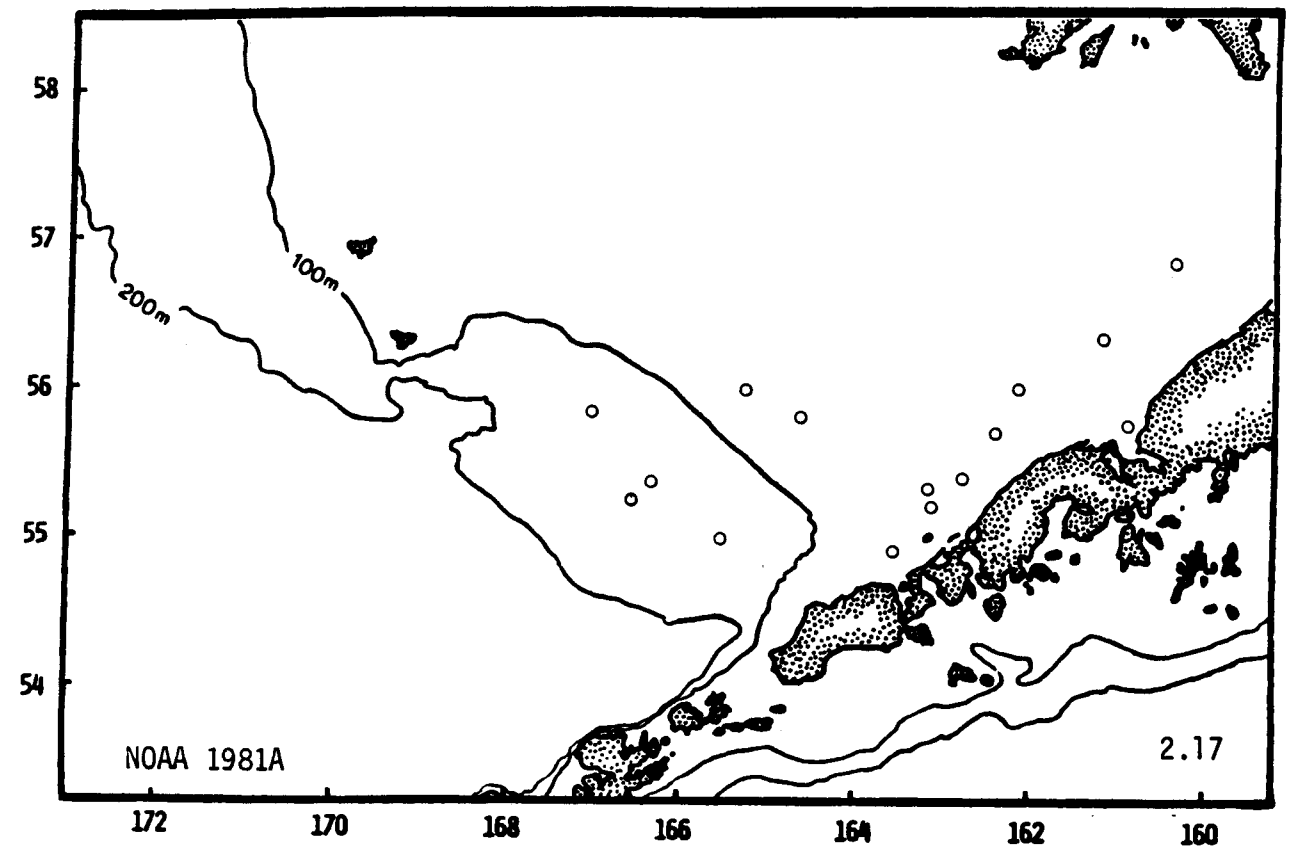
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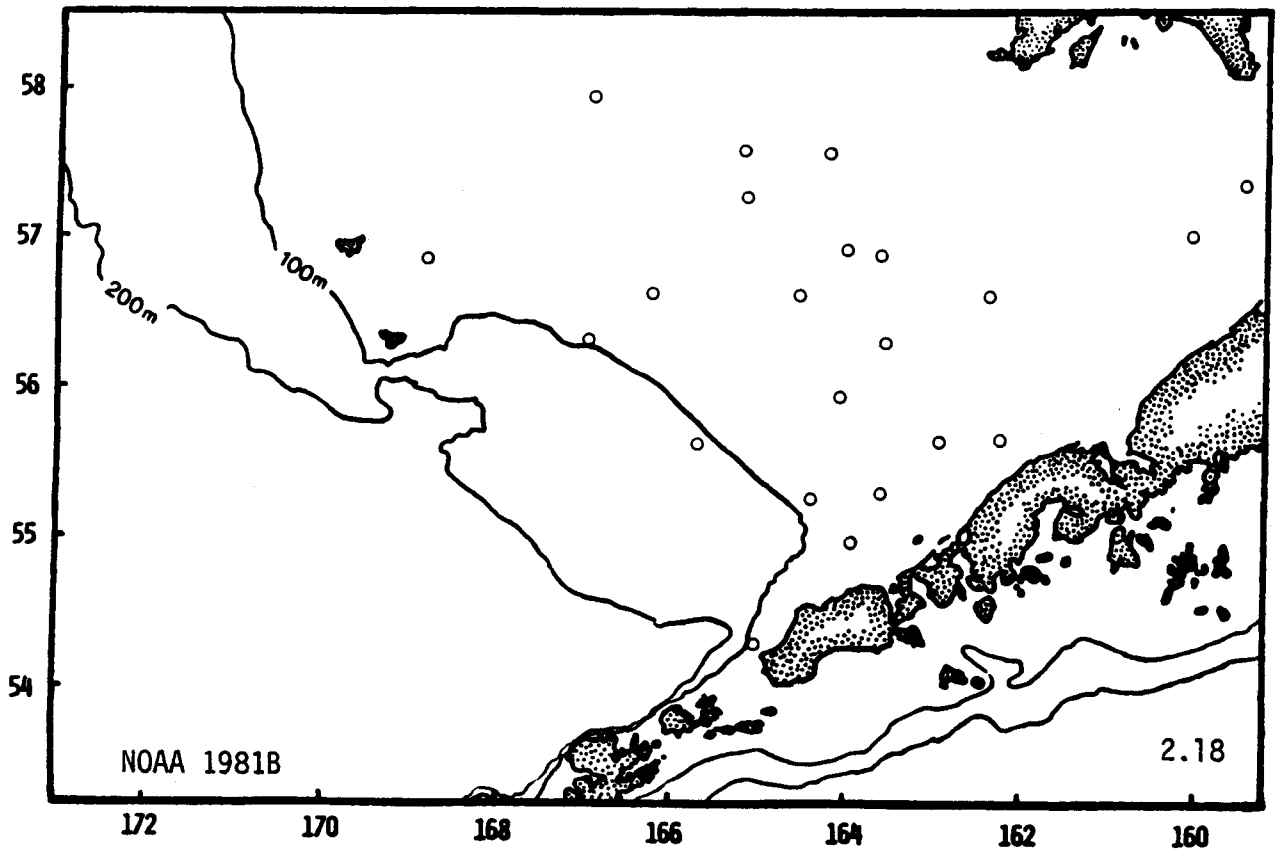
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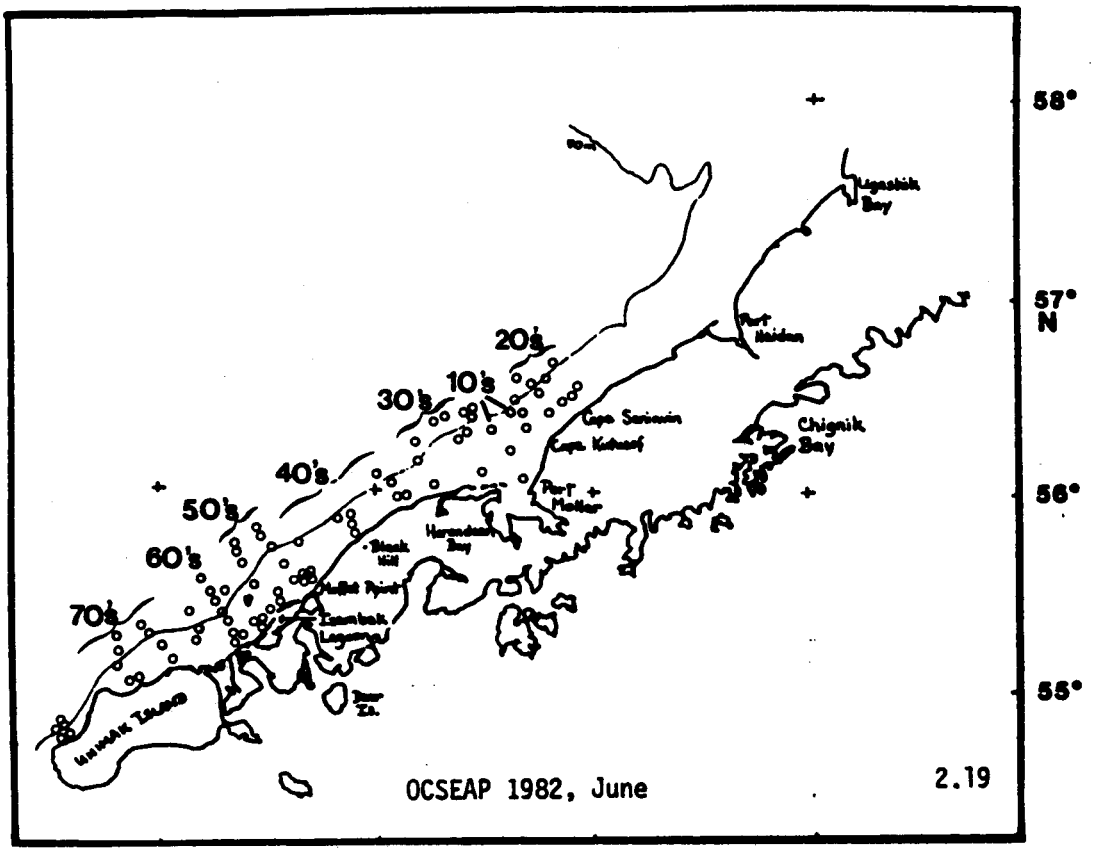


Figure 2.19 Station locations of June 1982 nearshore North Aleutian Shelf samples; OCSEAP Miller Freeman cruise. Units of ten indicate station sequence in time and space of zooplankton samples (see Section 4.0).

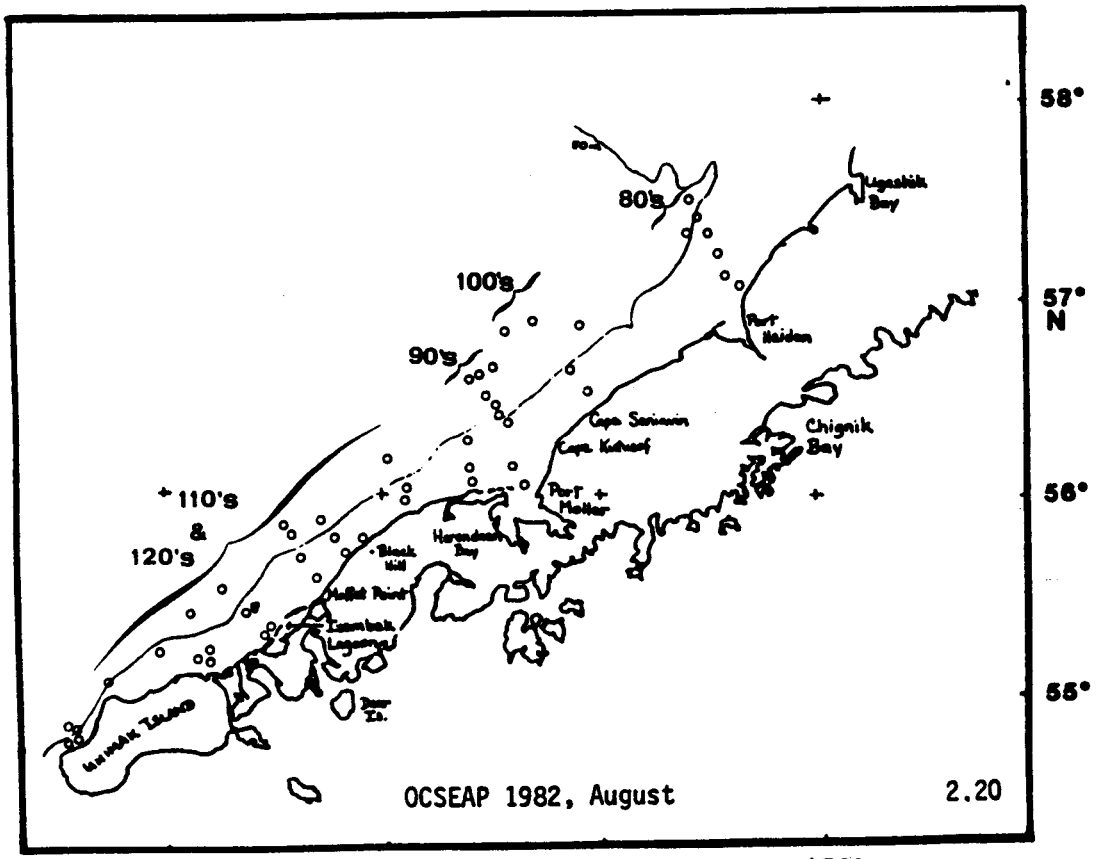


Figure 2.20 Station locations Aug. 3-10, 1982 nearshore North Aleutian Shelf samples; OCSEAP Miller Freeman. Units of ten show station sequence in time and space.

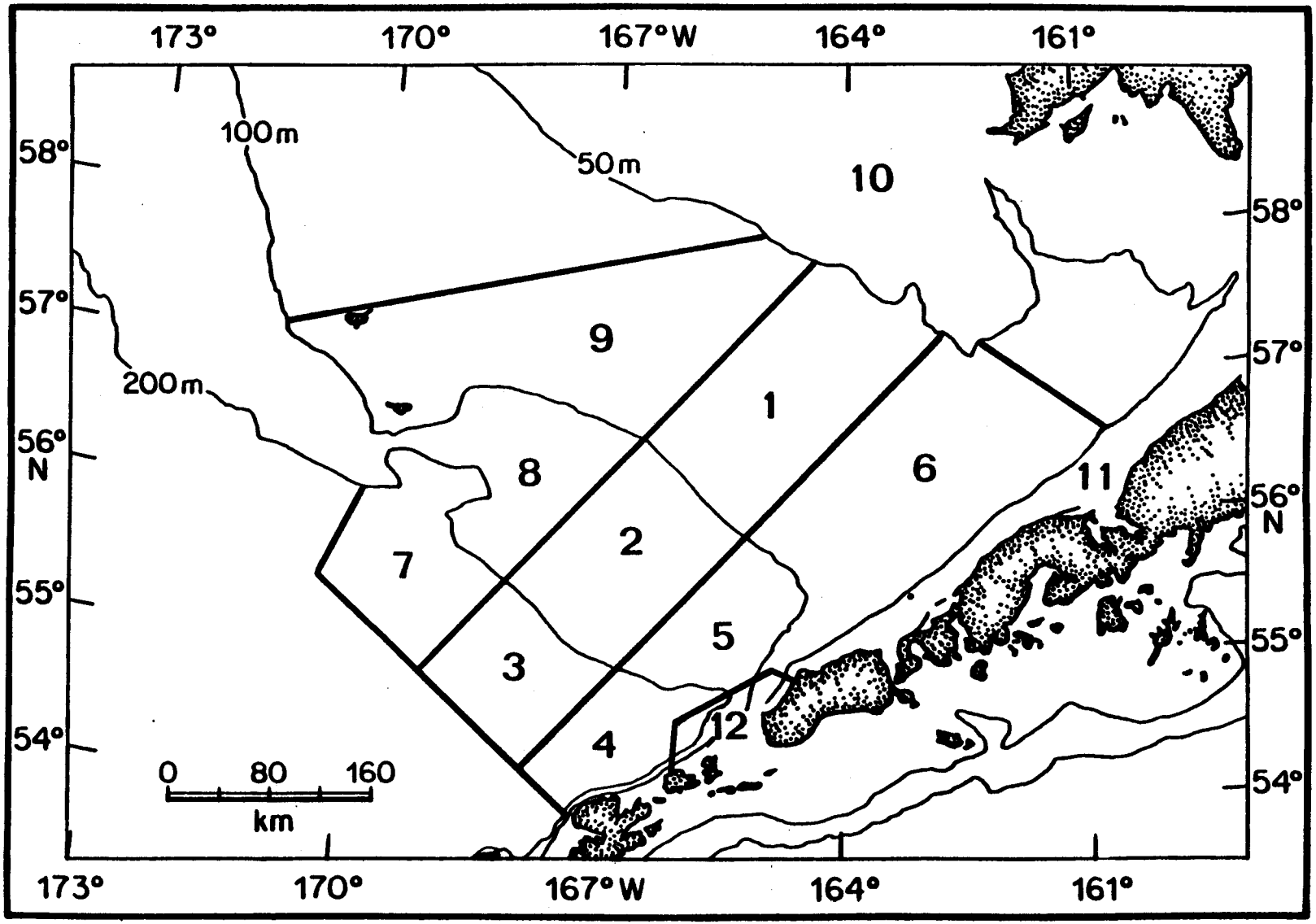


Figure 2.21 Locations and boundaries of strata used to contrast spatial distribution of decapod larvae in the S.E. Bering Sea. Strata 7, 3, and 4 encompass the shelfbreak/Oceanic domain; strata 8, 2, and 5 the Outer Shelf domain = the St. George Basin; strata 9, 1, and 6 the Middle Shelf domain; and stratum 11 the nearshore North Aleutian Shelf region.

3.0 DISTRIBUTION AND ABUNDANCE OF KING CRAB LARVAE, PARALITHODES CAMTSCHATICA, AND P. PLATYPUS, IN THE SOUTHEASTERN BERING SEA

David A. Armstrong

3.1 Life History and General Biology: Paralithodes camtschatica

3.1.1 Distribution and Abundance

The Bering Sea shelf including Bristol Bay has been characterized as three principal water domains, the coastal, middle shelf, and outer shelf domain that extend to about the 50 m, 100 m, and 200 m isobaths, respectively (Kinder and Schumacher 1981; Fig. 3.1). Information on distribution and abundance of red king crab in these shelf areas is more comprehensive than for any other decapod fished by U.S. fleets (see Section 4.0 for discussion of Tanner crab). For more than 12 years, the National Marine Fisheries Service has conducted broadscale trawl surveys in the southeastern Bering Sea (Fig. 3.2), and Otto (1981a) provides a history of information gathered by Japanese and Russian fleets during their participation in the fishery. A series of annual reports by the International North Pacific Fisheries Commission (INPFC) since the late 1950's provides a continuum of detailed data on king and Tanner crab stocks in the southeastern Bering Sea as well as in other locations fished by member nations.

Red king crab are widely distributed from the Sea of Japan in the western Pacific through the Kuril Islands to the Kamchatka Peninsula, across to the southeastern Bering Sea and as far south as British Columbia in the eastern Pacific (Marukawa 1933; Vinogradov 1946; Weber 1967). The species is rather uncommon north of latitude 57^{o}N and is

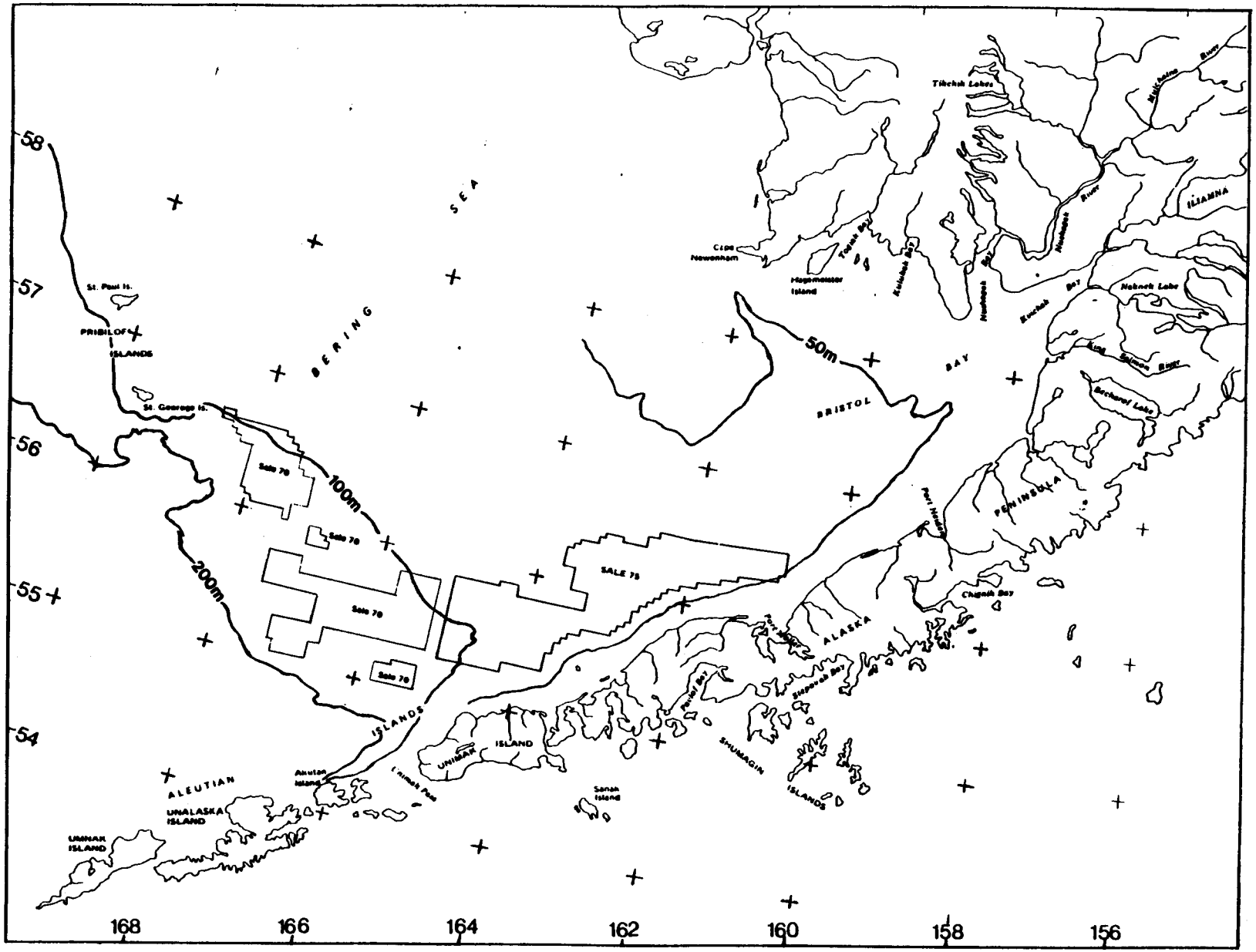


Figure 3.1. Location of proposed lease sale areas for the North Aleutian Shelf (Sale 75) and St. George Basin (Sale 70). Frontal systems marked by the 50m, 100m and 200m isobaths are also shown (after Kinder and Schumacher 1981a).

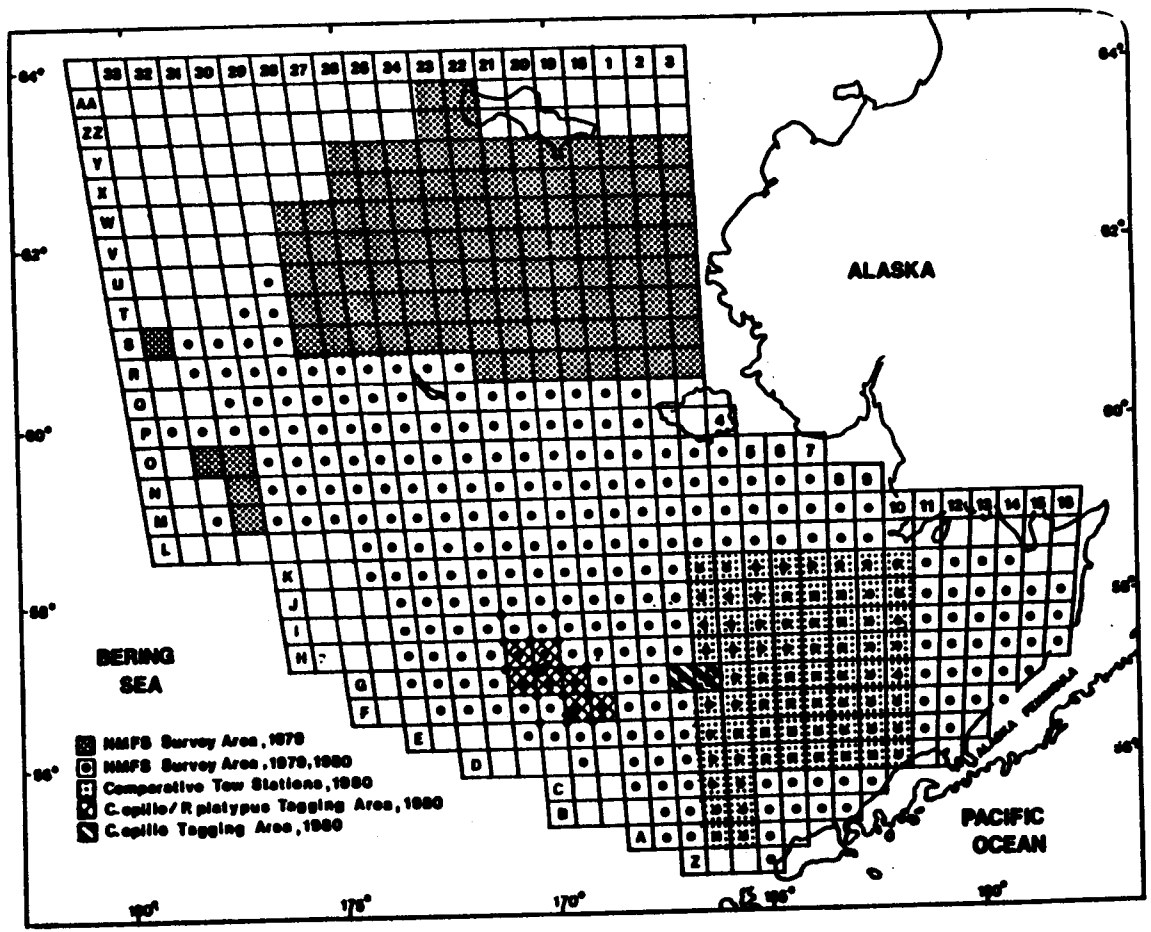


Fig. 3.2. NMFS eastern Bering Sea crab survey areas in 1979 and 1980. From Otto, MacIntosh, Armetta and Wilson (1980). These survey grids are typical of years since 1970 through 1982.

characterized as part of the subarctic-boreal faunistic system (Neyman 1963, 1969). Further, Russian scientists rarely find it in large numbers north of the Anadyr faunistic barrier (a line from the Anadyr River to St. Matthew Island), in marked contrast to the blue king crab which ranges farther north and seems to inhabit colder water (Slizkin 1973).

In the southeastern Bering Sea where a major fishery is centered, red king crab are distributed somewhat in accord with sex and life-history stage. In general, female and small male king crabs are found closer to shore and somewhat east of large males (Otto, MacIntosh, Armetta and Wilson 1980; Otto 1981b; Figs. 3.3 and 3.4; small crabs are classified as males <110 mm carapace length and females <89 mm). Very young juvenile red king crabs of 0+ to 4+ age classes are rarely caught in nets throughout the survey area of Fig. 3.2, even though mesh used will retain animals as small as 30 mm. The implication is that juvenile crabs up to 60 mm in carapace length (about 3 years old; Weber 1967) are absent from the survey area and likely very nearshore along the North Aleutian Shelf or upper Bristol Bay.

Abundance estimates have fluctuated between years in the last decade and cycles of high to low abundance may occur in this species' populations as observed for Dungeness crab, Cancer magister (Botsford and Wickham 1978). Landings from the Kodiak king crab fishery increased to 94×10^6 lb by 1965, fell to 10×10^6 lb by 1971, and have remained around 14×10^6 lb to the present (NOAA 1981); poor recruitment is cited as the cause. In the southeastern Bering Sea, crabs were in moderate abundance in 1953, increased in abundance to 1959, fell between 1964-70,

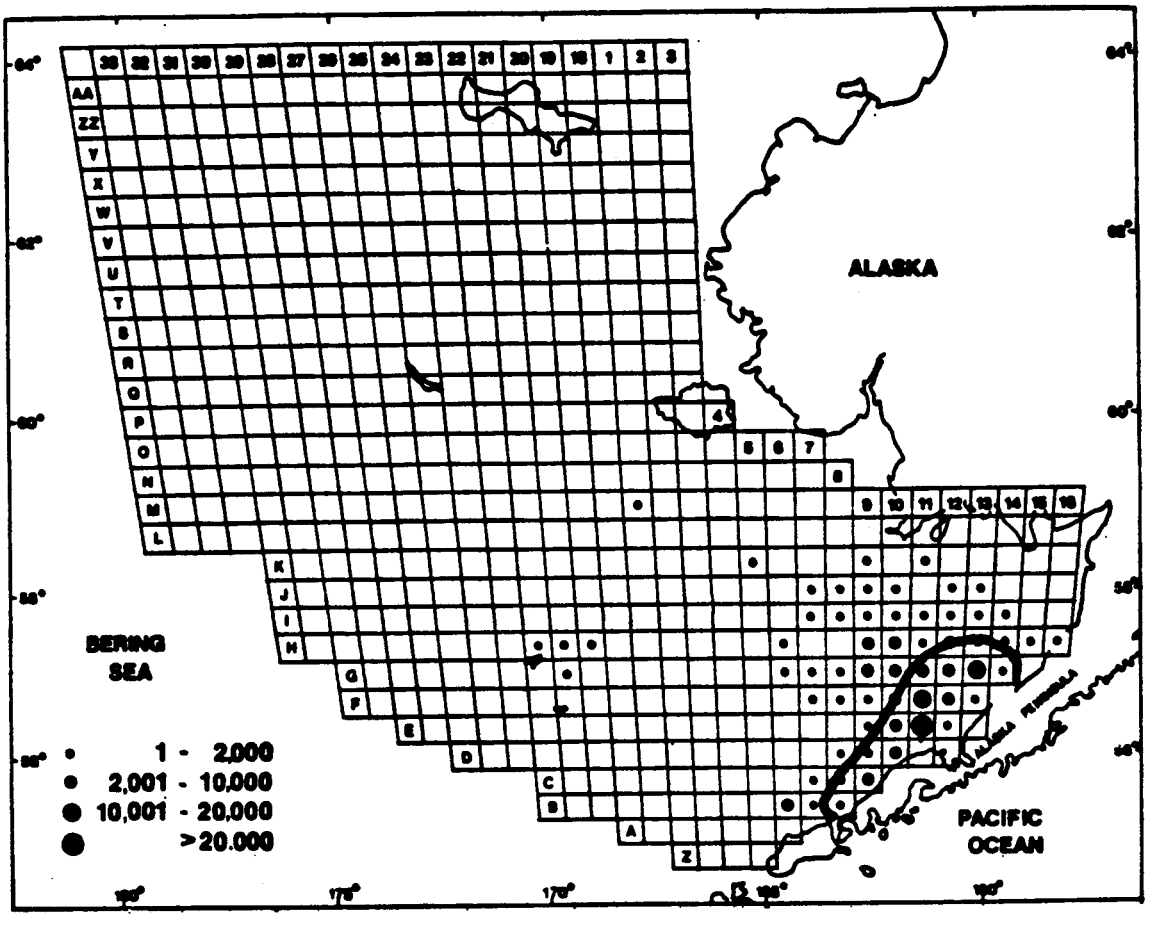


Fig. 3.3. Distribution of female red king crab (P. camtschatica) greater than 89 mm carapace length, in the eastern Bering Sea during May-July, 1980. From Otto, MacIntosh, Armetta and Wilson (1981).

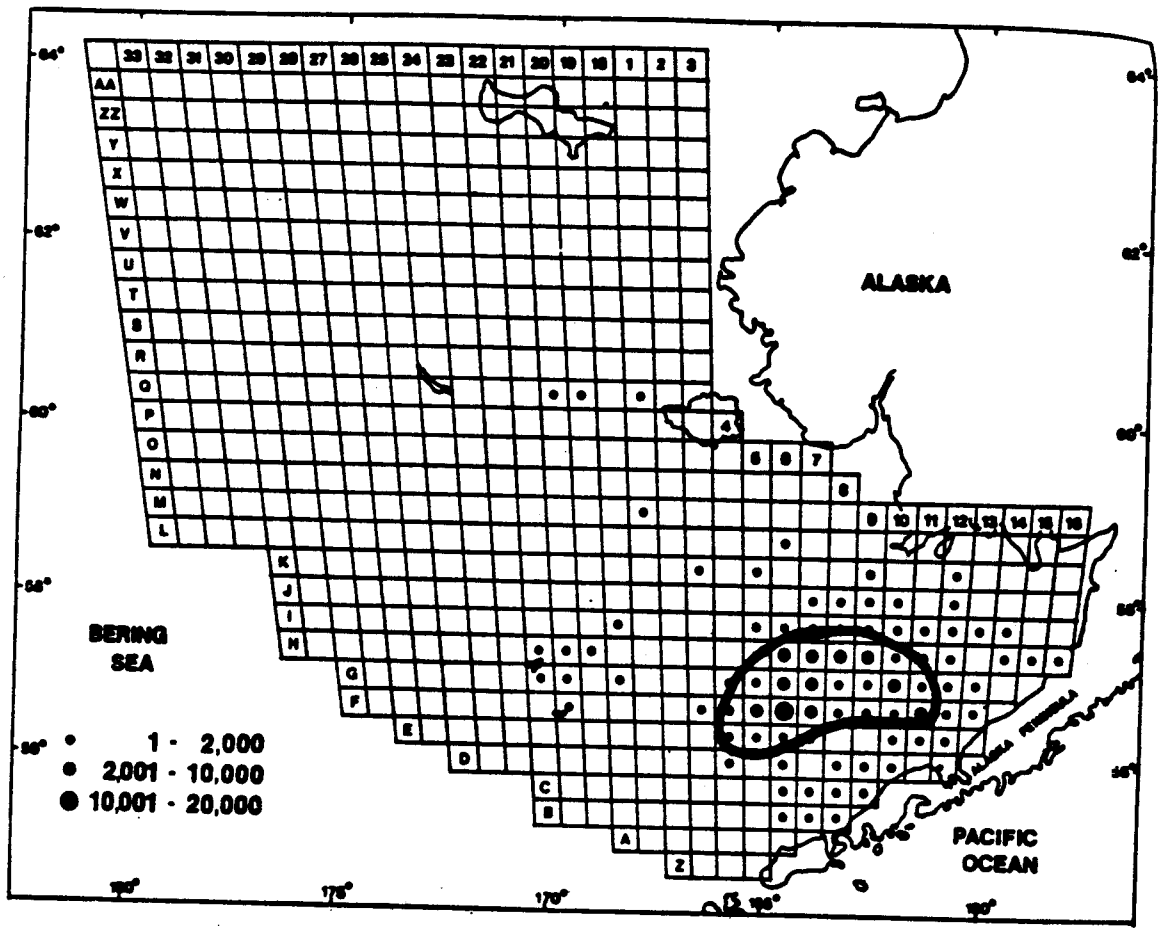


Fig. 3.4. Distribution of male red king crab (P. camtschatica) greater than 134 mm carapace length, in the eastern Bering Sea during May-July, 1980. From Otto, MacIntosh, Armetta and Wilson (1981).

and then increased through 1979 (Otto 1981a). However, abundance estimates for total male king crab in this area have declined from 181 million animals in 1977 to 129 million in 1982 (Otto et al. 1982). Most importantly, estimates of sublegal males one to two years from entering the fishery have declined nearly threefold from 64 to 17 million, leading to predictions of several consecutive years of poor fisheries. Abundance estimates of legal male crabs dropped from over 45 million animals in 1979 to about 5 million in late 1982 (Fig. 3.5; Otto et al. 1982; M. Hayes, NMFS, Seattle, pers. communication), which has resulted in severe reductions in commercial landings from 130 million lb to less than 4 million in the same period (see Section 1.0).

Change in abundance of king crab populations is an important biological factor to consider later in discussing oil impacts. Cycles of abundance suggest that year class failure or success may be based on survival of critical life-history stages such as larvae or young juveniles, probably in nearshore habitats. Annual instantaneous mortality rates of juvenile and sublegal, sexually mature crab are estimated to be low, about .10 until entering the fishery (Balsiger 1976; Reeves and Marasco 1980). Consequently the magnitude of a future fisheries cohort is largely determined by the reproductive success and survival of larvae and young-of-the-year (0+ crab) in nursery areas. Vagaries of temperature, food supply, and predator populations are factors affecting survival, now the question of potential oil perturbations could add to natural pressures on larval and juvenile populations and further suppress stocks.

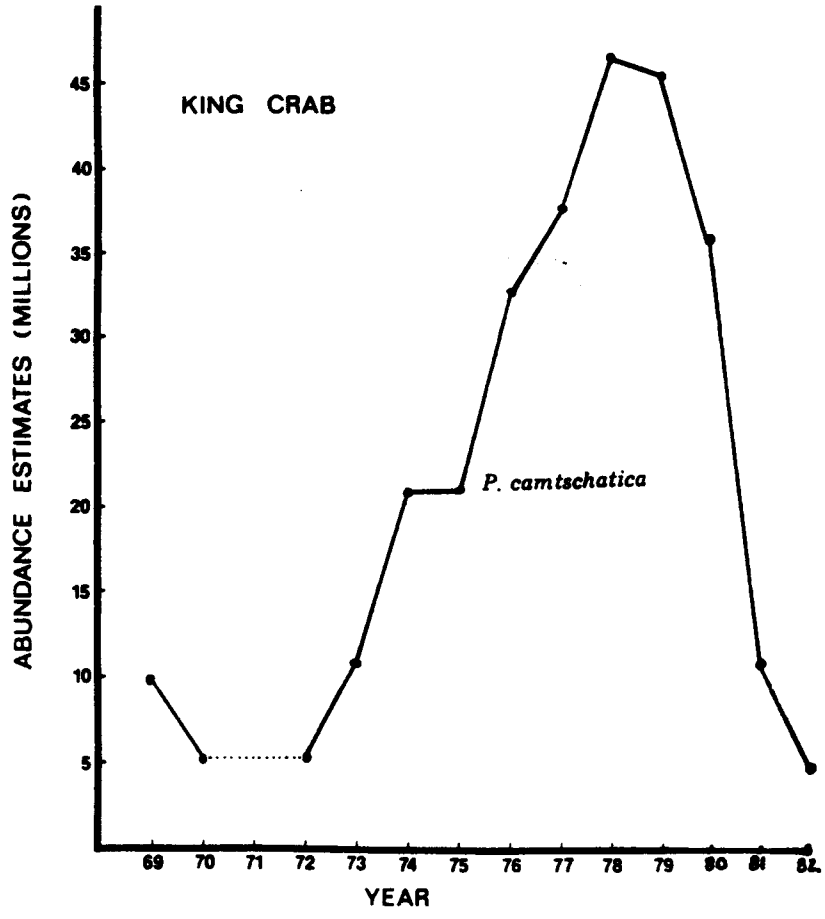


Figure 3.5. Abundance estimates of legal male red king crab based on annual NMFS groundfish surveys (from Otto 1981; Otto et al 1982).

3.1.2 Reproduction

In late winter and early spring adult males apparently migrate from deeper, offshore areas to join females in shallow water for breeding around Kodiak Island (Powell et al. 1974; Weber 1967; NOAA 1981; it is not known if such migratory behavior exists in the southeastern Bering Sea). Eggs carried from the previous year hatch about April 1-20 (Haynes 1974; Weber 1967) and females soon undergo physiological changes leading to molt. By pheromone attraction (NOAA 1981) sexually mature males locate preecdysial females, embrace them for as long as 16 days, and mate just after the female molts (Powell et al. 1974). The near-shore, shallow water habitat is apparently selected in part for warmer water temperatures (and perhaps greater food supplies). The average temperature inhabited by sexually mature males and females is 1.5° and 4°C, respectively; (NOAA 1981). Stinson (1975) correlated male and female abundance with temperature and, from NMFS survey data through 1975, located most sexually mature females inside a 4°C isotherm nearshore off Unimak Island and directly in front of Port Moller. Weber (1967) summarized data on temperature-related hatchout time and development, noting both regional and annual differences in larval appearance and rate of development attributable to temperature variations. Larval development time can double with a decrease of temperature from 10° to 5°C (Kurata 1960, 1961), and an average of 460 degree days (= cumulative average daily temperature from hatch of egg to metamorphosis of megalops) is required for the species (Kurata 1961).

After molting a female must be located and mated within 5 days for viable eggs to be produced (possible impact of oil on chemosensory

pheromone cues could impair males' search for females). For 97% of all mating pairs males are larger than females (Powell et al. 1974); insemination of larger females by smaller males results in reduced clutch size (egg number). Any combination of events through natural and fishery mortality and pollution that substantially reduce numbers of large males at some point in time could threaten the breeding potential of the species. Reeves and Marasco (1980) estimated that a male-female weight ratio of 1.7 is required for 100% copulation - this estimate based, in part, on behavioral observation by Powell et al. (974). Below this value, decreasingly smaller males will have less success breeding mature females. This relationship portends the observations of the 1982 NMFS survey cruise that found an unusually large number of barren female crabs (had not extruded eggs) in a year of very low male abundance (depressed fishery). Whether there is or is not a relationship between spawners and eventual recruits for this species is unclear (Reeves and Marasco 1980).

Females carry eggs for up to eleven months as embryos develop through naupliar stages to prezoea (Marukawa 1933). This protracted developmental time makes eggs (during early cleavage) and later embryos susceptible to long-term benthic oil pollution, and will be considered in scenarios of oil mishaps and possible perturbations to larval populations (see Section 8.0). Again, gravid king crab females are aggregated nearshore in relatively shallow water along the North Aleutian Shelf but such distribution is poorly studied to date.

3.1.3 Larval Development

Larvae are hatched nearshore (Haynes 1974), molt through four zoeal stages about every three weeks (Marukawa 1933), spend two-four weeks as megalopae and then metamorphose to first instars about late July to August (Kurata 1960; Weber 1967). Eggs normally begin to hatch in early April (Sato 1958; INPFC 1960, 1963, 1965; Haynes 1974), although female king crab may vary in time of hatch between widely separated populations from Unimak Island to Port Moller. Korolev (1968) summarized data collected by Soviet scientists for June, 1959 along the North Aleutian Shelf. Over 95% of the female populations between 161°25' to 164°10'W had spawned and carried new egg masses (purple to brown color) in June, while 90% of females east of 161°25'W (Port Moller and east) carried empty egg cases indicative of recent hatch and only 10% carried new purple egg masses.

Interannual timing of the onset of hatch and seasonal occurrence of pelagic larvae can vary by as much as a month. Japanese data (INPFC 1963, 1965) show that nearly 100% of gravid females sampled during 1960 carried "eyed" eggs (fully developed zoeae, hatch immiment) until May 10 and 50% carried empty egg cases by May 20-30. In 1963, eyed eggs were carried until April 20 and 50% had hatched by April 30. Such changes in the general timing of larval hatch are important for predictions of potential oil impact to pelagic larvae of the species.

Horizontal transport of king crab larvae by currents is thought to move them significant distances from the origin of hatch, and implies to some authors that recruitment of juveniles to a given area might depend

on larvae hatched elsewhere, including areas south of the Alaska Peninsula (Hebard 1959; Haynes 1974). Hebard (1959) calculated that larvae hatched at Amak Island could be transported over 60 miles to the northeast and metamorphose at Port Moller (net current speed of 0.04 knot moving northeasterly along the North Aleutian Shelf; Kinder and Schumacher 1981, show a current speed of 2-5 cm/sec in that region). He further discussed possible transport of larvae from south of the Peninsula through Unimak and False Pass. Haynes (1974) adds credence to this supposition by showing a northernly dispersion of king crab larvae off the southwest tips of Unimak Island, and a northeast shift in areas of larval abundance from Black Hills into Bristol Bay (May-July, 1969 and 1970; this pattern may in part be due to inadequate spatial sampling). Transport of larvae by currents is also important to consider in predicting oil impacts. Oil reaching relatively unproductive areas of the North Aleutian Shelf (low female abundance, few larvae hatched) could still be lethal if larvae are transported through such contaminated areas. Alternatively, oil and larvae could be transported together in a water mass resulting in relatively long-term exposure of sensitive zoeal stages to hydrocarbons.

Temperature is considered one of the most crucial physical factors affecting survival and growth of larvae, and Kurata (1960, 1961) calculated that 460 degree-days were required to progress from hatch to metamorphosis. Lethal temperatures are those greater than 15°C or lower than 0.5-1.8°C (Kurata 1960). He found greatest survival of zoeae between 5-10°C and formulated an equation that relates developmental time to temperature. Time from egg-hatch to molt of stage I (SI) to stage II

(SII) varies from 24 days at 2°C to 9 days at 8°C (Kurata 1960). Severe climatological changes could account for large fluctuations in survival of a year-class and later recruitment to the fishery. Niebauer (1981) shows the limit of ice in the southeastern Bering Sea (as a relative measure of water temperature) was several hundred kilometers farther south in 1976 than 1979 and actually extended to the Alaskan Peninsula near Black Hills. Both 1975 and 1976 were severely cold years and poor survival of larvae and juveniles then could account for low abundance of sublegal males 5-6 years later in 1981-1982.

Growth rates of 0+ and older juveniles have been studied and animals reach mean carapace lengths of about 11 mm, 35 mm, 60 mm, and 80 mm at 1, 2, 3, and 4 years, respectively (Powell and Nickerson 1965; Weber 1967). Growth models for the species have been developed by Weber (1967), McCaughran and Powell (1977) and Reeves and Marasco (1980). Young-of-the-year molt from 8 (Powell 1967) to 11 (Weber 1967) times in the first year; such high frequency molting could make them particularly susceptible to nearshore oil perturbations since ecdysis is the time of greatest sensitivity to toxicant stress (Armstrong et al. 1976; Karinen 1981).

Juvenile crabs in 2+ to 3+ age classes (entering their third through fourth year) form large aggregates called "pods" in the Gulf of Alaska (Powell and Nickerson 1965). Podding behavior is probably based on chemosensory cues (subject to oil effects) and is thought to serve as protection from predators. It is not known if the same behavior occurs among nearshore juveniles of the North Aleutian Shelf. If so, such

aggregations could influence susceptibility to oil since these "patches" of crab are fortuitous in space relative to oil mishaps, but if juxtaposed could affect large numbers of crabs in small areas.

Red king crab are sexually mature at about 95-100 mm carapace length for males (Weber 1967, NOAA 1981), and 85-90 mm for females in the Bering Sea (Weber 1967) or 93-122 mm in the Gulf of Alaska (Powell and Nickerson 1965). Animals are 5-6 years old at sexual maturity and males are therefore capable of breeding 2-3 years prior to entering the fishery at about eight years old.

3.2 Life History and General Biology: *Paralithodes platypus*

3.2.1 Distribution and Abundance

This is the most insular species of crab in the southeastern Bering Sea (Fig. 3.6), with major populations (and fisheries) centered at the Pribilof and St. Matthew Islands (Otto et al. 1982), and other populations at Kodiak Island in the Gulf of Alaska (Somerton and MacIntosh 1982). There is relative constancy in the location of benthic juveniles and adults around the Pribilof Islands in recent years (Otto et al. 1980, 1981, 1982), where greatest abundance is to the east and north of St. Paul Island, with few animals caught west near the shelf break or about St. George Island (Fig. 3.7a and b). This pattern of distribution is generally accurate for of pelagic larvae, although occurrence between and to the east of St. Paul and St. George Islands has been reported by Armstrong et al. (1981). The complete absence of blue king crab over most of the southeastern Bering Sea Shelf (where red king crab, *P. camtschatica* are abundant) suggests either inextricable dependence on

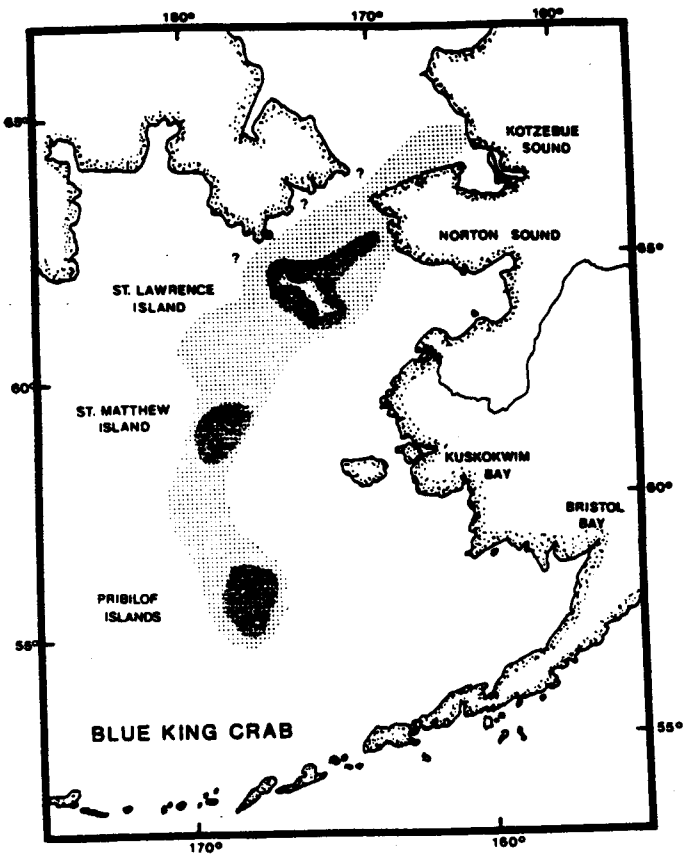


Fig. 3.6. Distribution of blue king crab (Paralithodes platypus) in the eastern Bering Sea. Darkly shaded portions indicate areas of consistent abundance (Otto, 1981).

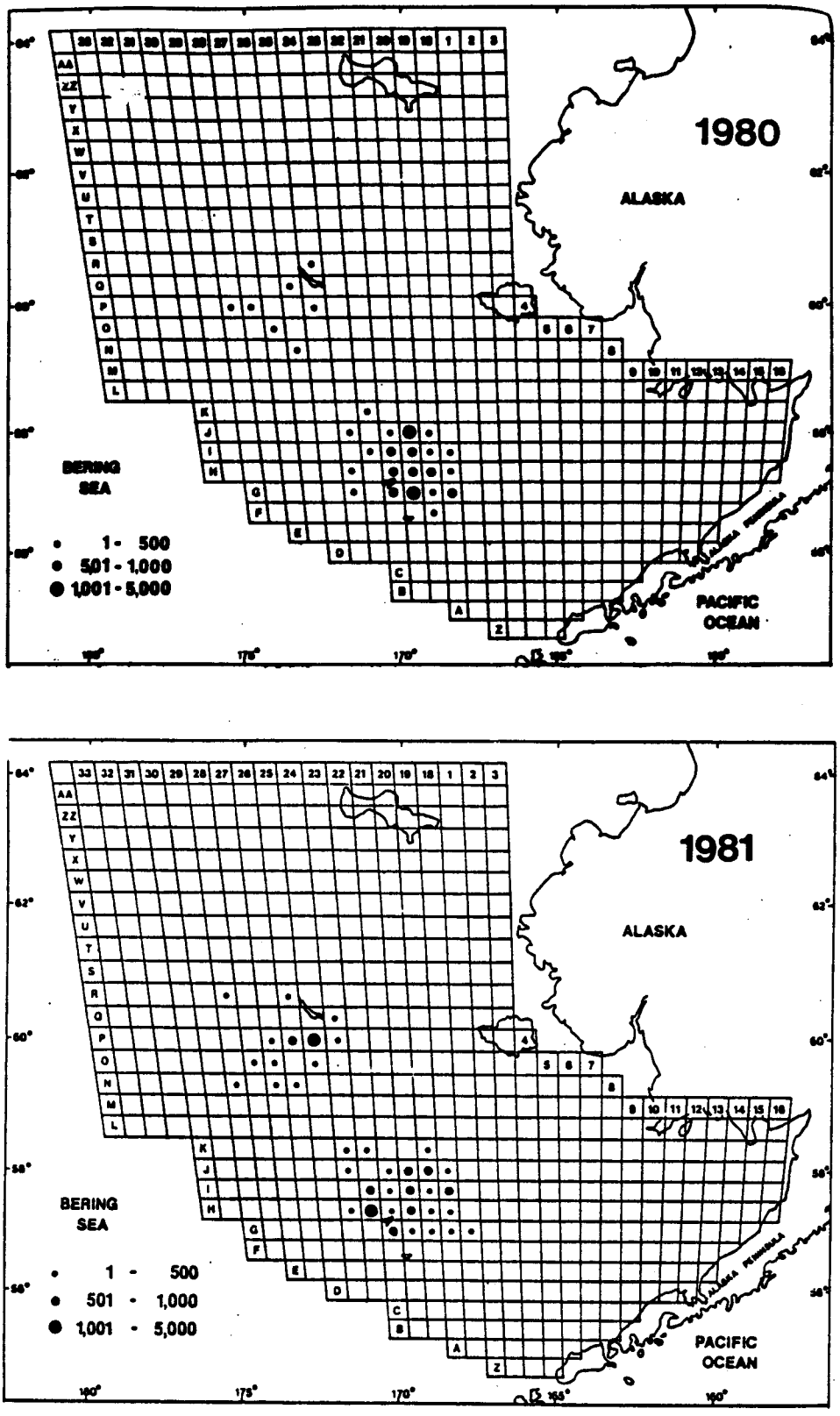


Fig. 3.7a. Distribution and relative abundance (number per square mile) of male blue king crab (P. platypus) greater than 134 mm carapace length in 1980 and 1981 (from Otto, MacIntosh, Armetta, and Wilson 1980; Otto et al. 1981).

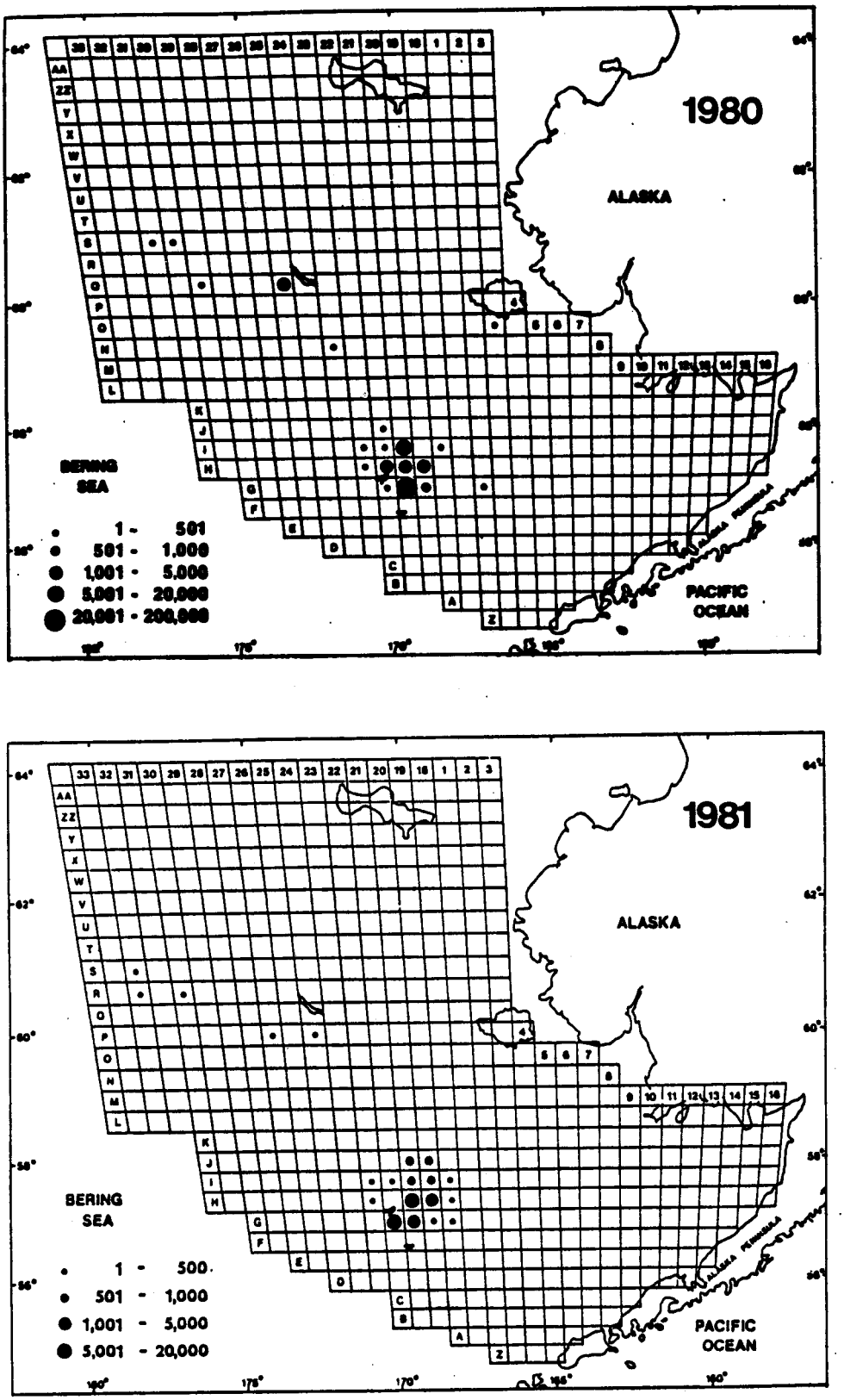


Fig. 3.7b. Distribution and relative abundance (numbers per square mile) of female blue king crab (P. platypus) greater than 89 mm carapace length, in the eastern Bering Sea in 1980 and 1981 (from Otto et al. 1980a, 1981).

the benthic habitat associated with the islands (e.g., predator refuge), and/or restriction by virtue of some sort of competitive, agonistic interaction with other species. Confinement of the species to a small area about St. Paul Island makes them extremely vulnerable to oil catastrophes originating in the northern St. George Basin lease sale area (Fig. 3.8).

On a broader scale, blue king crab tend to be more northerly in distribution than red king on both sides of the Pacific. Slizkin (1973) found high abundance of adults off Cape Navarin and reported juveniles even farther north to Cape Cukotsky (64°N latitude). He concluded that blue king crab are more tolerant of colder temperatures (1-2°C) than are red king crab, and that this differential partially explains species separation.

The depth range of main aggregations of blue king crab is about 45-75 m on a mud-sand bottom, although gravel to rocky substrate is found immediately adjacent to both Pribilof Islands. Otto et al. (1982) note that estimates of female and juvenile blue king crab around both the Pribilof and St. Matthews islands are low because of some distribution over rocky, untrawlable bottom. These observations strongly suggest that spawning and successful recruitment of first instar juveniles may depend on availability of nearshore, rocky-cobble substrate for protection of both females and small juveniles. Later, as older and larger animals, populations disperse farther offshore although still in a small area on the scale of the southeastern Bering Sea. Dependence of early benthic juveniles on refuge substrate is substantiated by

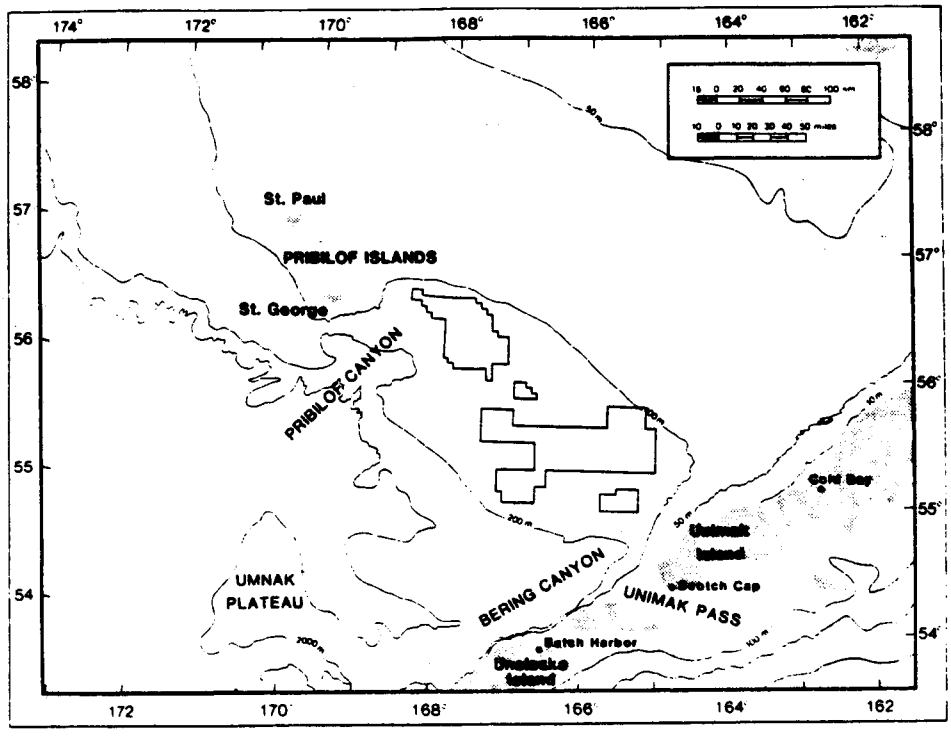


Fig. 3.8. Index map for proposed OCS Lease Sale #70, St. George Basin.

conclusions of Slizkin (1973) who reported finding no small juveniles over expansive areas of sand/silt bottom. Rather, these stages are abundant in areas of cobble and dense sponge, hydroid and barnacle assemblages.

Distribution and abundance of larval stages is poorly studied and only a few observations about the Pribilofs are available (Armstrong et al. 1981). Larval densities of blue king crab seem to be an order of magnitude less than high values recorded for red king crab, and larvae have only been found to the east of the Pribilofs.

Estimates of benthic blue king abundance made by NMFS indicate less fluctuation than found for red king crab, but still populations have decreased in recent years (Otto et al. 1981, 1982). Legal males (>134 mm) have declined from an estimated abundance of 9.4 million in 1977 to 2.2 million in 1982, and sexually mature females were calculated to be 35.5 million animals in 1978 and 8.6 million in 1982. Otto et al. (1982) conclude that stocks will remain low for several years.

3.2.2 General Biology

There is relatively little biological information published on blue king crab although Somerton and MacIntosh (1982, 1983a, 1983b) have recently summarized work from the Bering Sea and Kodiak Island. Animals are thought to grow at a rate comparable to red king crab and reach sexual maturity at about 96 mm and 108 mm carapace length for females and males, respectively, when they are about 6 years old (Powell and Nickerson 1965; Somerton and MacIntosh 1982; Weber 1967). Fecundity of females is a function of body size and ranges from 50,000-200,000 eggs

per female. Larvae hatch around the Pribilof Islands about mid-April based on limited data of Armstrong et al. (1981), and development rates may be similar to those of red king crab larvae. By June most larvae are third and fourth stage zoeae, and in July 1981 Armstrong (unpublished data) caught only megalops larvae off St. George Island. This implies that metamorphosis to benthic juvenile could occur in early to mid-August.

An intriguing question concerning reproduction of blue king crab is whether egg development may require more than one year thus putting individual reproductive effort on a biennial schedule. Sasakawa (1973, 1975) suggested that a high incidence of sexually mature, barren female blue king crab in the western Bering Sea was evidence of a 2-year cycle; 19 months to incubate eggs and 5 months barren. Somerton and MacIntosh (1982) disputed this hypothesis based on their study of female crabs in Olga Bay, Kodiak Island. They observed males grasping ovigerous females (prelude to copulation) as the mature egg masses were hatching, and from histological evidence of ovarian maturation they concluded that individual females may reproduce in sequential years. However, a high percentage of mature females within the Olga Bay population were barren throughout the year (38%-52%), dramatizing a greatly reduced reproductive potential compared to red king crab. If such impairment of population fecundity exists about the Pribilof Islands, then oil catastrophes could greatly exacerbate reproductive success in a year of low mature female abundance and a high incidence of barren animals.

A further observation germane to the female reproductive cycle at the Pribilof Islands is that egg hatching in Olga Bay occurred in both January and March (Somerton and MacIntosh 1982). Allowing for a latitudinal delay for reproductive events in the Pribilofs (e.g., Dungeness crab in California hatch eggs about 1.5 months earlier than populations in Washington), it may be that a portion of the females hatch eggs in February or early March, others in April and May. This notion may reflect timing differences between primiparous and multiparous females.

3.3 The Fishery

Red king crab until recently have been the most important crab fishery of the United States in both dollars and pounds landed. In 1980 king crab landings were 185 x 10^6 lbs and even exceeded blue crab (Callinectes sapidus) landings of the east coast (NOAA 1981). In 1979 to 1980 the value of king crabs landed was about $168.7 million or 58% of total U.S. ex-vessel value of crabs (Otto, MacIntosh, Armetta and Wilson 1980; Eaton 1980; Otto 1981b; NOAA 1981) (Fig. 3.8). Of the total Alaska statewide king crab landings in 1978-79 and 1979-80, over 75% came from catches in the southeastern Bering Sea (117 x 10^6 and 130 x 10^6 lbs, respectively; NPFMC 1980; Pacific Packers Report 1981). Red king crab commercial catches (Fig. 3.9) come largely from the middle shelf between 50 and 100 m, and 50 to more than 200 km offshore of the North Aleutian Shelf (Otto 1981a, b).

King crab are the largest and oldest crab caught by U. S. fisheries. Males are 50% recruited to the pot fishery at 8 years of age and fully recruited by 9 years (McCaughran and Powell 1977; Reeves and

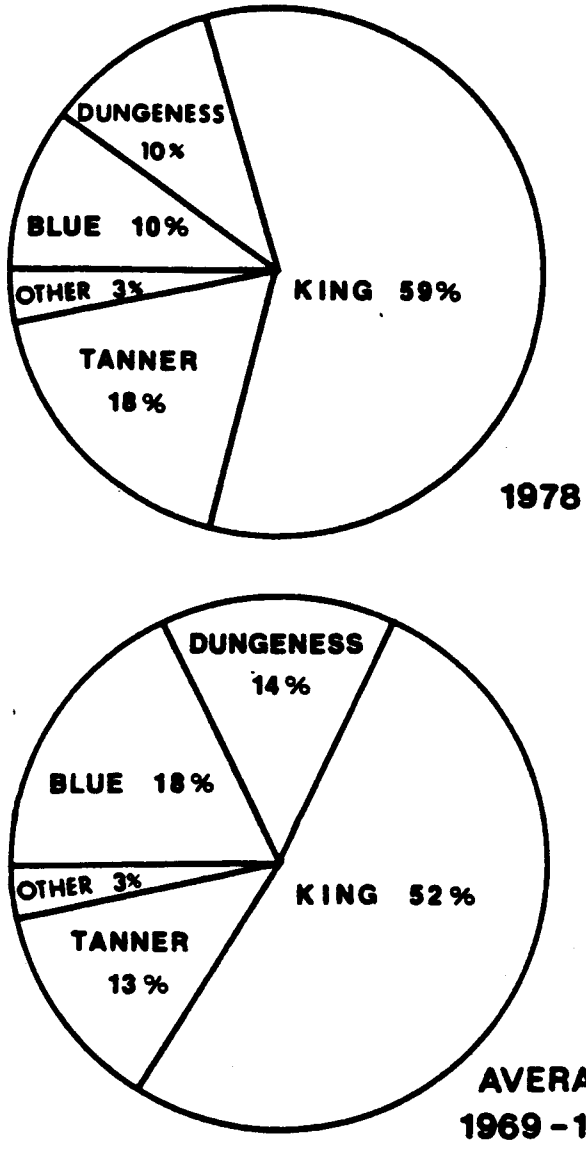


Fig. 3.9. Relative contributions of various crabs to the value of United States crab landings. From Otto (1981a).

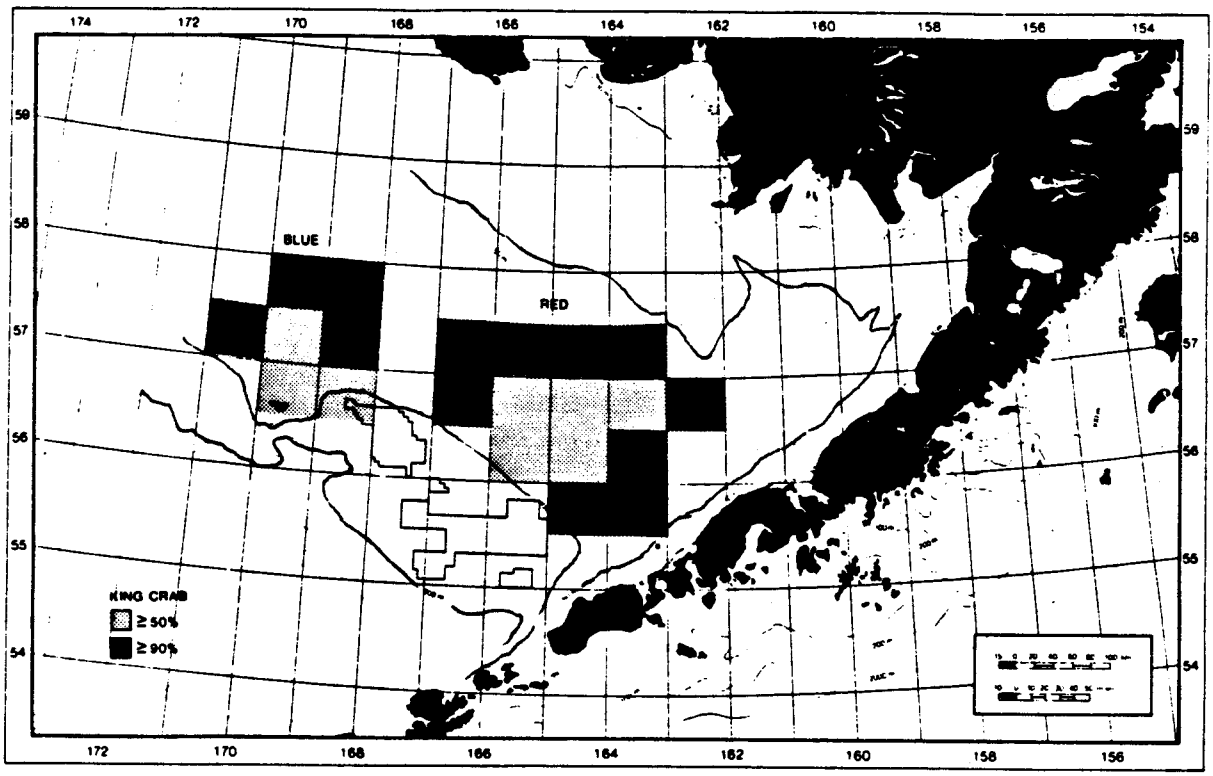


Fig. 3.10. Major king crab catch areas relative to St. George Basin lease area (Otto, 1981a).

Marasco 1980). Legal size at recruitment is about 135 mm carapace length and 165 mm (6 1/2") width and mean annual weight per animal fluctuates from 6.4 to 7.5 lbs (Eaton 1980; NOAA 1981). Annual fishing mortality is managed to approximate 40% (NOAA 1981) but the percent of the fishery constituted by new recruits has varied from 67% in 1977 to 47% in 1979, indicating that differential natural mortality rates can significantly affect the importance of any single year-class to the fishery (Eaton 1980). Oil pollution that adversely affects a significant portion of larvae in any year-class could eventually impact the fishery despite both longevity of the species and commercial stock comprised of two to three year-classes.

Most of the U.S. Bering Sea fishery for blue king crab is centered off St. Paul (Fig .3.6) and St. Matthew Islands. Landings have increased from about 2.4 million lb in 1975 to 10.8 million lb in 1980 (Otto 1981; Pacific Packers Report 1981). In 1981 landings from the Pribilof district decreased 20% and dropped further in 1982 (INPFC 1982; Otto et al. 1982), reflecting the reduction predicted by the NMFS trawl survey. It is significant that for the first time in the fisheries, landings of blue king crab surpassed those for red king in the southeastern Bering Sea during 1982 (R. Otto, NMFS Kodiak, pers. communication, 1-5-83).

3.4 Results

3.4.1 Distribution and Abundance

Analyses of over 1000 zooplankton samples collected between 1976 and 1981 clearly show that the overall distributions of both red king (*P. camtschatica*) and blue king crab (*P. platypus*) in the southeastern Bering Sea are restricted to discrete areas along the NAS into Bristol Bay and east of the Pribilof Islands, respectively (Fig. 3.11). As stressed in the annual report (Armstrong et al. 1981), the most striking feature of this pattern is the associated absence of larvae over most of the St. George Basin and the middle shelf between 50 m and 100 m. Larvae are only found in the very southern portion of the St. George Basin, north of Unimak Pass, as part of a nearshore band that continues to the northeast along the 50 m isobath.

Due to such restricted distribution of king crab larvae, use of strata delineated in Figure 2.21 to contrast temporal and spatial distribution and abundance did not work well, as it did for other decapod groups (see sections 5.0, 6.0., and 7.0). Not only was the spatial coverage of interannual sampling quite variable, but only portions of certain strata ever contained larvae. Therefore, to include all stations of a stratum in calculations of mean densities would always add numerous zeros to the observations. Areas of greatest larval king crab occurrence relative to strata are shown in Figure 3.12. Blue king crab larvae occurred in the western half of stratum 9 but not in any other strata. The majority of high density red king crab stations fell in southern half of stratum 6, with a few in stratum

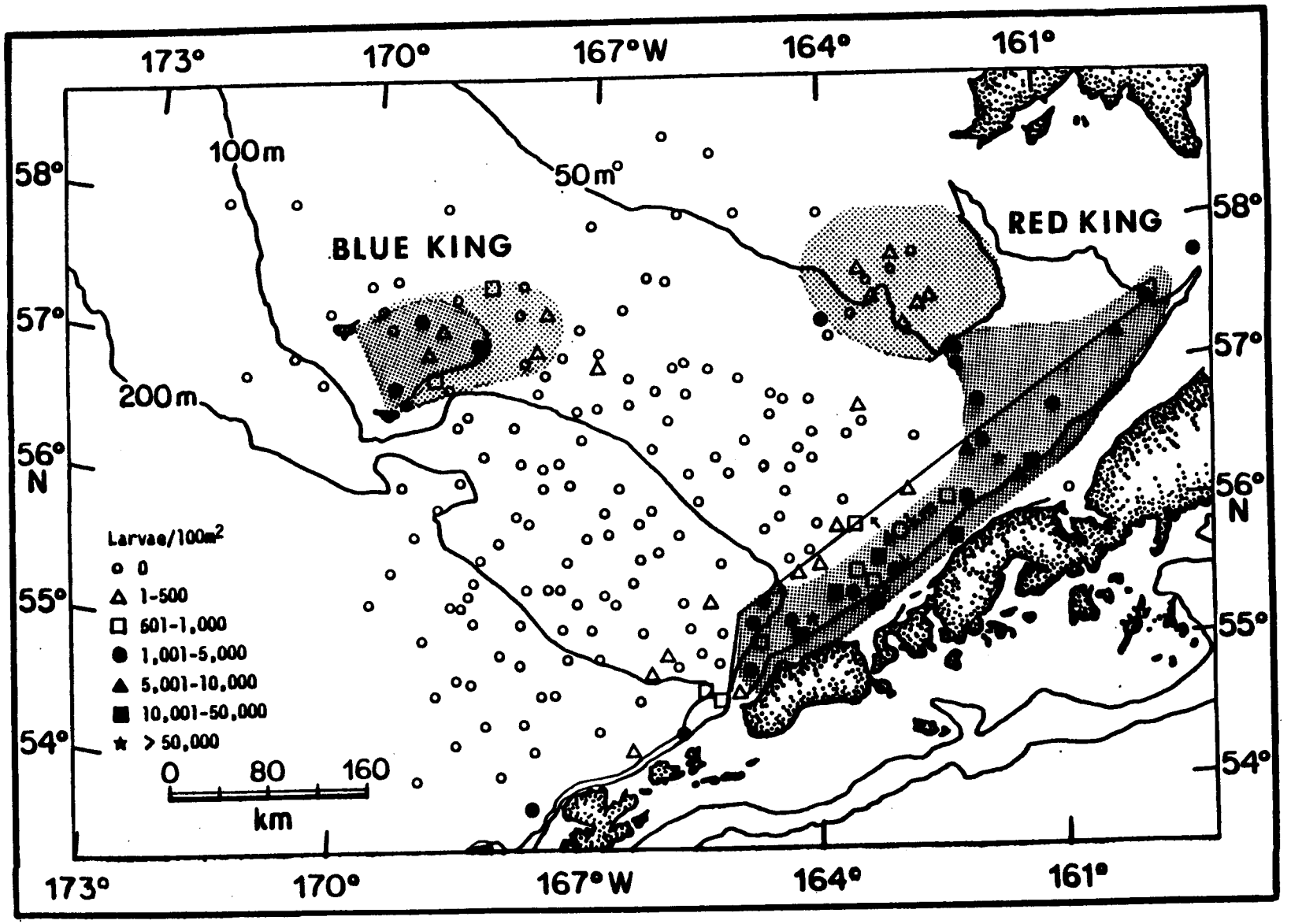


Fig. 3.11. Distribution and relative abundance of red king (P. camtschatica) and blue king crab larvae (P. platypus) in the southeastern Bering Sea. All data from years 1976-1981 combined. Most stations of high red king crab abundance fall in an area from the 50 m isobath to about 40 km seaward along the North Aleutian Shelf.

11 and 12 (Figs. 3.11, 3.12). Too few samples were taken in strata 9 and 10 on which to base any sort of interannual comparison of larval abundance. Only the area along the NAS was sampled with enough frequency to compare certain years and, to a lesser extent, areas. Two new strata, I and II, are shown in Figure 3.12 that divide the NAS region into an east and west sector at 162° W near Black Hills. These strata more realistically encompass major areas of king crab hatch, and thereby permit limited spatial and temporal comparisons of distribution and abundance.

Red King Crab: Distribution of red king crab larvae based on data of this project (1976-1981) is in accord with results of a 1970-1971 survey conducted by Haynes (1974) who also found larvae to be relatively nearshore along the NAS into Bristol Bay. Unfortunately, the survey patterns of most years between 1976 and 1981 were largely focused offshore over the outer and middle shelves and, as a consequence, relatively few samples were taken over the apparent spawning habitat of P. camtschatica. Figure 3.11 shows that only about 13 samples over six years were collected near the 50 m isobath from Unimak Island to Port Moller, and only three fell shoreward of this depth. In the years of best spatial coverage, 11% to 23% of samples sorted had king crab larvae (Table 3.1). However, this percentage range is even less in the case of red king crab since a number of samples were positive for blue king crab near the Pribilof Islands. Further, about half of all positive stations had larval densities of less than 500/100 m^2 (Table 3.1) which was the lowest numerical category used to quantify

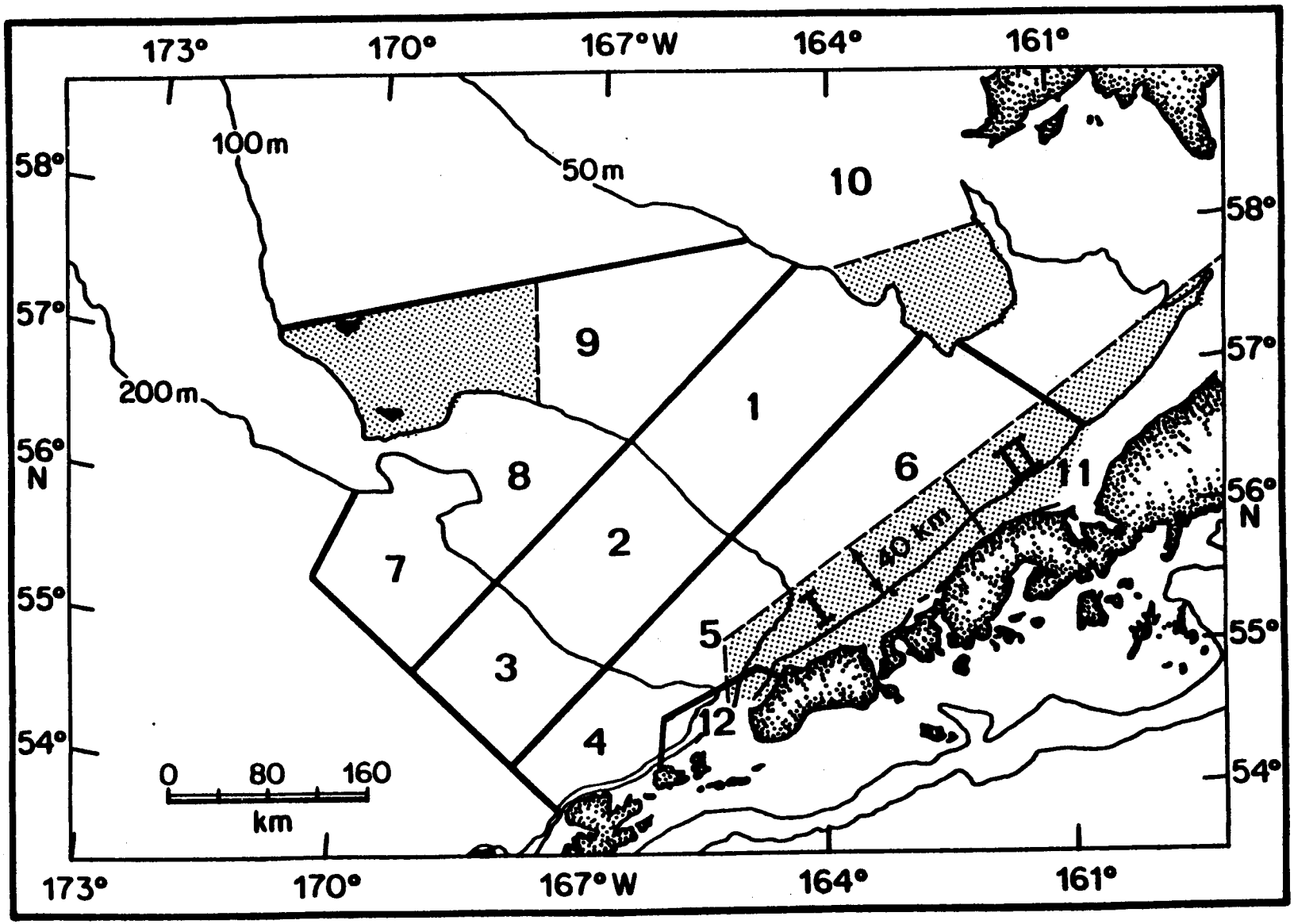


Fig. 3.12. A modification of Fig. 2.21 that shows areas of greatest larval king crab abundance relative to strata 1 to 12. Only areas nearshore along the North Aleutian Shelf were sampled with enough frequency to allow spatial and interannual comparisons. Two new strata I and II are shown that extend from shore to about 40 km seaward of the 50 m isobath.

Table 3.1. Number of zooplankton samples sorted between 1976-1981, and number that were positive for both blue and red larval king crabs (see Table 2.1 for full details). Although not officially a part of this study, data for 1982 are included to demonstrate the high percentage of samples positive for king crab larvae when stations were situated nearshore. Samples with less than 500 larvae/100 m^2 are summarized separately to show the proportion of positive stations that fell into this lowest density category (see Fig. 3.11 for density categories).

Year*	No. of** samples	No. samples with king crab larvae	No. samples with <500 larvae/100m^2	% with larvae	% positive samples with <500/100m^2
1976	30	7	2	23	29
1977	86	20	9	23	45
1978	213	23	14	11	43
1980	97	12	4	12	33
1981	208	36	22	17	61
Total	634	98	51	Average 15	52
1982	82	45		55	

*1979 was omitted because only two stations were positive for king crab larvae.

**The numbers of samples reported here are different than in Table 2.1 because MOCNESS data were integrated over the entire water column rather than left as samples from discrete depth intervals.

density. Such low abundance reiterates the fact that many positive stations were still collected in marginal areas probably off the main spawning grounds.

The highest densities of P. camtshatica larvae occurred from western Unimak Island to Port Moller. Densities that ranged an order of magnitude from 5,000 - 50,000 larvae/100 m^2 were typical of this area. The highest densities recorded were 67,000 larvae/100 m^2 north of Unimak Island in May 1977, and 114,000/100 m^2 just northwest of the 50 m isobath off Port Moller in May 1980 (Both values shown by star symbols in Fig. 3.11). The 50 m isobath is about 22-33 km (12-18 NM) offshore of the NAS coast from Unimak Island to east of Port Moller (about Cape Seviavin; Fig. 3.11), and marks the shoreward limit of zooplankton collections in most years. Virtually all high density red king larval stations occurred along this depth contour or within a 40 km band to seaward (Fig. 3.11, 3.12). Occasional collections made from the PROBES A line (Fig. 2.11) toward Port Moller revealed larval densities of a few hundred to 3000/100 m^2 out to the 50 m isobath at about 57°30'N, 162°30'W. Collections made from NOAA ships in 1981 also showed fairly high densities of 2000-4000 larval/100 m^2 up to Port Heiden in Bristol Bay (Fig. 3.11). However, these few stations north and east of Port Moller were the only available since 1976, so the extent and abundance of larvae east of Cape Seniavin into Bristol Bay remains unknown; a substantial informational gap in the picture of larval biology compiled to date.

Because of the poor spatial coverage of zooplankton stations between 1976-1981 in regards to king crab larvae, opportunistic collections were made in June and August, 1982, nearshore along the NAS from Unimak Island to Port Heiden (Figs. 2.19, 2.20). The primary objectives were to study nearshore distribution of larvae and gather information on growth rates. Samples were collected in water as shallow as 16 m within 3 km of shore, out to about 70 m depth some 40-50 km offshore. Collections were first made betwen June 14-28, which repeats a time frame typical of most previous years analyzed in this study, and again from August 3-10 which is the latest seasonal collection from king crab spawning grounds.

Larval red king crab in June, 1982, were most abundant from Amak Island (off Izembek Lagoon) east to the limit of sampling off Cape Seniavin (Fig. 3.13). Again as in previous years, samples were not collected throughout Bristol Bay and so the extent of larval distribution could not be fully gauged over the area occupied by benthic juveniles and adults. The most striking features of the distribution are: 1) the absence of larvae from western Unimak Island to about Amak Island [in contrast to data of Haynes (1974) and data of this study from 1976-1977; Fig. 3.16]; 2) the preponderance of larvae along the 50 m isobath and; 3) a decline of larvae close to shore in many areas sampled.

Larval distribution and abundance in 1982 were further analyzed by selecting groups of stations that constitute approximate transect lines running perpendicular to shore, although the opportunistic collection

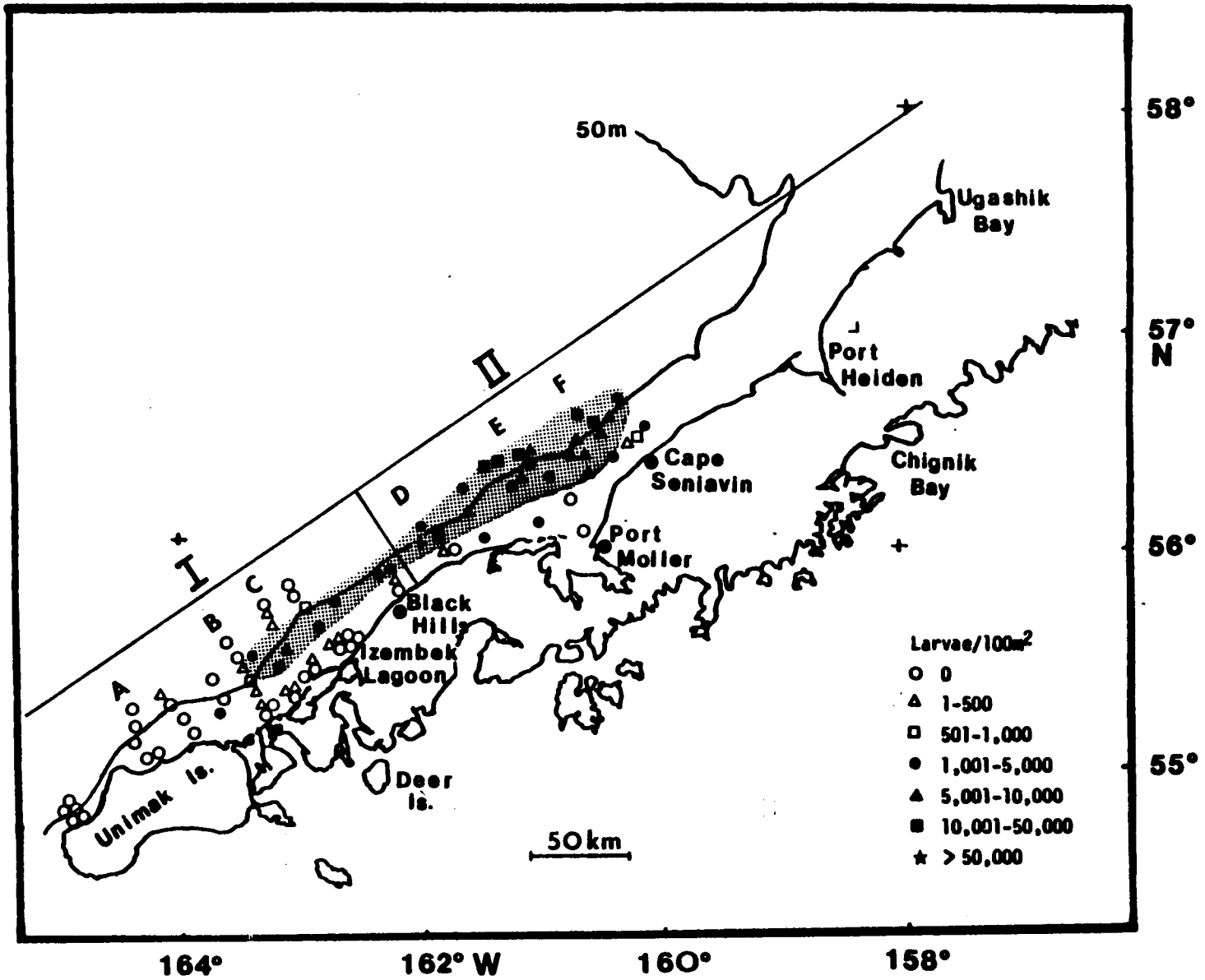


Fig. 3.13. Distribution and relative abundance of larval and king crab in modified strata I and II (see Fig. 3.12) during June, 1982.

made them imperfect in areas (Fig. 3.13, 3.14). Stations were grouped in broad depth intervals of 20-40 m, 41-60 m, and 61-80 m because narrower depth intervals were not common in all transect lines A to F. In fact, depths to 80 m were only collected on lines A to C, while D and E went only to 70 m and F had a deepest station at 63 m (Fig. 3.13).

The longshore pattern of distribution is one of relatively low densities inside 40 m with peak abundance of about 2,000 larvae/100 m^2 on the E line off Port Moller (Fig. 3.14). Virtually no larvae were found from mid Unimak Island through Black Hills, a distance of about 180 km. In contrast, densities between 41-60 m reached 6600 larvae/100 m^2 by the C line off Izembek Lagoon (Fig. 3.13), and averaged 6,300 to over 12,500 m^2 up to Cape Seniavin within this depth interval (Table 3.2; Fig. 3.13). Larvae were not found, or only in very low densities, farther offshore between 61-80 m from Unimak Island to Black Hills (Fig. 3.14). However, abundance off Nelson Lagoon and Port Moller was very high at depths from 61-70 m, and averaged 15,300 larvae/100 m^2 on the E line with a range from 8,800-24,700/100 m^2 (Fig. 3.14; Table 3.2).

Summary: 1) Larval densities in June were very low nearshore from 10-12 km off the coast throughout the entire study area. 2) Peak abundance occurred 25-30 km offshore from Amak Island to Cape Seniavin. 3) Abundance declined farther offshore in water of 61-80 m depth in the western portion (stratum I) of the sampling area (Fig. 3.13),

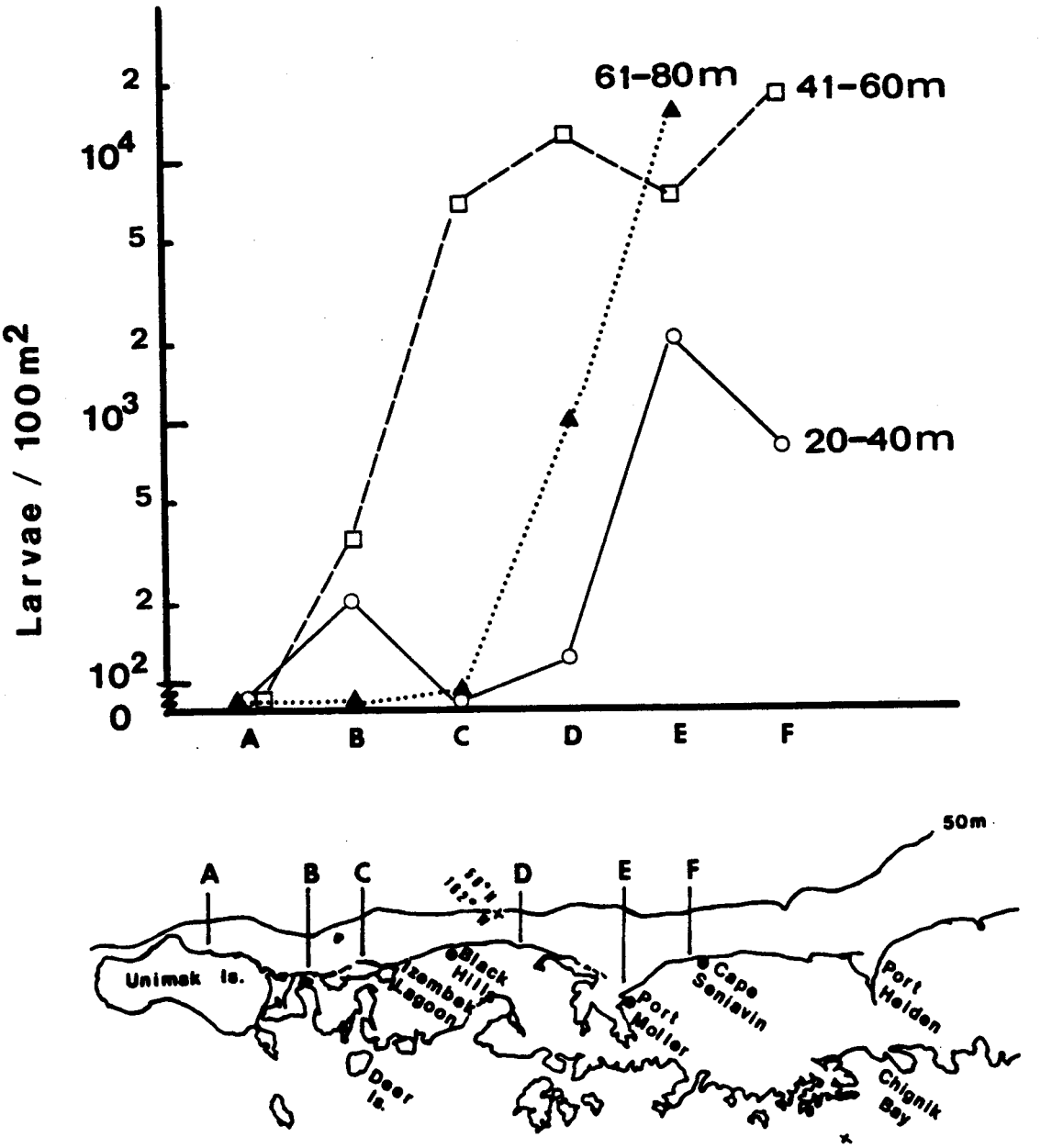


Fig. 3.14. Abundance of red king crab larvae as a function of depth (distance from shore) along the NAS. All stations used in this presentation were collected within six days of each other in June, 1982. See Fig. 2.19 for details of station locations.

Table 3.2. A summary of larval red king crab densities in June, 1982, along the North Aleutian Shelf. Stations were grouped into three depth intervals along six transect lines to contrast nearshore and alongshore distribution (see Fig. 3.14).

Transect line	Depth* interval	n**	$\bar{X}$ (No. larvae/100 m^2)	Range
	1	3	0	--
A	2	3	0	--
	3	2	0	--
	1	2	202	0-405
B	2	3	350	120-590
	3	2	0	--
	1	3	26	0-78
C	2	1	6,624	--
	3	3	80	0-126
	1	2	125	0-250
D	2	1	12,231	--
	3	1	1,120	--
	1	2	2,000	0-4,000
E	2	2	6,930	4,300-9,550
	3	5	15,350	8,800-24,700
	1	3	780	50-1,300
F	2	5	17,300	6,400-36,240
	3	0	--	--

* 1 = 20-40 m, 2 = 41-60 m, 3 = 61-80 m

** n = number of stations on the transect lines within each depth interval; see Fig. 3.13 for locations.

but larvae were very abundant in 61-70 m depth about 40-50 km off Port Moller (stratum II).

By early August, 1982, no red king crab larvae were found from western Unimak Island through stratum I and beyond to Port Moller (Fig. 3.15). Very low densities of 100-300/100 m^2 were sampled about the 50 m isobath off Port Moller. Higher densities were found only on a transect line off Port Heiden. Here again, shallow stations nearshore had less than 100 larvae/100 m^2 while stations betweem 41-60 m averaged 1535/100 m^2 (Fig. 3.15). It is not known whether the disappearance of larvae up to Cape Seniavin represents northeasterly transport out of stratum I or earlier metamorphosis to the benthos in the westerly area of hatch (see Section 3.4.3 for further discussion).

Blue King Crab: Few samples were taken in the area of blue king crab abundance east of the Pribilof Islands (Figs. 3.7a and b). Most larvae were found 50-90 km east of St. Paul and St. George Islands, and none were caught at five nearshore stations about St. Paul (Fig. 3.11). Densities were low compared to areas of larval king crab abundance. The highest zoeal density was 1550 larvae/100 m^2 ($n = 9$, SD = $\pm$ 478; all years combined).

3.4.2 Interannual Variations

There were too little data in strata 9 and 10 (Figs. 3.11 and 3.12) to note differences in abundance of blue king crab year to year. Only the nearshore of the NAS was sampled with some regularity, although the number of annual stations were few. As previously noted, two new

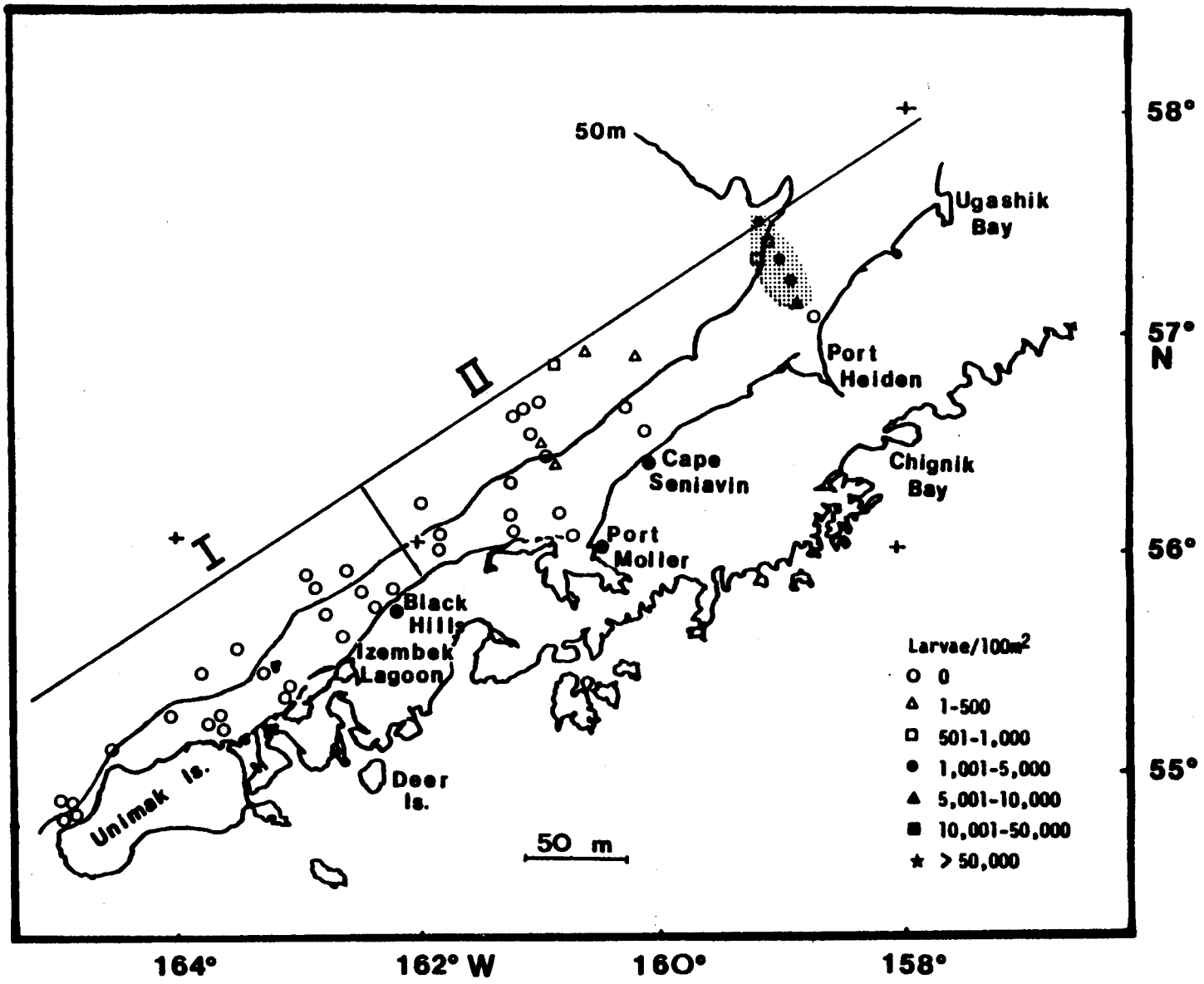


Fig. 3.15. Distribution and relative abundance of red king crab larvae in early August, 1982. Note the virtual absence of larvae from Unimak Island to Port Heiden.

strata (I and II) were created to give a qualitative sense of interannual spatial and temporal changes in abundance. No statistical contrasts were attempted since extensive sampling was done only in 1982 (Tables 3.2 and 3.3). In all other years, sample size for the two-month period of May through June never exceeded 15 per stratum for areas that exceed 12,000 km^2 (Fig. 3.12).

Large differences in density of larvae were noted both between years and between strata I and II (Fig. 3.16 and Table 3.3). Most samples were taken in the western NAS area in stratum I, which was sampled every year from 1976 to 1982. The years of greatest abundance were 1976-1977 when densities averaged 13,200 larvae/100 m^2 (Fig. 3.16; densities in this stratum were very similar in both 1976 and 1977 and so stations were combined to increase sample size). Average densities in the years 1978-1982 were about 20 times lower in the range of 450-710 larvae/100 m^2 (Fig. 3.16, Table 3.3).

Stratum II was sampled only in the years 1980, 1981 and 1982. Densities of larvae were highest in 1980 at 47,200 larvae/100 m^2 (only three stations), and substantially less in 1981 at 1,780/100 m^2. Comparison of strata averages (Figure 3.16 and Table 3.3) shows that larvae were always more abundant in stratum II than in I when both were sampled in the same years (only two samples in stratum II, 1976 and 1977 combined). In 1982, average densities were 7,900/100 m^2 and 441/100 m^2 in strata II and I, respectively, and the few samples collected in 1980 indicate a 100-fold increase in average densities from west to east.

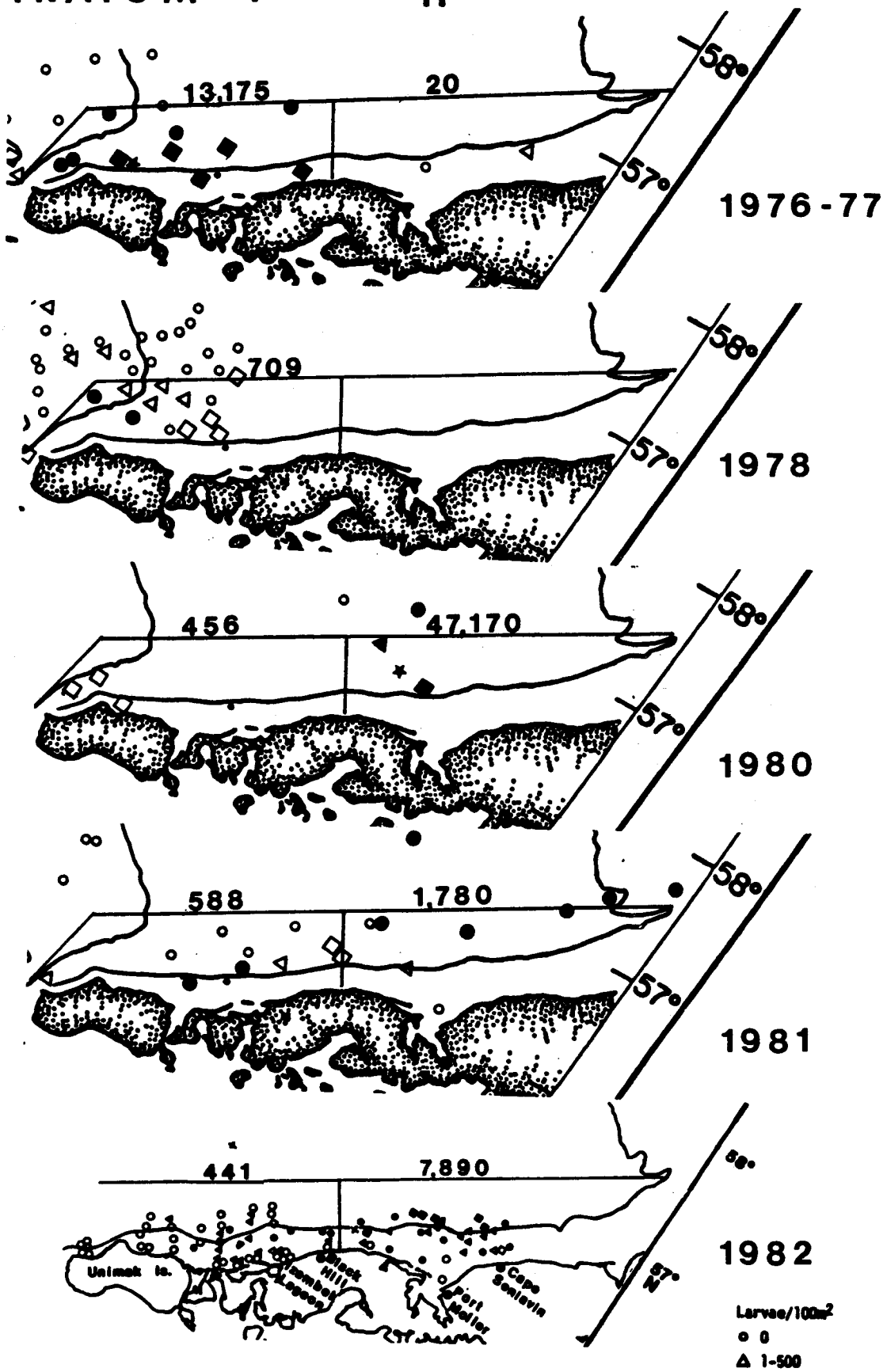


Fig. 3.16. Interannual differences in distribution and abundance of red king crab larvae in strata I and II along the NAS. Shown are station locations and symbols of abundance and the average density for each stratum (see Table 3.3 for details).

Table 3.3. Mean abundance of larval red king crab along the North Aleutian Shelf during May and June in 1976 through 1982. The region is divided into two strata that separate distributions east and west of 162°W latitude near Black Hills. Values are larvae/100 m^2. (See Fig. 3.12 for strata boundaries).

	Stratum I				Stratum II			
Year*	n**	$\bar{X}$	± SD	Range	n	$\bar{X}$	± SD	Range
1976-77	15	13,175	17,200	650-67,000	2	20		0-39
1978	12	709	537	170-1,760			none	
1980	5	456	421	0-850	3	47,170	58,300	7,500-114,000
1981	8	488	943	0-2,570	9	1,780	1,512	0-4,500
1982	48	441	1,181	0-6,620	30	7,893	1,584	0-36,240

*Larval densities in 1976-77 were very similar in Stratum I so they were combined for a larger sample size. No samples were collected in either Stratum in 1979.

**n = the total number of stations collected, including zero stations.

[An interesting note on annual abundance: collections made along the NAS in April and June, 1983, indicate a drastic reduction in larval densities from 1982 levels. Samples taken along similar transect lines and throughout Bristol Bay to Cape Newenham show larvae are at least 10 to 20 times less abundant this year than in 1982 (D. Armstrong, University of Washington and VTN, Oregon, unpublished data).]

Summary: 1) Larval densities were much lower along the western NAS from Unimak Island to Black Hills (stratum I) than in the eastern area from Port Moller into Bristol Bay (stratum II). 2) 1976-77 was a year of highest average densities in stratum I and 1980 in stratum II. 3) Lowest densities in both strata occurred in 1981. 4) Both 1980 and 1982 were probably good years of larval production along the NAS.

3.4.3. Hatchout and Settlement

Red King Crab: The time series of samples collected in any year from 1976 through 1982 were never long enough to span the period of complete larval development from hatch through metamorphosis. Enough data are available, however, to: 1) assign a realistic average date of hatch and discuss interannual differences in timing of peak hatch; 2) calculate the appropriate duration of each larval stage and the frequency of molt (next subsection 3.4.4); and 3) follow development to the megalops stage and predict an approximate period of metamorphosis and settlement to the benthos.

Six time intervals were established to study larval hatch and development (Fig. 3.17a and b). They are based on average sampling dates of cruise legs in various years, and usually span three-week intervals. The earliest zooplankton samples collected that contained red king crab larvae were prior to April 18 in 1977; the latest collections were made in August, 1982. Based on data from 1977 and 1978, SI larvae were abundant by mid-April and SII by late April, 1978 (Fig. 3.17a). In some years, therefore, larvae hatch as early as April 1 (note that 40% of all larvae were already SII in late April 1978). In other years hatching can begin a month or more later. In mid-May, 1976, virtually all larvae were still SI and in early June, 1980, 40% of larvae were SI. (During the first NAS leg from April 18 to May 7, 1983, no larvae were found along the entire NAS from Unimak Island to Port Heiden on the first pass. Larvae were present on the return, however, at stations revisited between May 1-6, indicating hatch began about May 1). The largest interannual difference in apparent time of hatch was between the years 1976 and 1979 (Fig. 3.17a) when all larvae were SI in mid-May, 1976, but all were SIV in mid-June, 1979, indicating a very late and early hatch, respectively.

Larval hatch is apparently not a synchronous event throughout the female population along the NAS as evidenced by the presence of several larval stages at most stations (Fig. 3.17a and b). Data of 1980, 1981, and 1982 show that four larval stages were present in the water column during several time intervals, although only two stages were usually dominate (Fig. 3.17b).

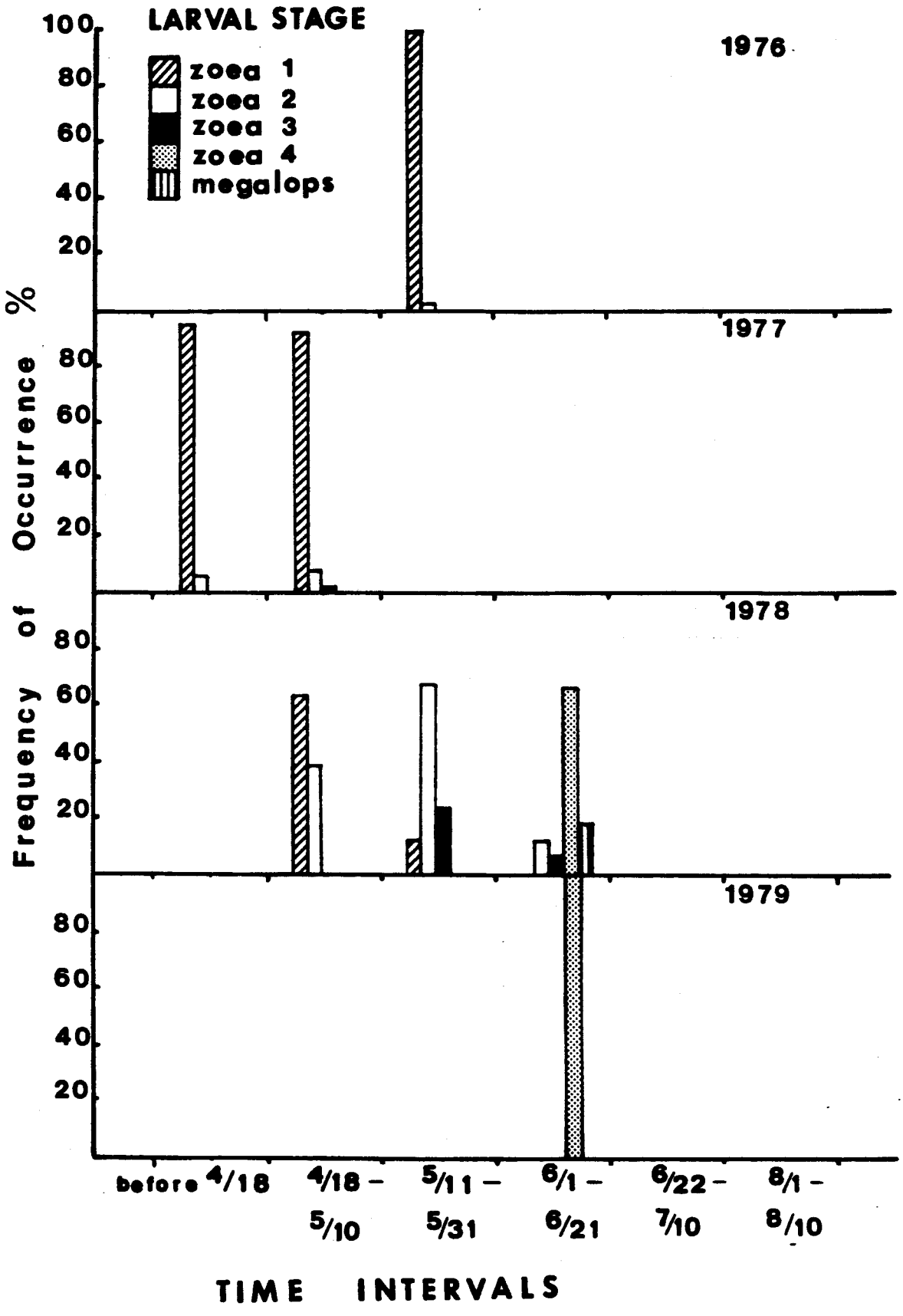


Fig. 3.17a. Frequency of occurrence of one megalops and four zoeal larval stages of red king crab in the years 1976-1979. There were no samples collected between July 10 and August 1 of any year.

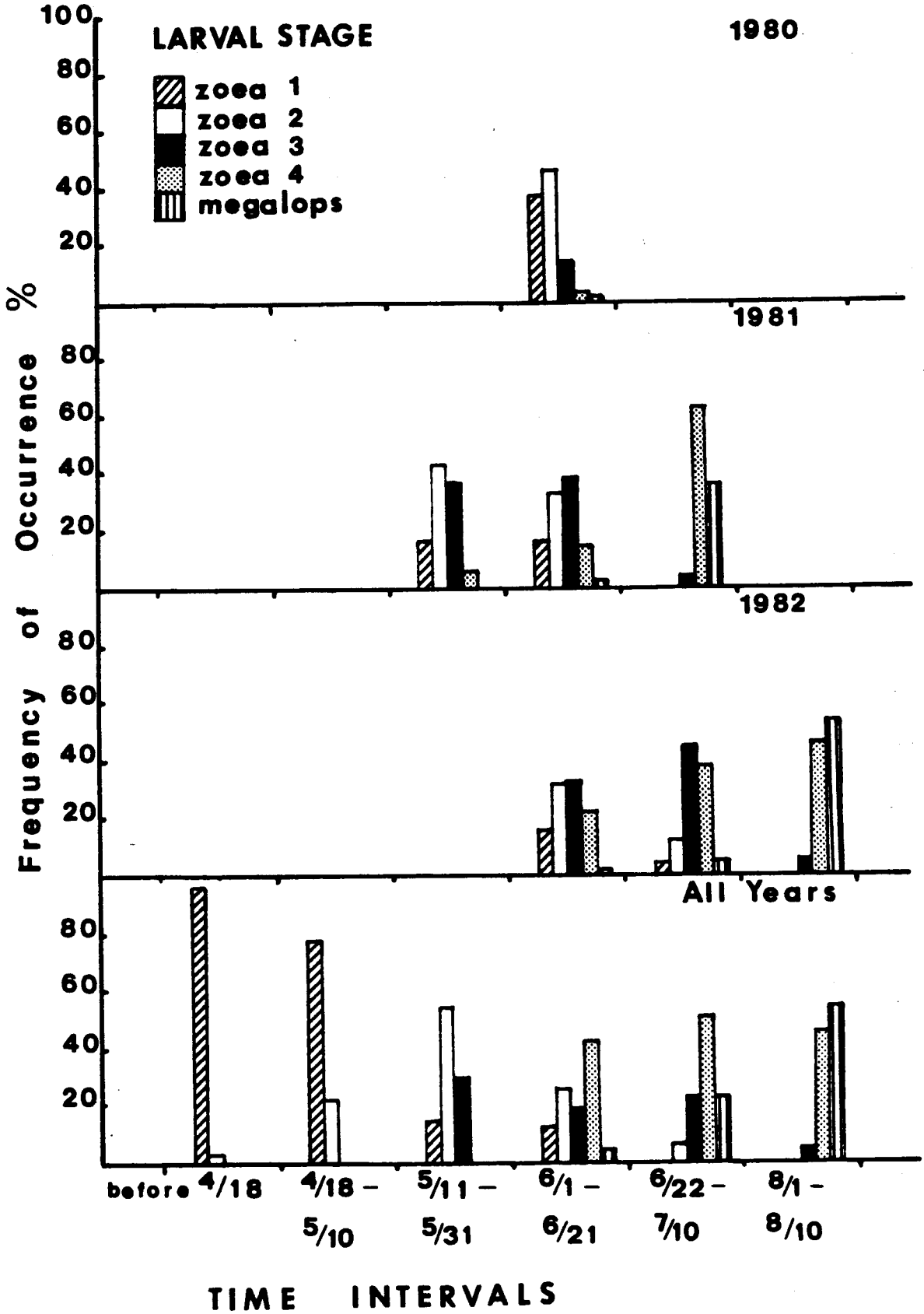


Fig. 3.17b. Larval frequency of occurrence in the years 1980 through 1982. The data from all years 1976 through 1982 have been summarized in the last frame to show a pattern of the change in proportion of each larval stage over time.

The occurrence of a multi-stage larval population may, in part, simply reflect geographic differences in hatch time. Data in Figures 3.17a and b were grouped from the entire geographic area of strata I and II for the time intervals shown because samples were so few. However, in 1982, stations from Amak Island to Cape Seniavin were collected in a six-day period along this 215 km distance. By grouping zoeal stages SI+SII and SIII+SIV, and calculating frequency of occurrence, the resultant data suggest an earlier hatch along the western than along the eastern NAS (Fig. 3.18). Around Amak Island, SIII+SIV larvae comprised 80 to 100% of total populations but by Cape Seniavin SIII+IV were only 32% (Fig. 3.18).

The total period of larval development is estimated to take about 4.5 months from hatch of first zoeal in early April, to metamorphosis of megalopae in mid to late August (Fig. 3.17b). Megalopae were collected as early as June 15 in 1978, but more typically in early July and August, 1981 and 1982, respectively. Since 45% and 55% of larvae were SIV and megalopae in early August, 1982 (Fig. 3.17b), metamorphosis to the benthos probably did not occur until late August to early September for much of that year class.

Blue King Crab: Very little data are available with which to gauge hatch and metamorphosis of *P. platypus* (the OCSEAP FY83 Pribilof Island program on blue king crab should improve this data base). The earliest samples containing blue king crab were collected in late May, 1976, and all larvae were SI and II. In late June, 1978, a few Pribilof Island stations had SIV larvae, and in early July, 1982, all larvae caught were

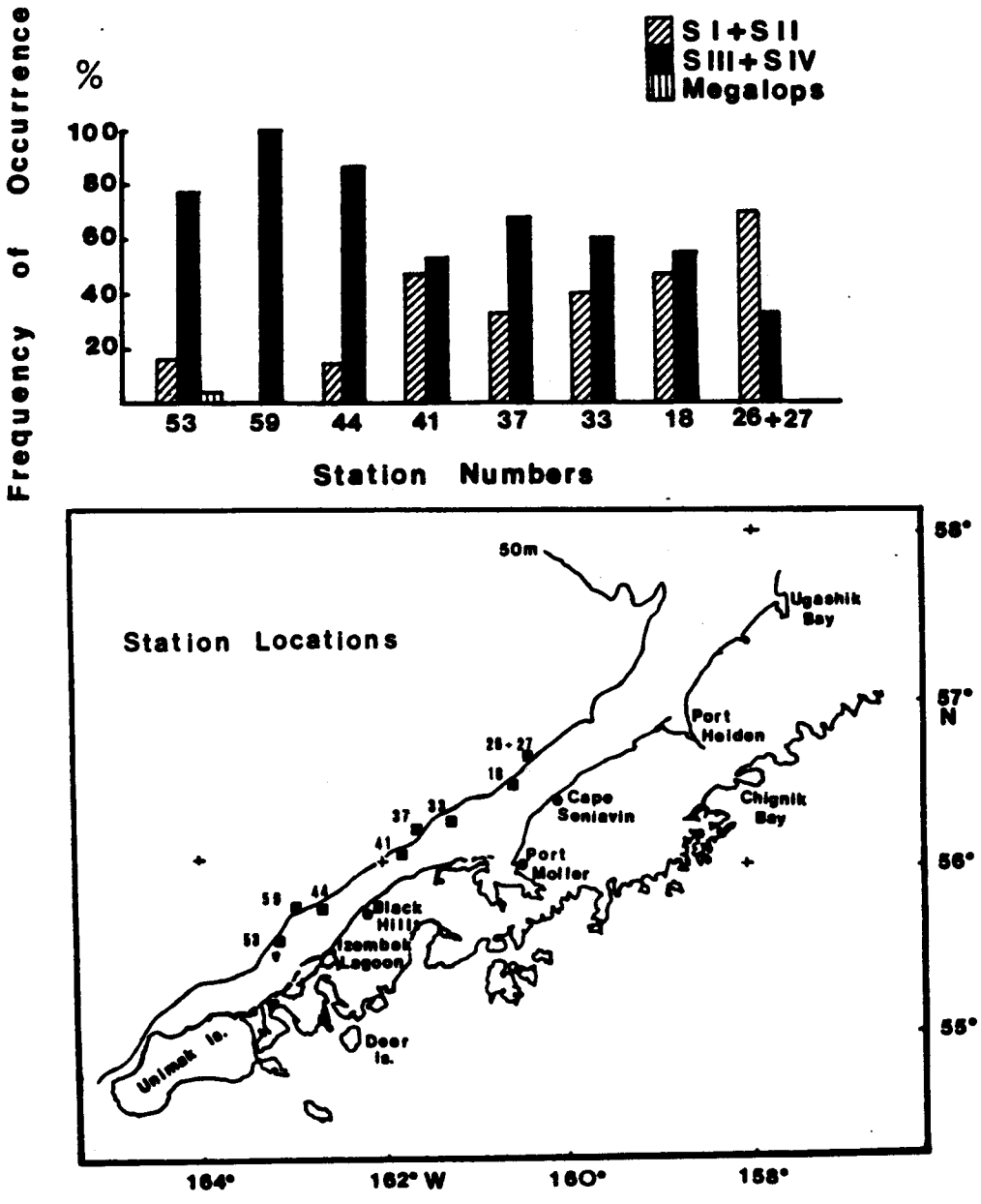


Fig. 3.18. Differences in apparent hatch time of red king crab larvae in the western and eastern NAS area. All samples were collected within a six day period. Note that at western stations around Amak Island there is a higher percentage of older SIII + IV larvae than found farther east off Cape Seniaven.

megalopae. These combinations of years and larval stages are similar to data for red king crab (Fig. 3.17a and b). There is, however, an indication that larval hatch and, therefore, metamorphosis might occur somewhat earlier for blue king crab based on data of 1981. All larvae in early July were megalopae and many were approaching the molt to first instar juveniles. Almost 50% of megalopae held in rearing chambers onboard ship molted to first instars within a week of capture (by July 14; D. Armstrong, University of Washington, unpublished data). Metamorphosis to the benthos for blue king crab might, therefore, occur by mid to late July; a month earlier than predicted for red king crab.

3.4.4. Molt Frequency and Growth

Red King Crab: Data on molt frequency for red king crab larvae were previously summarized in Figures 3.17a and b. A preliminary analysis of frequency of occurrence of various larval stages was done on data of 1978 (Fig. 3.19; Armstrong et al. 1981). Based on the proportion of each larval stage (SI, II, II, IV, megalops) in samples from four cruises between April 10 to June 29 (see Section 2.0 for cruise maps), it was estimated that larvae molt every 2.5-3.0 weeks (Fig. 3.19). If so, then the elapsed time of development from hatch to metamorphosis would be about 12.5-15.0 weeks, or about 3.0-3.5 months. However, a summary of larval stage data from all years 1976 to 1982 combined, indicates that development might take 4.0 to 4.5 months from hatch to metamorphosis (Fig. 3.17b). Although annual hatching time will vary (section 3.4.3), mid-April seems a reasonable annual time to expect the hatch of *P. camtschatica* larvae. Megalopae are common from early July

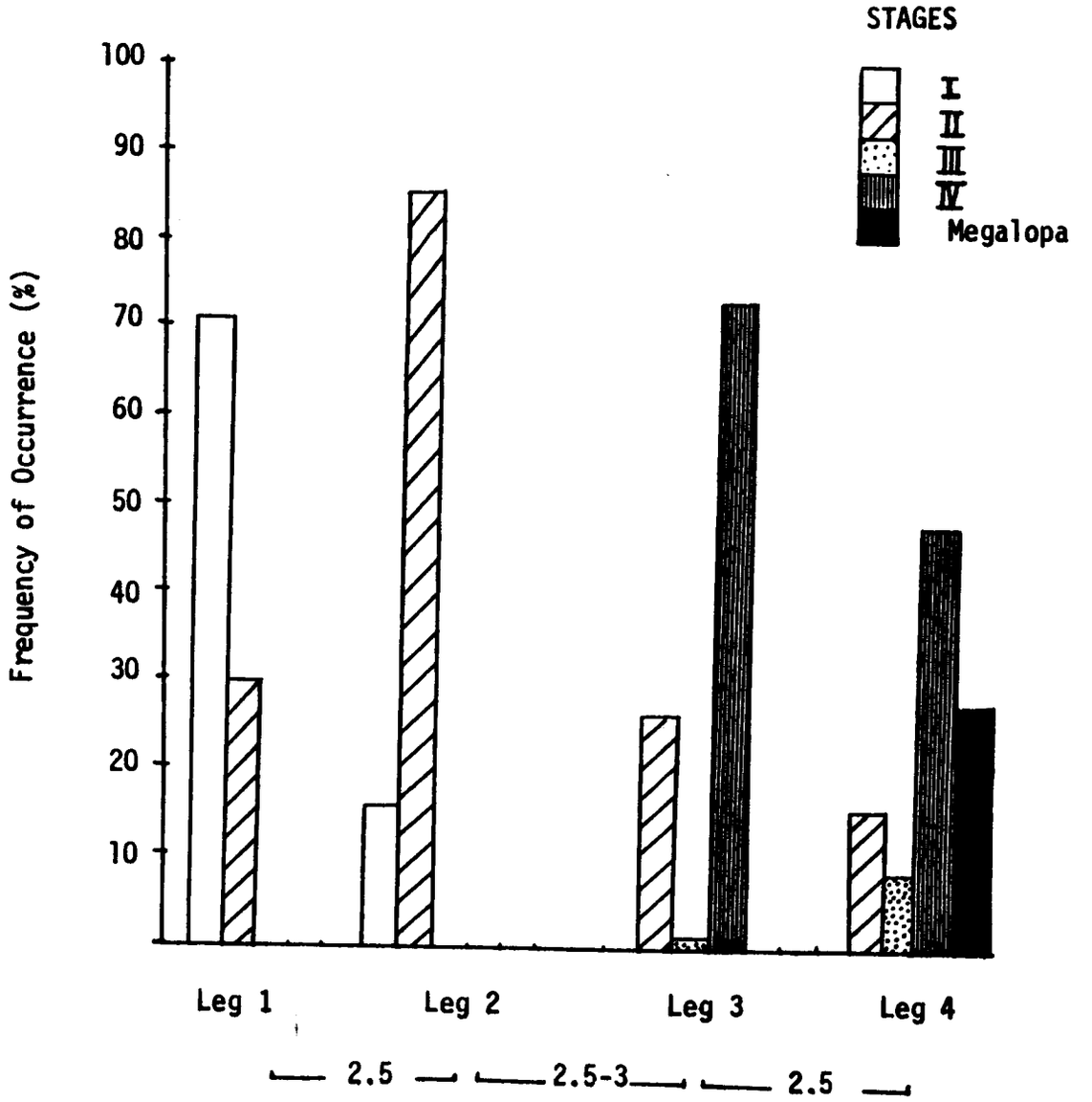


Fig. 3.19. Frequency of occurrence of Paralithodes spp. larval stages collected during four legs of the 1978 PROBES cruises. The number of weeks between mid-points of legs are shown along the bottom axis and serve as an approximate gauge of molt frequency.

to early August (Fig. 3.17b), and still have three to four weeks development before molt to first instar juveniles; an event predicted to occur from mid-August to September.

Molt frequency of larval red king crabs is estimated to be once every three weeks, based on a simple division of four months development time by five larval stages. Examination of frequency-of-occurrence data for all years combined (Fig. 3.17b), shows a major shift in the proportion of larval stages occurs in three-week intervals depicted. It is not known from these data, however, if the intermolt duration changes with stage (e.g. shorter as SI, longer as megalopae) as a function of temperature and mass, or is rather constant as assumed above. Relative to oil pollution, it seems reasonable to assume that exposure of larvae for a week or more would encompass ecdysis of some portion of an asynchronous population (see Section 8.0 for further discussion of this point).

Growth of larvae is substantial during this four-month period. From a mean egg weight of 220 mg dry wt., larvae increase almost six-fold to 1300 mg as megalopae (Fig. 3.20). The data of Figure 3.20 were obtained by collecting fresh red king crab larvae in the southeastern Bering Sea, staging, drying and weighing each animal on an electrobalance. The data not only show the weight gain from one larval stage to the next, but also the increase in dry weight within a single stage (i.e. intermolt growth). Stage II larvae had initial mean weights of 370 mg/larva but increased to 440 mg/larva prior to the molt from SII to SIII (Fig. 3.20). Likewise, the mean weight of SIV larvae was

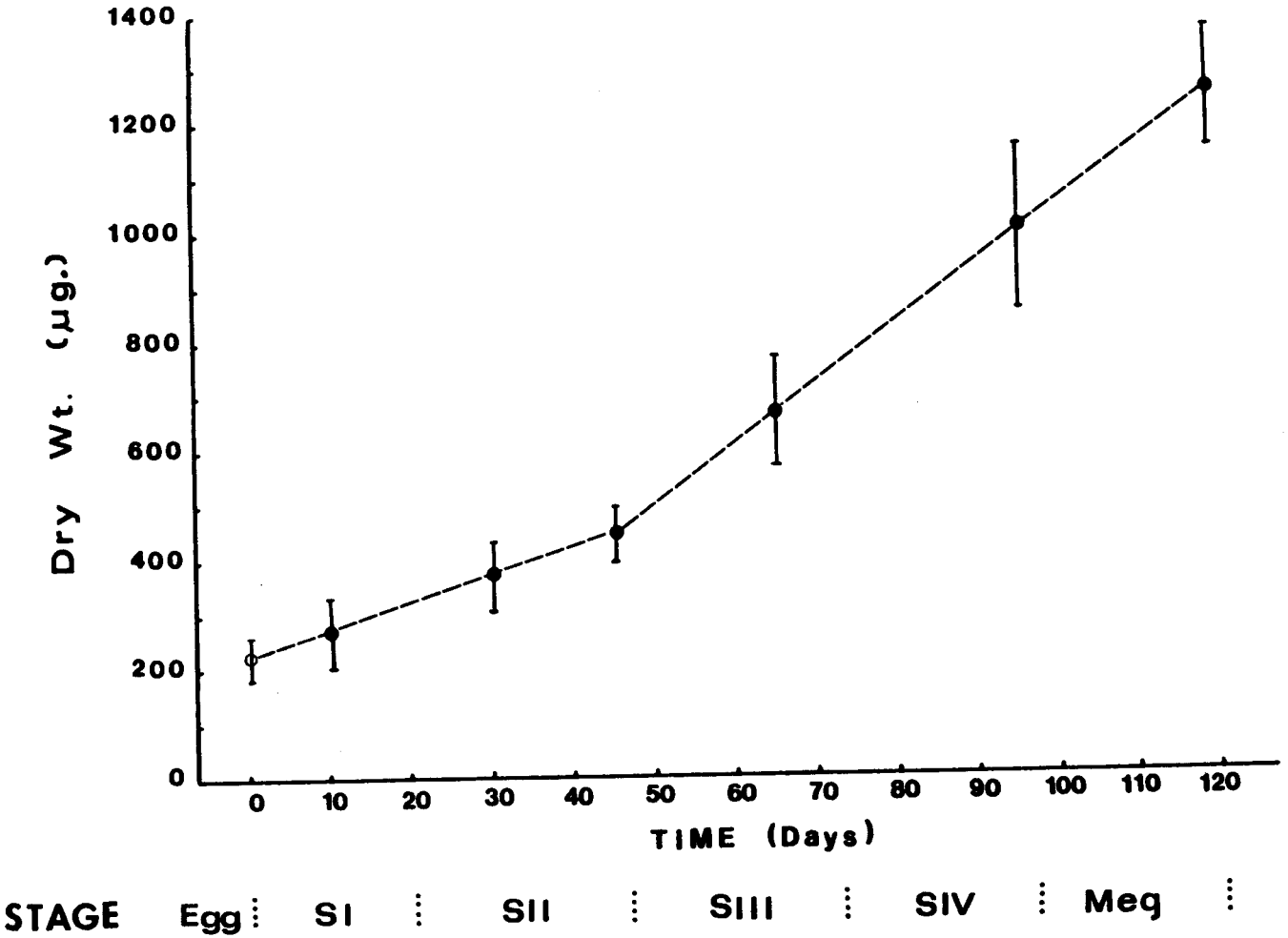


Fig. 3.20. Increase in dry weight of red king crab larvae from the mature egg through megalops stage. The approximate duration of each stage is shown for a total development period of about 4.0 months. Data are the mean ± SD; n = 15 to 30 for each mean.

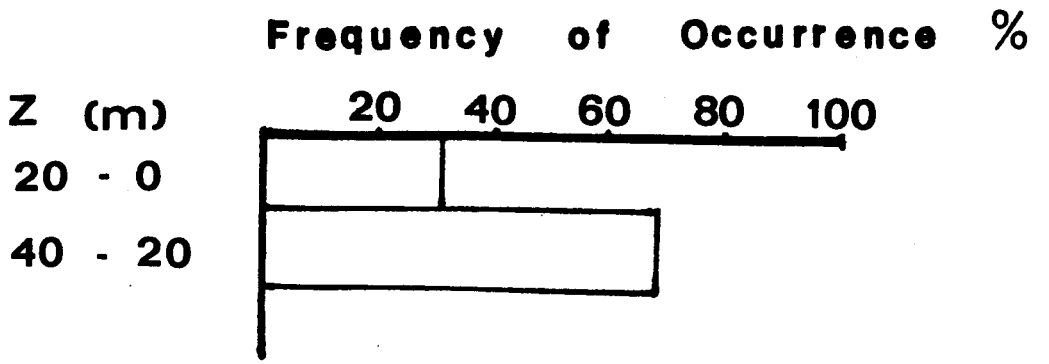


Fig. 3.21. Vertical distribution of red king crab larvae from six MOCNESS stations, PROBES 1981. Percent frequency of occurrence is based on a total of 600 larvae from the six stations.

1008 mg/larva, but those molting to megalopae weighed 1200 ug/larva. Such change indicates that growth is not a static event that occurs only at molt. Rather it is a process that continues throughout an intermolt period as larvae feed. Perturbations that disrupt feeding for portions of an intermolt cycle could inhibit weight gain necessary for ecdysis to the next stage.

Blue King Crab: No comparable data on larval growth of this species are available.

3.4.5. Vertical Distribution

Few MOCNESS samples were taken in areas where larval king crab occurred. Most larvae were caught at shallow stations where MOCNESS intervals were 0 to 20 m and 21 to 40 m depth. In such samples, 68% of larvae were in the lower depth interval of 21 to 40 m (Fig. 3.21). At a few MOCNESS stations in deeper water, larvae were also least common in the upper 20 m and equally distributed at 42% occurrence in both the 21 to 40 m and 41 to 60 m intervals. However, very few larvae comprise this last observation (n=7 larvae) and, in general, more work is needed to clarify patterns of vertical distribution and possible diel changes.

3.5 Discussion

If oil development in the southeastern Bering Sea impacts king crab, it would likely be most severe as exposure of pelagic larvae or, possibly, of egg-bearing females, since reapidly developing embryonic and larval life-history stages are usually more sensitive to chemical perturbations than are older individuals of a species. (The nature and

consequences of oil exposure scenarios are discussed in Section 8.0). In this section, data have been summarized that pertain to the general biology and ecology of larval king crab, primarily P. camtschatica. Information gained from data of 1976-1981 is fragmentary and a story of larval biology is far from complete. Opportunistic work in 1982 and OCSEAP programs along the NAS in 1983 have and will greatly contribute to a backdrop of biological information against which oil impact scenarios can be cast and analyzed. With the data gathered in this study, a sense of the spatial and temporal susceptibility of red king crab larvae to oil has been gained.

The ultimate effects of oil perturbations would be to reduce year-class (es) strength and, in turn, reduce the number of animals entering the fishery. Year-class strength is highly variable as evidenced by the tenfold decline in legal males between 1979 and 1982 (Fig. 3.5), and a decrease from 150 million mature females in 1977 to 55 million in 1982 (Otto et al. 1982). Year-class strength is probably determined by some combination of: 1) reproductive success of the mature female population; 2) survivorship of larvae and; 3) survivorship of young benthic juveniles for one to two years after metamorphosis.

A suite of biotic and abiotic factors (e.g. temperature, currents, food, refuge habitat, predators) act in optimal or perturbational combinations on these three life-history links to produce changes in abundance. Even the fishery itself may exacerbate the effects of suboptimal conditions influencing reproductive effort and survivorship of environmentally sensitive life-history stages. Important points to

consider in regard to king crab biology, lease sale areas, and oil perturbations are: 1) the distribution and abundance of mature females; 2) abundance, distribution and transport of larvae; 3) time and duration of annual larval hatch; 4) frequency of molting; and 5) area(s) of larval metamporphosis and settlements of juveniles.

Distribution of red king crab larvae nearshore along the NAS is in partial accord with that of the sexually mature female population in the southeastern Bering Sea. The annual NMFS groundfish survey in that area shows that female crab are abundant in the area of high larval density (Figs. 3.5, 3.11), but also for greater distances offshore (up to 120 km) and in northwestern Bristol Bay (e.g. high abundance around 57°30'N, 162°W as a focal point; Fig. 3.3). While females seem to be distributed more widely than larvae along the NAS, a similar conclusion cannot be drawn for Bristol Bay (east and north of Cape Seniavin) because of very limited larval sampling in that area. Still, since larvae of red king are apparently found over a more restricted range than adult females, a variable percentage of the females may be superfluous to the annual reproductive effort because they spawn in areas unsuitable for larval and/or early juvenile survival. Therefore, exposure of females to oil in the area of larval hatch may be a more important consideration than exposure of females elsewhere within the species range in the southeastern Bering Sea.

Larval abundance appears to vary appreciably on an annual and geographic basis along the NAS, although data are few for some years and areas (see Fig. 3.16 and Table 3.3). The extent to which larval

abundance in time and space is correlated to that of mature females cannot be solidly analyzed from data on hand; specifically a long-term series of comprehesnsive larval red king crab collections does not exist. Still, there is an indication that changes in abundance and distribution of benthic females might influence larval production in the water column.

Population estimates for mature female red king crab (as well as males and other species of crab) are computed by NMFS for 400 NM^2 quadrats as part of an annual groundfish survey (see Otto, MacIntosh, Armetta and Wilson 1980; Otto et al. 1981, 1982). Fig. 3.22 shows data for four years and depicts major shifts in numbers and location of mature females in southeastern Bering Sea. A gross analysis of this data was performed by averaging population estimates in quadrats that fell within three general areas: 1) stratum I along the western NAS; 2) stratum II to the east; and 3) the remainder of Bristol Bay (all three areas are shown for the year 1978 in Fig. 3.22; strata I and II correspond to areas used for larval analyses in Fig. 3.16). Actual catch values could not be obtained from NMFS in time for this report, so mean female abundance was calculated by taking midpoint values for the ranges shown in each quadrat. In the years 1975-1977 ranges were 1-2,000 crabs (midpoint = 1,000), 2,001-5,000 (3,500), 5,001-20,000 (12,500), and greater than 20,001 (25,000). From 1978 through 1982 ranges were somewhat different; 1-2,000 (midpoint = 1,000), 2,001-10,000 (6,000), 10,001-20,000 (15,000), and greater than 20,000 (25,000).

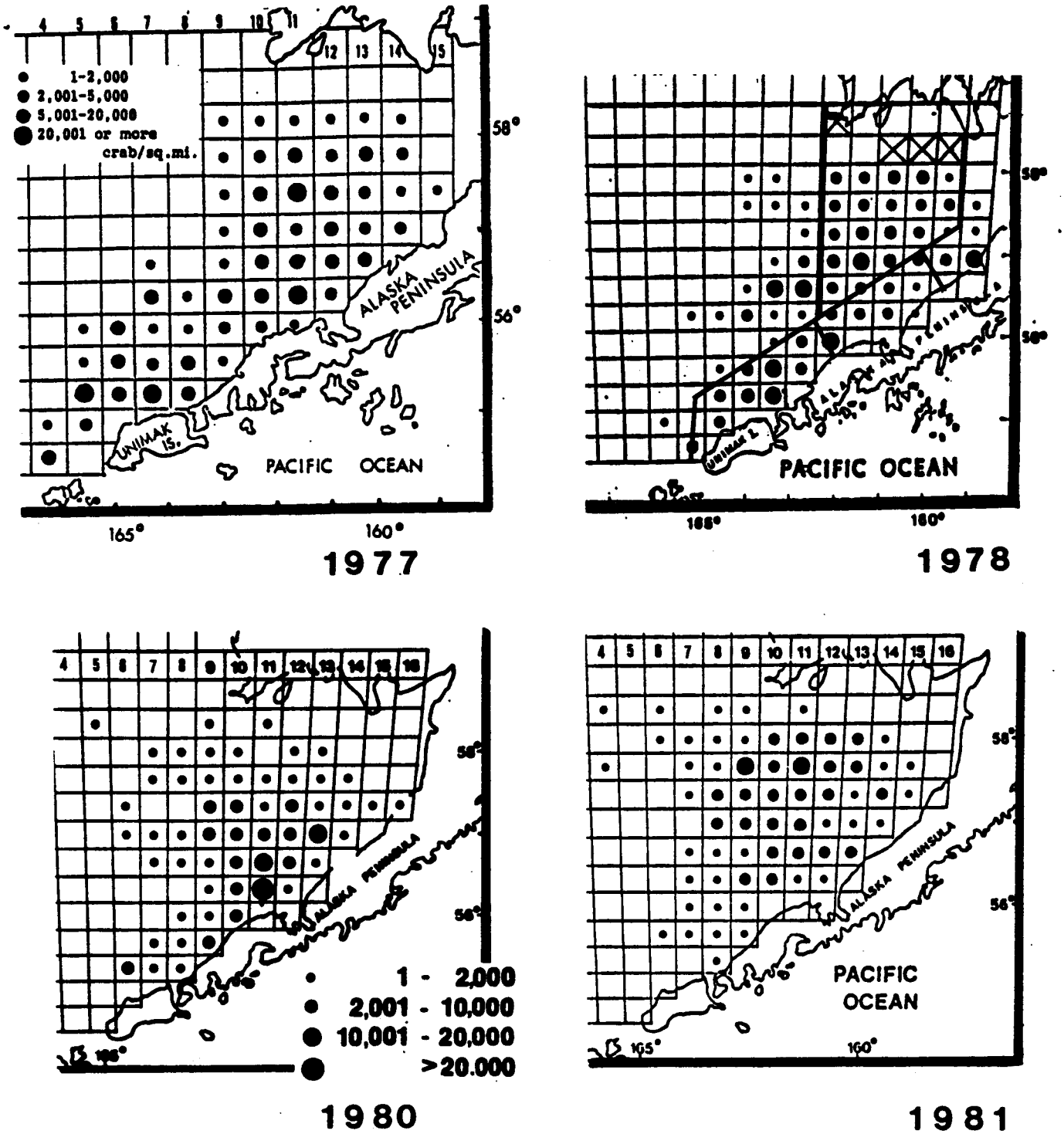


Fig. 3.22. Annual distribution and relative abundance of female red king crab greater than 89 mm carapace length (sexually mature). Note the decrease in numbers along Unimak Island to Black Hills from 1977 to 1981. The boundaries of three areas used to constrast spatial and temporal abundance are shown for 1978 (see Table 3.4). Note the difference in ranges of abundance between 1977 and all other years (all data from NMFS, e.g. Otto et al. 1980a, 1981).

Female crabs were abundant in stratum I from 1975 through 1978 and averaged about 8,000 to 10,000/NM^2, but had declined in this area to less than 1,000/NM^2 by 1981-82 (compare 1978 and 1981 in Fig. 3.22; Table 3.4). Corresponding larval abundance was high in stratum I in 1976-77 and low in 1980-82 (Fig. 3.16), but this trend was not always consistent since in 1978 larval abundance was low and that of females high (Figs. 3.16, 3.22).

Female abundance was more constant within stratum II off Port Moller, and ranged from yearly averages of 3,000 to 9,000 NM^2. In the only years of concomitant data (1980 to 1982), larvae seemed abundant in 1980 but less so in 1981-82 when female abundance declined from 7,500 to 3,800/NM^2 (Tables 3.3, 3.4). However, because larval data are so few between 1967 through 1981, any relationship between female abundance and larval production is highly speculative at this time. There has unquestionably been a shift of females away from the area of stratum I in recent years, and larval densities there are also very low. There is only a suggestion that the decrease in female abundance in stratum II since 1980 has resulted in fewer larvae, but the subject deserves further study as the population continues to decline in 1983.

Female abundance in the remainder of Bristol Bay generally ranged from 2,000 to 8,000/NM^2, and the contribution of this population to larval production remains unknown to date because very few zooplankton samples have been collected in that area.

Table 3.4. Relative annual abundance of female crabs greater than 89 mm carapace in the three areas of the southeastern Bering Sea. Stratum I and II are along the North Aleutian Shelf (see Fig. 3.16), and Remaining Bristol Bay is delineated in Fig. 3.22 for the year 1978. Values are the mean ± 1 SD of crabs per square mile (see the text for details on calculations).

Year*	Stratum I (n = 11)**	Stratum II (n = 10)	Remaining Bristol Bay (n = 19)
1975	7,700 ± 11,150	3,055 ± 3,690	550 ± 446
1976	8,400 ± 7,360	4,000 ± 4,681	2,200 ± 3,005
1977	9,400 ± 8,840	9,300 ± 7,080	6,400 ± 6,800
1978	10,100 ± 9,800	7,100 ± 7,200	8,300 ± 6,800
1980	1,600 ± 2,200	7,500 ± 7,700	2,000 ± 2,300
1981	635 ± 500	3,600 ± 2,700	5,900 ± 2,950
1982	820 ± 920	3,800 ± 4,800	3,380 ± 3,870

*Data for 1979 were not available.
**Numbers of NMFS stations used for calculating the mean of each area.

If a positive relationship exists between mature female abundance and larval production, it is not clear how this relates, in turn, to eventual year-class strength as measured by abundance of five-year-old juveniles (youngest prerecruits routinely sampled by NMFS; Reeves and Marasco 1980) or older age-classes. Reeves and Marasco (1980) attempted to model spawner-recruit relationships with ambiguous results from both Beverton-Holt and Ricker models. The only reasonable conclusion to be drawn was that very high levels of mature females are not always correlated to high recruitment. This reasoning could be expanded by

observing that: 1) the mature female population could fall below a level needed for strong recruitment (Fig. 4.A in Reeves and Marasco, 1980); and 2) populations of adequate spawning strength could be poorly situated geographically in terms of hatching larvae in areas for optimal growth and metamorphosis of juveniles to protective benthic habitat.

As noted in Section 3.4.2, surveys in 1983 have revealed a greatly reduced larval hatch compared to 1980-1982, and mature female abundance has also declined precipitously (D. Armstrong, U. Washington; VTN Inc., Portland; R. Otto, NMFS, Kodiak; unpublished data). Oil mishaps in years of low larval production could impact eventual juvenile settlement more severely than during years of high production (obviously the extent of any oil impact is inextricably linked to the timing, duration, and coverage of the spill).

As to the influence of geographic distribution of females on survival of larvae and eventual settlement of juveniles to appropriate refuge habitats, only speculative comments can be made. The greatest data gap in this regard is definition of areas where 0+ juvenile crab settle and survive. Rarely does the NMFS survey catch very small crab (gear and survey area limitations). Based on data of Smith and Bakkala (1982) and of 1983 surveys throughout the NAS and Bristol Bay (D. Armstrong, U. Washington; VTN Inc., Portland; unpublished data), much of the southeastern Bering Sea would not be suitable for survival of newly settled king crab. Very large populations of flatfish (e.g. yellowfin and rock sole) and other predators, coupled with a uniform bottom of mud/sand that affords little refuge, would probably result in tremendous

predator pressure and low (to no) survival of 0+ crabs metamorphosing in such areas. Preferred habitat of young king crab around Dutch Harbor and Kodiak Island (Weber 1967; Jewett and Powell 1981), indicate the species relies on cobble, shell, and aggregates of invertebrates (polychaetes, barnacles, ascidians, etc.) and algae for refuge. To date, an OSCEAP survey of nearshore juvenile crab distribution confirms this juvenile-refuge association in the southeastern Bering Sea.

Consequently, while the sheer magnitude of initial larval hatch and numbers surviving to metamorphosis may be important determinants of year-class strength, the geographic location of survivors at metamorphosis could be more important if refuge habitat is scarce and/or patchy. As suggested by Hebard (1959) and Haynes (1974), larval populations are probably transported varying distances from the origin of hatch. From data on development time of this study and current speeds (Kinder and Schumacher 1981c), larvae could be transported over 200 km from hatch to metamorphosis. Larvae hatched off western Unimak Island could reach Cape Seniavin; those hatched off Port Moller could reach Kvichak Bay. Whether the bottom of one area is better suited for survival of 0+ crabs than the other is presently unknown. If optimal bottom type does not occur uniformly along the NAS into Bristol Bay, then location of spawning female populations and the interplay of oceanographic factors and influences (e.g., currents and direction, wind speed and direction, storm events) during development time could be the major determinants of placement of larvae over optimal benthos at metamorphosis.

Much research on king crab biology and ecology should yet be done. Some topics of importance include:

1) Examination of NMFS survey data to detect interannual differences in female abundance relative to areas of larval hatch and development in the southeastern Bering Sea.

2) Reexamine spawner-recruit relationships developed by Reeves and Marasco (1980) in light of Item 1 and results of juvenile surveys. This effort would enable a better gauge of minimum numbers of spawners required for high recruitment based on abundance in "optimal spawning habitat," and estimates of progeny younger than the five-year lag currently required of NMFS data.

3) Study interannual variation in peak egg hatch based on NMFS "clutch" data. Annual shifts of 1 - 1.5 months might reflect winter-spring temperatures and influence larval development time, settlement, and first-year summer growth of 0+ juvenile crab.

4) Investigate timing of the oogenic cycle to partially determine if adverse temperature would sometimes delay reproductive events (e.g., molting and copulation, egg extrusion note late hatch of 1976 larvae, Fig. 3.17a) with detrimental effects on larval growth and survival.

5) Examine NMFS data to determine major annual shifts in the percentage of the mature female population that are primiparous (newly recruited mature year-class) or multiparous in regions suggested under item 1. Incorporate data on clutch size and relate both factors to

fecundity to derive potential larval hatch. Correlate annual reproductive effort lagged to population abundance of juveniles.

6) Conduct several consecutive years of larval surveys to compare initial abundance at hatch and survivorship at metamorphosis to later abundance of specific juvenile year-classes.

7) Incorporate physical oceanographic events (notably current patterns and rates, and storm events) to examine the annual direction and extent of larval transport. Use information to gauge the extent of settlement onto optimal "refuge" habitat as a prediction of 0+ survivorship.

8) Determine lower lethal thermal limits of zoeae and their energetic-growth responses to very low temperatures as an indication of potential survival in years of below-average cold (e.g., 1976).

9) Study food preferences of larvae and also feeding rates as a function of temperature and prey density to address requirements for adequate growth and the possibility of starvation.

10) Determine areas along the NAS and in Bristol Bay where major populations of young juveniles occur (0+ through 4+ age-classes).

11) Characterize the substrate and plant-animal assemblages associated with juveniles to define "refuge" habitat. Estimate the extent of such habitat in different regions of the southeastern Bering Sea.

12) Determine interannual differences in location of year-class settlement and relate to annual distribution of female stocks, areas of larval hatch, and predictions of larval transport as previously noted.

13) Synthesize such data into a qualitative prediction of annual 0+ survivorship based on the extent of settlement into appropriate refuge habitat. Incorporate information on the magnitude of potential prey populations (e.g., yellowfin and rock sole, Pacific cod) as an indication of the importance of such habitat.

4.0 DISTRIBUTION AND ABUNDANCE OF THE LARVAE OF TANNER CRABS IN THE SOUTHEASTERN BERING SEA

Lewis S. Incze

4.1 Introduction

Tanner crabs are brachyuran crabs of the genus Chionoecetes (Family Majidae). In the southeastern Bering Sea (SEBS) Chionoecetes bairdi, C. opilio (both numerous) and unknown numbers of C. angulatus and C. tanneri occur (Garth 1958; Somerton 1981). The latter two species are deepwater organisms inhabiting slope water generally more than 300-400 m deep. These crabs are small, are of no commercial interest, and probably have an exceedingly small role in the benthic and pelagic shelf sea environments. On the other hand, adult C. bairdi and C. opilio are comparatively large organisms which occur over a large portion of the southeastern Bering Sea shelf from depths of 50 to 200m; they are the target of a large commercial fishery of growing economic importance (Otto 1981) and they are dominant organisms in the benthic ecosystem (Feder and Jewett 1981). This section examines the larval life history of these two species of Tanner crab. Of particular concern is the definition of spatial and temporal patterns of larval abundance.

4.2 Description of the Fishery and Stocks

Prior to 1964 the catch of Tanner crab was only incidental to the king crab catch of Japanese and Russian fisnermen. After 1964, however, U.S. restrictions on foreign harvest of declining king crab stocks encouraged exploitation of Tanner crabs as a substitute. The initial fishery was based exclusively on C. bairdi because of its larger size, its better quality of meat for processing, and its occurrence in and

around the traditional king crab fishing areas. By 1969 the directed harvest of this species had increased to the level where fishing quotas became necessary. As a result of restrictions imposed by the United States, foreign vessels began harvest of C. opilio, a smaller animal which occurs in greater numbers and over a wider geographic area than its congener.

As total landings of Tanner crab from the eastern Bering Sea (EBS) increased (from 12 to 24 million crabs from 1967 to 1970), so did American interest in the fishery. Through a series of unilateral (U.S.) harvest quotas and bilateral agreements, foreign participation in the EBS Tanner crab fishery was gradually reduced and forced north and west. Today, all Tanner crab fishing in the southeastern Bering Sea (except for by-catch) is conducted aboard American vessels (154 vessels in 1979-80) and is directed at both C. bairdi and C. opilio. Landings from this region steadily increased from 1975 to 1980 and totaled more than 74 million pounds (40.4 million crabs) during the 1979-80 fishing season (November-September, Fig. 4.1). The contribution of C. opilio to the Tanner crab fishery has increased dramatically in recent years (Table 4.1). In 1981 and 1982, total Tanner crab landings, mostly from the SEBS, exceeded those of king crab by 65% and 140%, respectively. However, total landings of Tanner crabs also have declined over the past two fishing seasons (unpublished data, National Marine Fisheries Services, R. Otto, pers. communication).

Eastern Bering Sea stocks of Tanner crabs have been assessed by annual trawl surveys conducted by the National Marine Fisheries Service

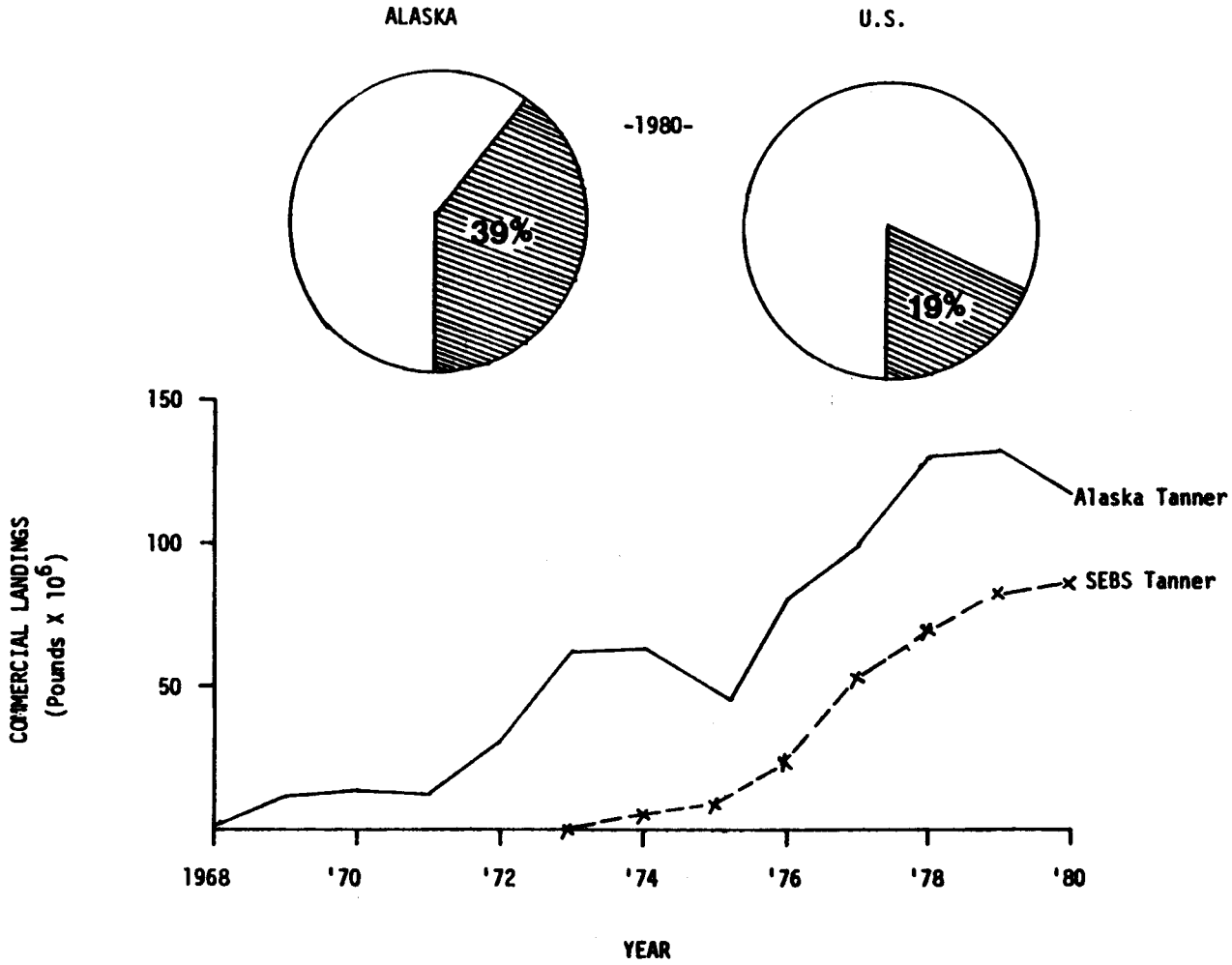


Fig. 4.1. Commercial landings of Tanner crabs from the southeastern Bering Sea (SEBS) compared to total commercial catch for Alaska, 1968-1980 (lower). Pie diagrams show Alaska tanner crab landings as a percentage of total Alaska and total U.S. commercial crab landings for all species combined for 1980. [Compiled from data of Eaton (1980), Fisheries of the United States, 1980 (1981) and Pacific Packers Report, Spring 1981 (1981)].

Table 4.1. Historic U.S. Tanner crab catch in the eastern Bering Sea, 1968-1982 (From Eaton, 1980, 1981)

Year	Number of Vessels*	Number of Landings	Number of Crab	Number of Pounds	Number of Pot Lifts	Average Weight	Average Crab Per Pot	Price Per Pound
1968		7	6,408	17,858	1,426	2.8	5	
1969		131	353,273	1,008,898	29,851	2.9	12	
1970		66	482,307	1,410,721	16,372	2.9	29	
1971		22	61,347	166,058	7,343	2.7	8	
1972		30	42,561	119,170	6,728	2.8	6	
1973		45	132,941	301,868	16,530	2.3	8	
1974	18	69	2,531,825	5,044,197	22,014	2.0	115	
1975	27	80	2,773,770	7,028,378	38,462	2.5	72	.13
1976	66	305	8,949,886	22,341,475	141,179	2.5	63	.19
1977	83	580	20,412,566	51,876,235	305,052	2.5	67	.30
1978								
C.bairdi	119	823	26,188,543	66,228,040	508,776	2.5	51	.38
C.opilio	15*	38	1,267,196	1,716,249	13,177	1.3	96	.30
TOTAL		861	27,455,739	67,944,289	521,953	2.5	53	
1979								
C.bairdi	138	801	16,711,455	42,518,233	393,788	2.5	42	.52
C.opilio	101*	490	22,118,498	32,187,039	190,746	1.5	116	.30
TOTAL		1,291	38,829,953	74,705,272	584,534	1.9	66	N/A
1980								
C.bairdi	154	804	14,739,611	36,614,315	488,434	2.5	30	.52
C.opilio	141*	603	25,706,262	39,538,896	272,065	1.5	94	.21
TOTAL		1,407	40,445,873	76,153,211	760,499	1.9	53	N/A

(CONTINUED)

Table 4.1 (Cont.)

Year	Number of Vessels*	Number of Landings	Number of Crab	Number of Pounds	Number of Pot Lifts	Average Weight	Average Crab Per Pot	Price Per Pound
1981								
C. bairdi	169	759	11,873,513	29,702,071	588,621	2.5	21	.58
C. opilio	155*	867	34,416,334	52,753,034	435,762	1.5	79	.26
1982								
C. bairdi	136	785	4,937,736	10,977,390	487,463	2.2	10	1.35
C. opilio	126*	797	24,032,434	29,229,193	467,895	1.2	51	.60

*Vessels landing C. opilio also have C. bairdi, so the total number of vessels participating in the EBS Tanner crab fishery is equal to the number landing C. bairdi for 1978-1982.

(NMFS) since the early 1970's. In addition, an extensive, joint NMFS-OCSEAP survey was conducted in the EBS in summer 1975 and reported by Pereyra et al. (1976). Two of the sub-areas defined in the NMFS-OCSEAP survey (Fig. 4.2a) are of particular interest in this report. Sub-area 2 contains nearly all of the St. George Basin and Sub-area 1 contains the proposed oil lease areas of the North Aleutian Shelf. Both areas contain large stocks of Tanner crab (Fig. 4.2b and Pereyra et al. 1976:326, 331) and are the principal focus of recent commercial fishing efforts (Fig. 4.3). The prognosis is for a continued high yield from the fishery when both species are considered together, although the stocks have continued to show a decline since 1975 (Otto 1981).

The fishery for Tanner crabs is managed for the harvest of males only. For C. bairdi, the lower legal size limit is 139 mm (5.5 inches) across the widest portion of the carapace (carapace spines not included). No size limit was in effect for male C. opilio through the 1982 fishing season. The average landed Tanner crab of the two species was 2.2 and 1.2 pounds, respectively, in 1982, with mean carapace widths (CW) of 148.7 and 109 mm (Eaton 1982). The catch per unit effort (CPUE) for C. bairdi and C. opilio have shown a steady decline since 1979 (Table 4.1). The number of vessels involved in the American Tanner crab fishery increased from 1974 to 1981, but decreased in 1982 to 136 (Table 4.1). Primary landing ports for Tanner crab caught in the SEBS are Dutch Harbor and Akutan. Otto (1981) provides a detailed history of the Tanner crab fishery of this region.

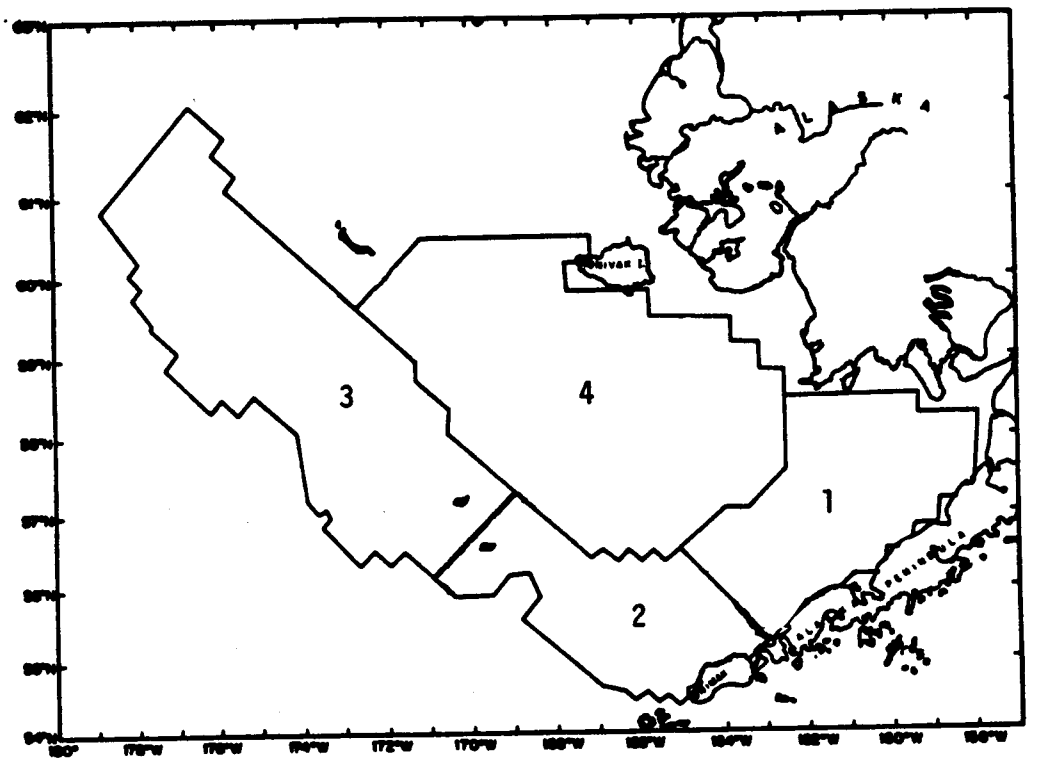


Fig. 4.2a. Sub-areas defined for the NMFS/OCS-BLM benthic faunal resource survey of 1975 (from Pereyra et al., 1976). Areas 1 and 2 contain large stocks of commercial Tanner crabs.

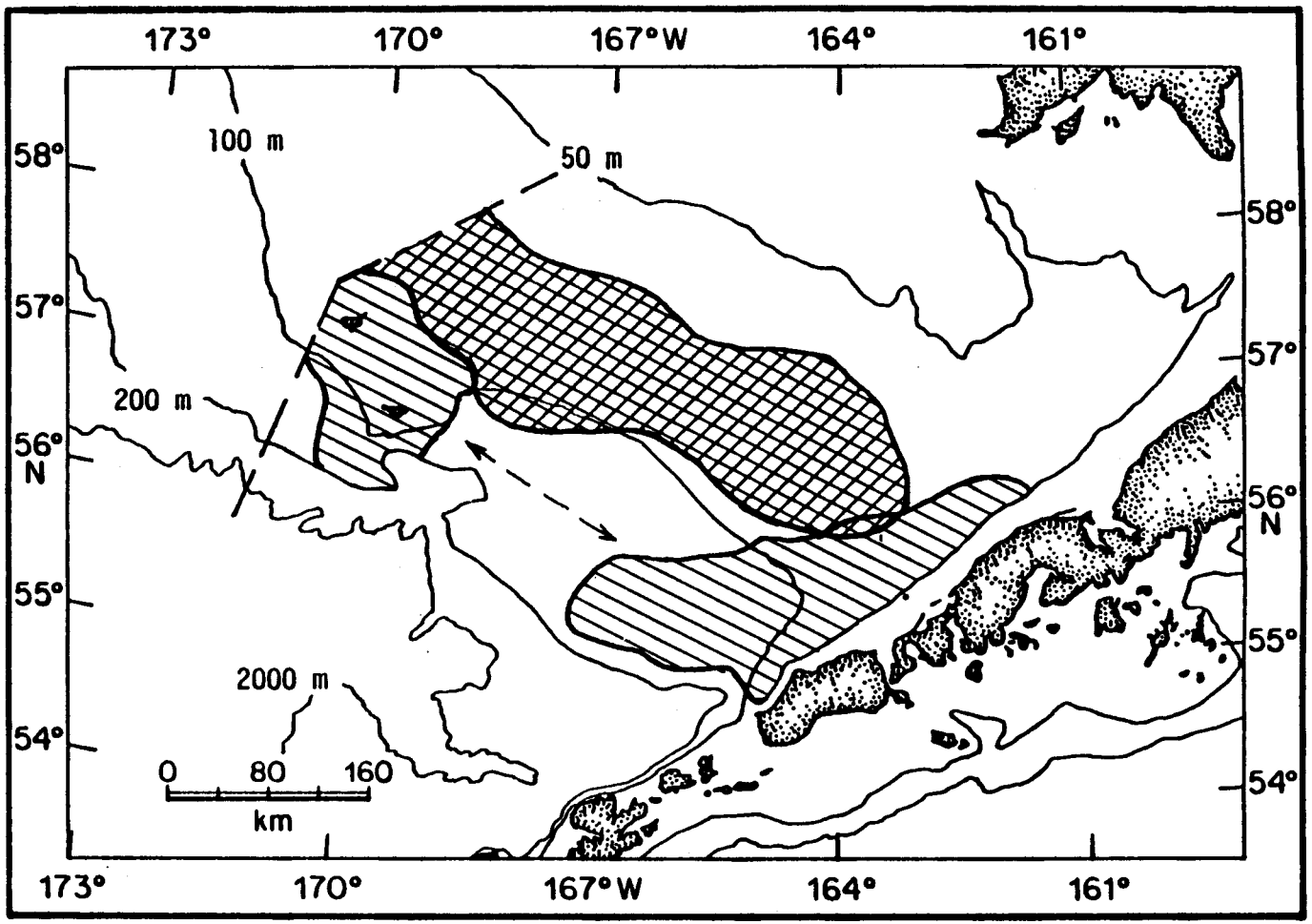


Fig. 4.2b Centers of abundance of benthic C. bairdi (diagonal) and C. opilio (crossed diagonal) in the southeastern Bering Sea. Areas are smoothed from illustrations of Pereyra et al. (1976: Figs. IX-93, IX-101) and show areas ≥ 10 kg live weight/km of bottom trawl. Greatest biomass densities for both species exceed 50 kg/km. Arrows in outer shelf denote the continuity of the C. bairdi population, but at slightly lower biomass levels.

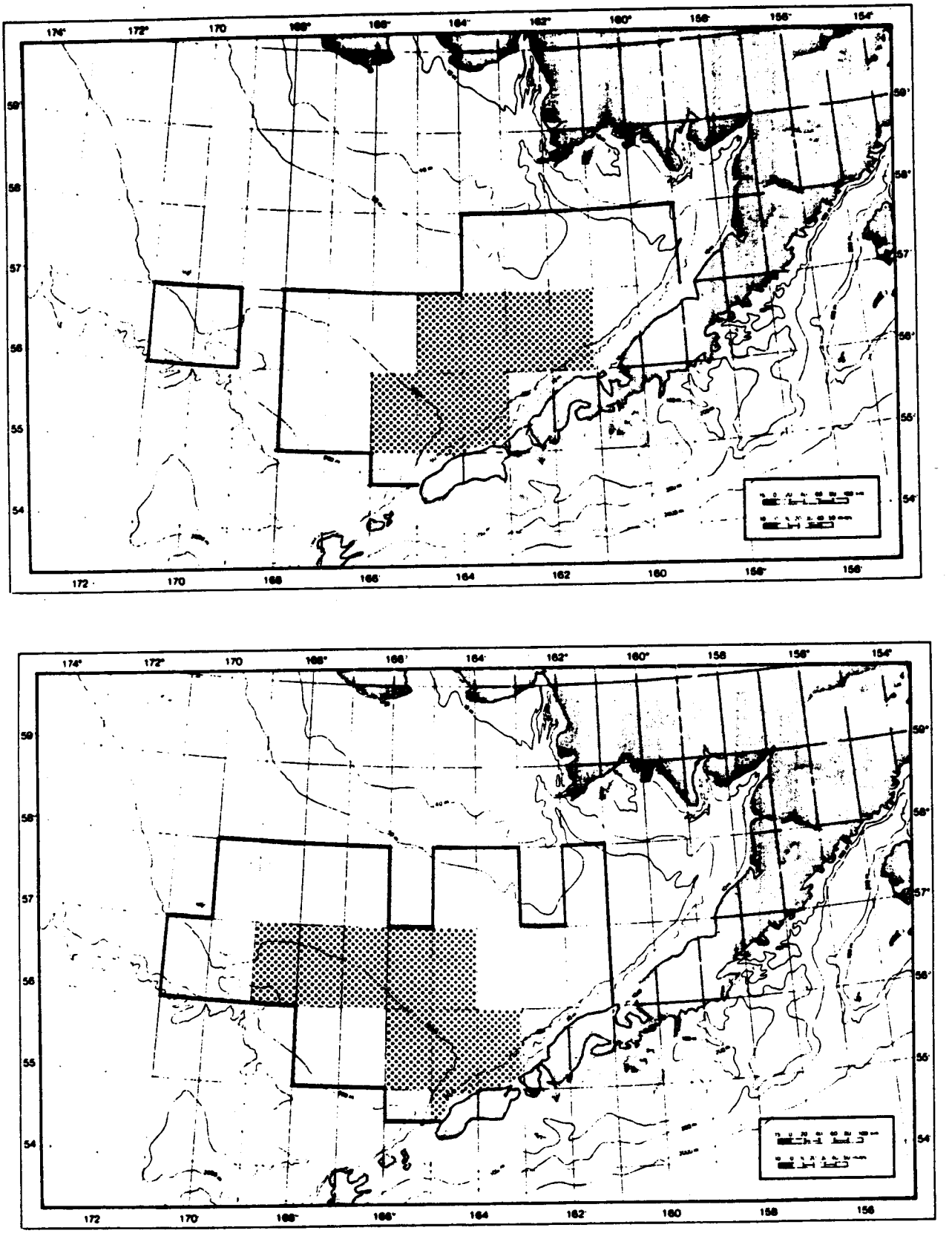


Fig. 4.3. Principal areas of 1980 Tanner crab catch in the southeastern Bering Sea, Chionoecetes bairdi (upper) and C. opilio (lower). Shaded areas yielded 1 x 10^6 pounds or more. (After Eaton, 1980).

4.3 Reproduction and Description of Spawning Stocks

Populations of juvenile and adult Chionoecetes bairdi and C. opilio in the southeastern Bering Sea are surveyed each year by the National Marine Fisheries Service for purposes of fishery forecasting. Distribution and abundance of the spawning stocks are consequently well known. While both species are found over a wide region of the shelf from depths of 50-200 m, the majority of the populations of each (see Fig. 4.2b) are associated with areas which are distinguishable on the basis of average summer hydrographic conditions. The bulk of the population of C. opilio is found in the middle shelf environment betwween 70 and 100 m depths, where relatively cold bottom water temperatures prevail throughout summer. [The cold bottom water mass is formed in situ during winter and is isolated by stratification of the water column in spring.] Most of the population of C. bairdi is found in the outer shelf environment at depths of 100-200 m and in the middle shelf environment near the Alaska Peninsula. Sexually mature female crabs appear to be patchily distributed within these regions, but generally are found over wide areas similar to the rest of the population of each species.

The age at sexual maturity is about five years for females of both C. bairdi (Donaldson et al. 1980) and C. opilio (from Adams 1979: Tables 10 and 11; and Watson 1970). Females undergo a terminal puberty molt at sexual maturity, but the size (carapace width) at which this occurs can vary substantially (Ito 1970; Haynes et al. 1976; MacIntosh et al. 1979; Jewett 1982). The size at which 50% of C. bairdi females reach sexual maturity is about 84 mm (post-molt) carapace width (Hilsinger

et al. 1975; Donaldson et al. 1980); 50% maturity in C. opilio females occurs at about 50 mm carapace width in the Gulf of St. Lawrence (Watson 1970) and the southeastern Chukchi Sea (Jewett 1982), and slightly more than this in the Sea of Japan (Ito 1970). These data and size frequency plots of female crab of the two species found in the southeastern Bering Sea (e.g., Pereyra et al. 1976) provide an approximation of the size of sexually mature crabs in the study area.

Fecundity varies with size and reproductive year of these crabs. Haynes et al. (1976) estimated the number of eggs from 42 female C. bairdi of mixed spawning history (primiparous and multiparous spawners) from the southeastern Bering Sea in the autumn (September-October). Using a regression equation relating number of eggs to carapace width gives an estimate of about 175,000 eggs per 95 mm female, which roughly corresponds to the average mature female C. bairdi from the 1975 survey of the southeastern Bering Sea (Pereyra et al. 1976:325). The regression estimate of number of eggs produced by an average size, 60-65 mm carapace width, female C. opilio is about 40,000 eggs for primaparous spawners from the southeastern Bering Sea (23 specimens) and multiparous spawners from the Gulf of St. Lawrence (99 specimens). [The numbers are not strictly comparable because the St. Lawrence crabs were caught in spring and presumably had lost part of the egg mass during winter (Hilsinger 1976)]. Most of the difference in female egg production between the two species appears to be due to differences in average size of the crab. Haynes et al. (1976) found similar egg numbers for

both species for 80 mm specimens, but this size represents opposite extremes of mature female size for the two species.

Eggs hatch in the spring, generally April for C. opilio and late April-early May for C. bairdi in the southeastern Bering Sea (Incze et al. 1982; Incze 1983). Within a few weeks after the old eggs have hatched, a new egg mass is extruded and attached to pleopods on the female's abdomen. These eggs remain attached until they are fully developed and hatch, about one year after spawning. The larvae emerge as prezoeae, about 2.5 mm long, which are covered with an embryonic cuticle and molt to first stage zoeae generally within an hour (Kon 1967, 1970; Kuwatani et al. 1971; Haynes 1973). The two zoeal stages (Haynes 1973, 1981) and the megalops stage (Jewett and Haight 1977) last about one month each (Incze et al. 1982; Incze 1983; see also Adams 1979, Table 9), and remain primarily in the upper 20 m of the water column during this period (Incze 1983). The megalops is the final planktonic stage in the life history of these crabs; all subsequent stages are benthic.

4.4 Taxonomy

Chionecetes bairdi and C. opilio zoeae were identified by D. Wencker using criteria outlined by Wencker et al. (1982; manuscript is appended to this report). These criteria make use of descriptions of the species by other authors (Kurata 1963, 1969; Motoh 1973, 1976; Haynes 1973, 1981), but also include some new diagnostic characteristics which were necessary for distinguishing between the two species in the southeastern Bering Sea. The morphological descriptions by Wencker et al. (1982) were corroborated by field studies on larval dynamics which

are reported in detail by Incze (1983). The description by Jewett and Haight (1977) was used to distinguish megalops larvae of the two species.

4.5 Results and Discussion

4.5.1 Timing of Hatchout

The timing of initial hatchout of larvae of the two species was examined by plotting against time the mean larval densities (number/ $1000m^3$) estimated from samples collected during April and May of 1977, 1978, 1980, and 1981. Because crab larvae were relatively rare during these months, plankton samples were searched completely, not sub-sampled. The following criteria were used to select stations with data adequate for this analysis: 1) if a sample from a station contained larvae, the estimated abundance at that station was recorded for the corresponding date; 2) if a sample did not contain larvae but subsequent occupation of the sampling area (within a radius of approximately 27.8 km, 15 NM) showed that there were eventually larvae there, the "zero" abundance was recorded for the earlier date; 3) if a sampling location did not contain larvae and was not occupied again later, or was occupied and continued to show no larvae, the "zero" datum was not entered into the analysis. In this way, the period before any detectable hatchout occurred could be identified without risk of biasing the analysis with data from sample locations not yielding zoeae of that species in that year. Sample coverage in the study area was not sufficient during any one year to enable a statistical comparison of initial hatchout times for different sub-areas (eg. middle shelf vs. outer shelf). Consequently, the data

from all stations were pooled for various dates. The data presented here describe initial hatchout periods of larvae primarily for areas where water depth exceeds 90 m.

The results of the analysis of hatchout for C. bairdi are listed in Table 4.2, which shows the number of stations involved in the analysis and the mean value and range of larval densities encountered. The analysis is not shown beyond the time of maximum mean larval densities. Sampling continued well beyond these dates in 1978 and 1981, and no further significant increases in abundance were observed. Thus, the "peak" of hatchout as determined by larval density estimates had occurred. Figure 4.4 presents the data from Table 4.2 as plots of relative density of larvae over a 40-day period in each of three years. A value of 1.0 represents the maximum mean density observed in a particular year. Data for 1980 were infrequent during the period of predicted peak hatchout (early May) but also show extremely low larval densities ($\leq 6/100m^2$, n=7) for the period 18-20 April.

For the three years shown in Figure 4.4, the greatest increase in mean larval abundance occurred between late April and early May and was quite abrupt, implying a relatively synchronous hatch of larvae throughout the adult populations underlying these stations. In 1978 and 1979, these stations covered a large part of the outer shelf, so hatchout from a considerable portion of the outer shelf adult population of these species was sampled. The fact that a discernible time-averaged contribution to the larval population did not occur after the peak densities of early May had been attained suggests an appreciable decline in hatching activity. This is corroborated by the fact that nearly all egg-bearing

Table 4.2. Timing of appearance of Stage I zoeae of Chionoecetes bairdi in the southeastern Bering Sea by year and date. N1: number of stations sampled during specified period; N2: number of stations used in the analysis. Density of larvae is reported as number per 100 m^2 (range in parentheses).

Year	Dates	N1	N2	Density of Larvae
1977	18-19 Apr	13	8	150 (0-1140)
	24-25 Apr	19	7	138 (0-600)
	16 May	9	8	8,058 (0-28,446)
	18 Apr	*	1	348
	24 Apr	*	1	7,476
	9 May	*	1	11,634
1978	16-21 Apr	31	16	6 (0-114)
	26-28 Apr	26	23	966 (0-4,224)
	11-14 May	6	6	65,052 (1,644-148,000)
1981	17 Apr	4	4	36 (0-150)
	1 May	1	1	888
	11-14 May	6	3	3,288 (768-7,572)

*observations from a single station outside the area of other stations; data are provided here for comparison.

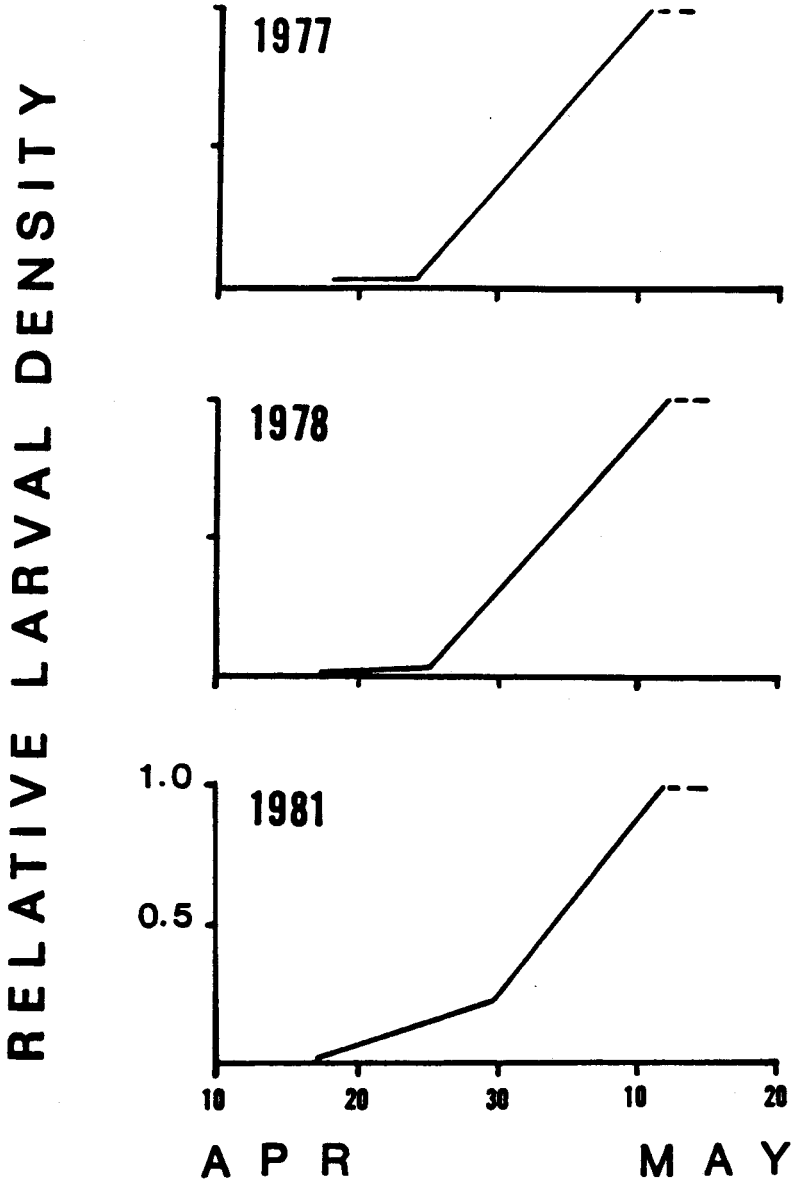


Fig. 4.4. Timing of appearance of larval C. bairdi in plankton of the southeastern Bering Sea. Data on mean larval density (Table 4.2) are represented as cumulative proportion of the maximum mean density observed at peak hatchout.

female crabs sampled in late May and early June by National Marine Fisheries Service surveys have immature (recently extruded) egg masses (Somerton 1981).

The initial hatchout period of C. opilio larvae was not documented as well as that for C. bairdi. There appeared to be a considerably earlier hatchout for this species, as shown in Table 4.3 with data from 1977 and 1978. Although there is a considerable range in larval densities shown over time (possibly due to a wider range of sample locations than was used for C. bairdi), high densities were clearly found by 20 April in both years (sampling started 6 April 1977 and 11 April 1978). Throughout most of the area of the southeastern Bering Sea sampled in this study, 1980 and 1981 were both markedly "poor" years for C. opilio larvae (see later discussion) and collections were not adequate in either year to define a hatchout curve. However, larval densities typical of those two years were also found by middle April. Data on development rates of Stage I (SI) zoeae of C. opilio and on the time of appearance of Stage II (SII) zoeae of this species in 1981 (see Incze 1983 and following section) further support the suggestion that significant hatchout of C. opilio larvae occurred two to three weeks prior to the major hatch of C. bairdi larvae.

4.5.2 Rates of Larval Development

The rates of development of C. bairdi and C. opilio SI zoeae in the southeastern Bering Sea were analyzed by examining the ratio of SI to total zoeae (SI:SI+SII) for each species at stations where at least six individuals of a species were examined in the sample or subsample. Using

Table 4.3. Timing of appearance of Stage I zoeae of Chionoecetes opilio in the southeastern Bering Sea by year and date. N1: number of stations where C. opilio larvae were found; N2: mean number of zoeae per 100 m^2. (range in parentheses).

Year	Dates	N1	N2
1977	17-19 Apr	9	8,592 (1,710-33,234)
	24-25 Apr	8	10,026 (1,452-19,596)
	10 May	9	21,462 (828-134,970)
1978	16-21 Apr	23	103,870 (0-626,700)
	26-28 Apr	23	154,300 (96-1,523,712)
	11-14 May	14	17,628 (,638-82,050)

this low number of larvae increased the number of observations (stations) which could be included in the analysis and produced no obvious detrimental impact on the data variance, since a large variance existed even among stations with abundant larvae. The data were grouped into time periods not exceeding 10 days and the mean ratio calculated (unweighted ratio method). The number of larvae examined in each 10-day period ranged from 43 to over 2,000. From one to thirty stations were included in each period.

Rates of development of second stage (SII) zoeae were analyzed by examining the ratio of SII:SII + megalops larvae (no SI zoeae were present during this period). The data were grouped into time periods of not more than 13 days. The number of larvae examined in each period ranged from 780 to 2032, while the number of stations ranged from 10 to 41.

For both molting analyses above, weighted ratios were also calculated by pooling data on all larvae of a species from each 10-day period and determining the ratio of the larval stages in question. This method gave results similar to the unweighted method, but the results of the unweighted ratio method were used for illustration because these data allowed variance of data to be expressed.

Observations of the stomach contents of yellow fin sole (Limanda aspera) collected in early September 1980 (K. Haflinger, Univ. of Alaska, unpubl. data) and plankton samples collected in October 1980 provided some information on the late summer-early autumn presence of

megalops larvae of both species and first post-larval (first instar) crabs of C. opilio.

Data on rates of larval development show considerable variability from one station to the next once molting in the population was under way. This is reflected in a large variance about the mean over 10-day periods (Tables 4.4 and 4.5). The weighted ratios are provided for comparison in Table 4.6, which also shows the number of larvae examined in each period. Despite the large variance, larval stage data are useful for pointing out several features of the larval development process in the populations: 1) the point in time where molting to SI begins for each species can be fairly well defined; 2) the length of time required for the population of SI zoeae to molt to SII can be seen; and 3) differences in timing of the onset of molting in larval populations of the two species can be seen.

Observations (1) and (3) are generally consistent with earlier observations on the timing of first appearance of larvae in the plankton. In particular, data for 1978 and 1979 both show that the molt to SII was well underway in the C. opilio population before C. bairdi larvae noticeably began this process (Figure 4.5). However, this pattern did not appear to hold true in 1980 or 1981. These interannual differences will be discussed later in this report. Observation (2) indicates that most of the hatchout occurred within a period of 30-40 days, although other factors (temperature regime, planktonic feeding conditions or survival of only part of a year-class) also may affect apparent duration of the inter-molt period.

Table 4.4. Zoeal development of Chionoecetes bairdi and C. opilio showing proportion of Stage I to total zoeae: Mean of sample observations ± one standard deviation (number of stations sampled in parentheses).

Year	Species	Date				
1978		7-17 May	27-31 May	1-10 June	11-20 June	21-29 June
	C. opilio	1.0 (11)	0.92±0.17(20)	0.81±0.22(30)	0.34±0.25(10)	0.25±0.29(21)
	C. bairdi	1.0 (7)	1.0 (7)	0.99±0.01(17)	0.99±0.01(6)	0.85±0.23(8)
1979				1-6 June	19 June	21-22 June
	C. opilio			0.53±0.33(8)	0 (3)	0.01±0.02(6)
	C. bairdi			0.99 (7)	0.31±0.17(4)	0* (2)
1980		13 May	26-29 May	2-8 June		
	C. opilio	1.0 (1)	1.0 (5)	1.0 (2)		
	C. bairdi	1.0 (1)	1.0 (7)	1.0 (20)		
1981		15-16 May	23-30 May	1-10 June	11-19 June	
	C. opilio	1.0 (4)	0.98 (2)	0.94±0.08(5)	0.14±0.25(3)	
	C. bairdi	1.0 (19)	1.0 (15)	0.98±0.04(19)	0.54±0.36(13)	

*Four other stations sampled during the period 21-27 June contained Stage I zoeae of C. bairdi but contained too few larvae (< 6) to be considered in this analysis; the zero datum is thus artificially low.

Table 4.5. Proportion of Stage II to megalops larvae (total larvae) of Chionoecetes bairdi and C. opilio in plankton samples from the southeastern Bering Sea in 1981: Mean of sample observations ± one standard deviation (number of samples in parentheses). Number of larvae examined is shown beneath date. No Stage I zoeae were present for either species during the time period shown.

	27 June - 10 July N=2032	11-20 July N=780
C. opilio	0.78 ± 0.34 (23)	0.11 ± 0.20 (10)
C. bairdi	1.0 (41)	0.78 ± 0.22 (17)

Table 4.6. Weighted average proportion of Stage I to total zoeae of Chionoecetes bairdi and C. opilio: Proportion of all zoeae examined during specified time periods (number of larvae examined is in parentheses).

Year	Species	Date				
1978		7-17 May	27-31 May	1-10 June	11-20 June	21-29 June
	C. opilio	1.0 (396)	0.97 (2,357)	0.82 (1,846)	0.31 (329)	0.25 (1,398)
	C. bairdi	1.0 (255)	1.0 (90)	0.99 (456)	0.99 (267)	0.83 (518)
1979				1-6 June	19 June	21-22 June
	C. opilio			0.46 (305)	0 (43)	0.02 (125)
	C. bairdi			0.99 (176)	0.39 (69)	0 (15)
1980		13 May	26-29 May	2-8 June		
	C. opilio	1.0 (318)	1.0 (423)	1.0 (33)		
	C. bairdi	1.0 (22)	1.0 (130)	1.0 (528)		
1981		15-16 May	23-30 May	1-10 June	11-19 June	
	C. opilio	1.0 (45)	0.98 (133)	0.93 (142)	0.17 (52)	
	C. bairdi	1.0 (1,513)	1.0 (1,411)	0.98 (1,555)	0.29 (463)	

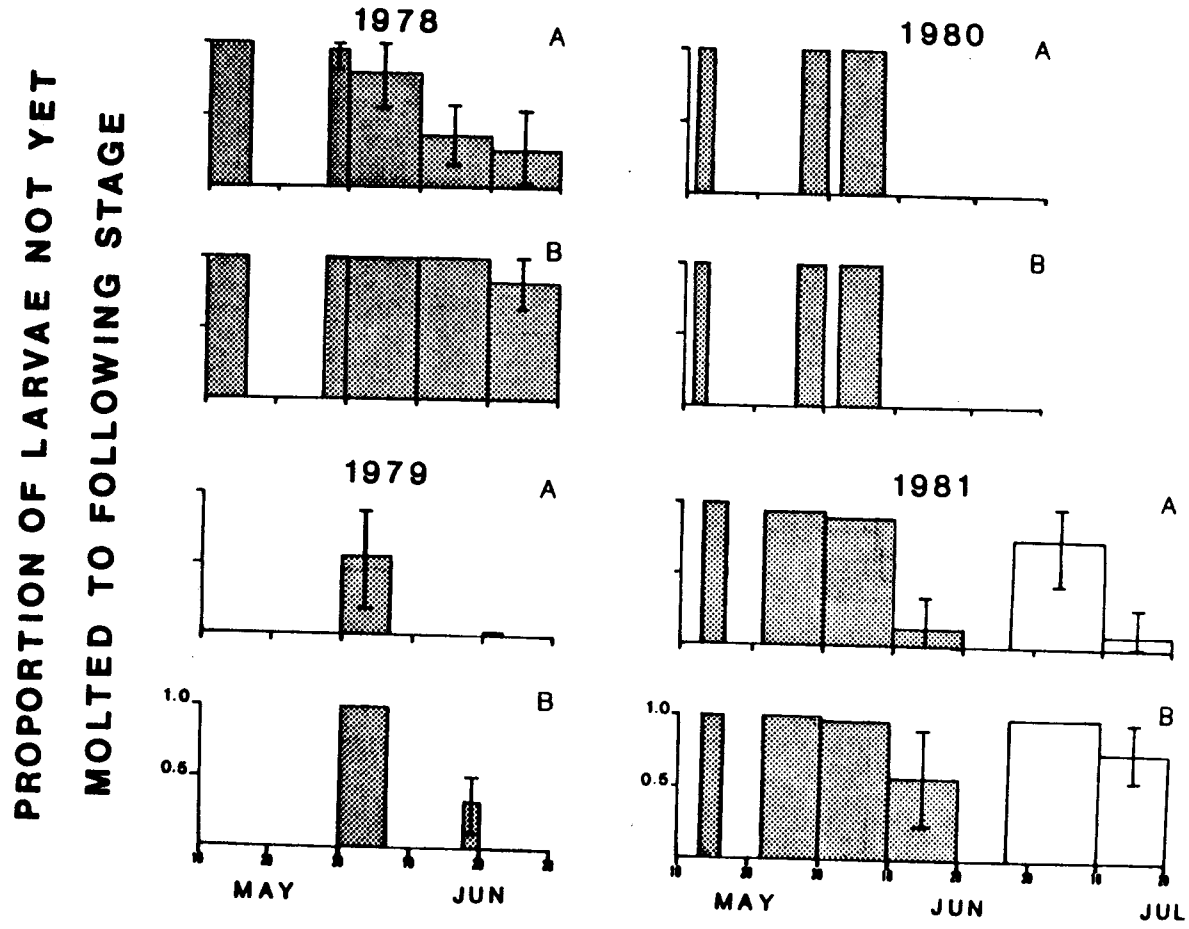


Fig. 4.5. Temporal aspects of development in larval populations of C. opilio (A) and C. bairdi (B) during four years of study. Shaded bars show proportion of Stage I to total zoeae (no megalops present); open bars show proportion of Stage II to total larvae (no Stage I present). Values shown are mean proportions from sampled stations ± one standard deviation; standard deviations are truncated at 1.0. Data are summarized in Tables 4.4 and 4.5.

Data on the timing of molt from SII to megalops larvae in 1981 show the beginning of this process in C. bairdi and the end for C. opilio (Table 4.5, Fig. 4.5). Although the data do not cover the entire period for this molt, the rate of change in the population as a whole during the time period sampled indicates that the SII: megalops molting is about as long as the earlier SI:SII transition. The data for C. bairdi in 1981 further show that the molt to megalops stage larvae began approximately one month after the first SII zoeae appeared. The same situation is indicated for C. opilio, since no megalops stage larvae were found before 20 June.

The data presented above show an approximate 30-day period for each of the two zoeal stages for both species in the southeastern Bering Sea. Furthermore, the approximate 30- to 40-day period of molting in larval populations of each species is an indication that the hatchout period is of similar duration. The estimates of the duration of the two zoeal stages in the southeastern Bering Sea are in close agreement with most of the observations of C. opilio larvae in Japanese waters (Yamahora 1965; Fukataki 1969; Fukui Pref. Mar. Exp. Sta. 1969), although some estimates for the latter environment are for periods as brief as 19-20 days for each stage (Kon 1970).

Samples collected in early October 1980 indicate that substantial numbers of C. bairdi megalops were still in the water column at that time (the estimated densities from October samples ranged from 560-1370/ 100 m^2, number of stations = 4, compared to May samples of SI zoeae ranging from 1,800-18,000/100 m^2 at the same stations). This comparison

assumes a relatively homogeneous distribution of C. bairdi larvae in the outer shelf since advection over this time period is not considered. No C. opilio larvae were collected in October of 1980, but this may have been due to low larval abundance for this species in 1980 in most of the area of our plankton studies.

Examination of the stomach contents of yellow fin sole (Limanda aspera) collected at 57°09'N Lat., 166°39'W Long. on 9 September 1980 indicated that settlement of C. opilio larvae and metamorphosis to first instar crab had begun by that date, but that substantial numbers of megalops larvae remained, presumably somewhere in the water column. [The stomachs of small sole (20 cm length) which contained the megalops contained no organisms of benthic origin at the time of sampling. Stomachs of larger sole (24-69 cm length) contained first instar C. opilio. Unpublished data are from K. Haflinger, University of Alaska.] These data indicate the beginning of settlement of C. opilio larvae to the benthos, but provide no insight into the duration of this transition. According to observations in Japanese waters, there may be considerable variation in the duration of this stage, since megalops larvae were observed in the plankton up to six months after their initial appearance (Fukataki 1969). Prolongation of the megalops stage in Japanese waters was also indicated by examination of the stomach contents of salmonid (Fukataki 1965, 1969) and zoarcid (Ito 1970) fish. A review of estimates of the duration of the larval stages of Chionoecetes spp. from other environments is provided by Adams (1979:78).

Kon (1970) reported on the basis of laboratory studies that the duration of the larval stages of C. opilio was inversely proportional to temperature over some physiologically acceptable range of temperatures. This response has been experimentally demonstrated with the larvae of other crabs as well (Anger and Nair 1979; Johns 1981), and the results presumably also apply to Chionoecetes spp. larvae in the plankton. During the course of this study, however, temperature effects on duration of the larval stages could not be isolated for certain from the effects of other environmental factors (Incze 1983). A period of about 30 days for each zoeal stage and a period of at least 30 days for the megalops stage appears to be a reasonable estimate of the duration of larval stages of these species over the shelf of the St. George Basin and outer portion of the middle shelf.

4.6 Vertical Distribution of Larvae in the Water Column

Knowledge of the vertical distribution of larvae is essential to understanding the role various factors and processes may have in determining larval distribution and abundance. For example, the influence of environmental temperature on rates of growth, development and metabolism; the effects of subtidal- and wind-driven transport on larval distribution patterns; the impact of predators on larvae; the availability of appropriate food for larval feeding and the impact of catastrophes, such as major oil spills, cannot be properly interpreted without fairly accurate knowledge of vertical distributions. Estimates of larval abundance made from oblique plankton tows, such as with Bongo nets, can also be improved when patterns of depth distribution of larvae are known.

Methods for analysis of depth distribution patterns are discussed in Section 2.8. Results of that analysis and examination for potential vertical migrations are discussed here.

4.6.1 General Patterns

The vertical distribution of zoeae from 1980 and 1981 MOCNESS samples is shown in Fig. 4.6. C. bairdi and C. opilio zoeae show similar depth distributions, with more than 95% of the larvae occurring in the upper 40 m and 80% or more occurring in the upper 20 m.

For all data collected after 11 May in 1981, the depth distribution pattern for SI and SII zoeae combined was virtually the same as in 1980 for SI. Only prior to 12 May 1981 and only for C. bairdi zoeae was there a significant departure from this pattern (Figure 4.7). The pattern seen for this species before 12 May is primarily the result of four separate tows taken approximately six hours apart at a single station during a 24-hour period on 11 May.

A comparison of the vertical distribution of SI and SII zoeae made in two ways showed no significant difference in distribution between the two stages. First, data were considered only from stations where both SI and SII zoeae occurred (8 stations sampled during 1981). The results are shown in Figure 4.8. Second, all data for SI zoeae (15 stations) and all data for SII zoeae (24 stations) during 1981 were tabulated separately. Again, similar patterns of distribution for the two stages were indicated; overall, 92% and 93% of SI and SII animals, respectively,

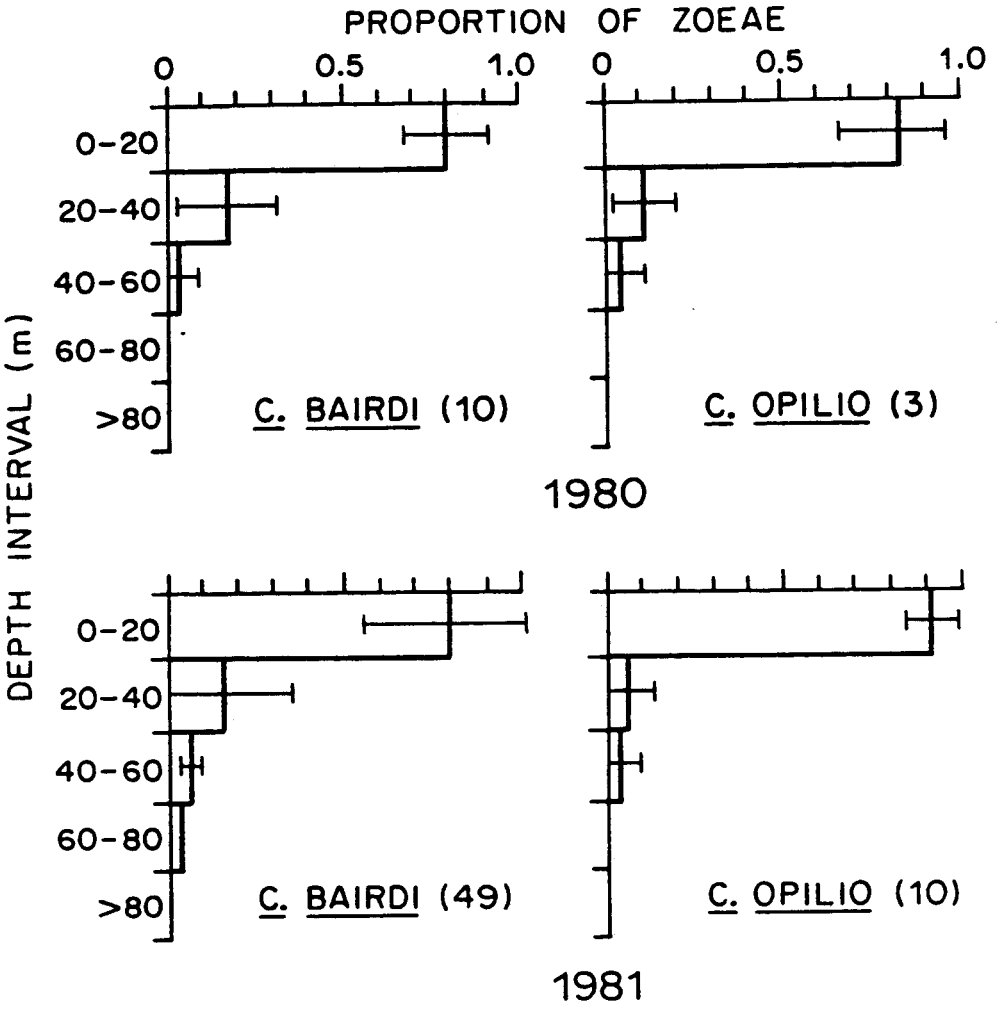


Fig. 4.6. Vertical distribution of zoea larvae of C. bairdi and C. opilio sampled by MOCNESS nets, 1980-1981. Horizontal bars show mean proportion of larvae in depth interval ± one standard deviation. Both Stage I and Stage II zoeae are included (cf. Fig. 15). Number of stations from which data were taken is shown in parentheses.

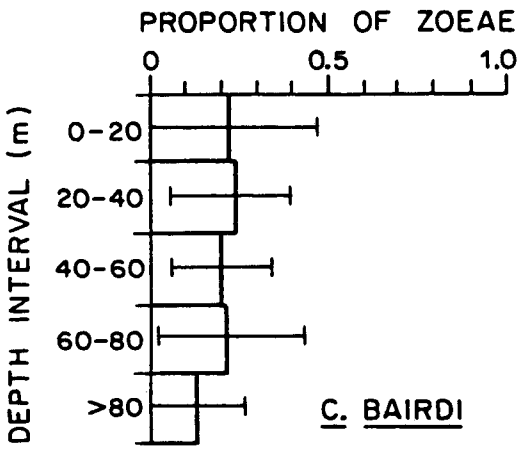


Fig. 4.7. Vertical distribution of C. bairdi Stage I zoeae sampled during the hatchout period for that species, early May 1981. Horizontal bars are mean proportion of larvae in each depth interval ± one standard deviation.

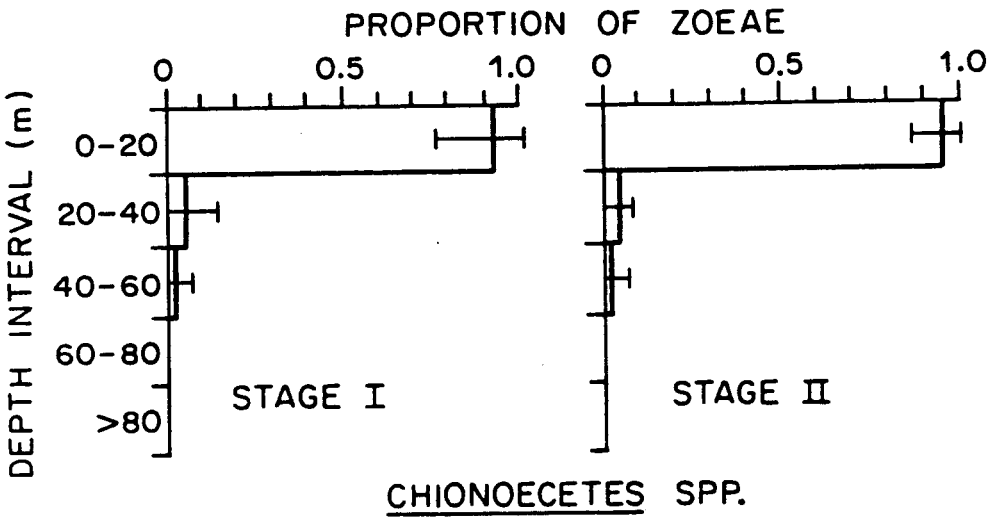


Fig. 4.8. Vertical distribution of Stage I and Stage II zoeae from eight stations (1981) where both occurred in sufficient numbers for analysis. Horizontal bars show mean proportion of larvae in each depth interval ± one standard deviation. Both species were combined for the analysis.

were found in the upper 40 m. Eighty-six percent of SI and 82% of SII zoeae were found in the upper 20 m.

The depth distribution of megalops larvae, analyzed with both species combined, also showed a tendency for distribution higher in the water column. However, greater variability was found at all depths for this stage than for the zoeal stages and a greater proportion of megalops occurred at 40-60 m depth compared to zoeae (Fig. 4.9). At 16 stations (18 tows) during June and July 1981, only one megalops larva was found below 60 m depth.

4.6.2 Vertical Migrations

Although the data indicated that only a small proportion of all Tanner crab larvae were found below 40 m, the data were further analyzed for possible diurnal patterns masked by the overall analysis. This was done by examining the proportion of larvae found below 40 m at various times of the day. Forty meters was selected because on the average few larvae were found below this depth, so any diurnal pattern should be readily seen. The day was divided into six periods (0000-0300, 0300-0600, 0600-0900, 0900-1800, 1800-2100 and 2100-0000), roughly corresponding to various light intensities and periods of increasing or decreasing light. The data (proportion of larvae below 40 m) for each station were entered according to the time of day the sample was taken. Data from twelve diel (24-hr) stations were analyzed and then the data from all 79 stations were analyzed. The data were re-examined using the proportion below 20 m as the migration criterion.

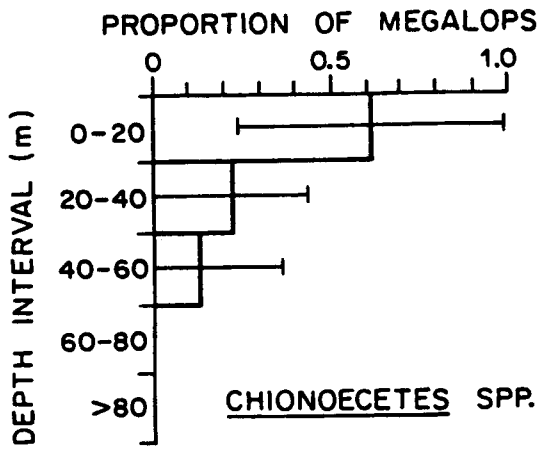


Fig. 4.9. Vertical distribution of C. bairdi and C. opilio megalops larvae at seven sampling locations in 1981. Horizontal bars are mean proportion of larvae in each depth interval ± one standard deviation.

From the diel stations, 10% or more of the zoeae occurred below 40 m six times during night-time sampling (2100-0300) and four times during day-time sampling (0600-1800). When all samples were considered together, 10% or more of the zoeae occurred below 40 m nine times during daytime and five times during night. More than 10% of the megalops larvae occurred below 40 m only once during night-time and twice during daytime sampling. When the proportion of larvae below 20 m was listed, the results were variable and showed no diurnal pattern. The ratio of daylight (0600-1800) to night-time (2100-0300) samples in these anlyses was 1.5:1. The ratio of daylight (0600-1800) to twilight and dark (1800-0600) samples was 1.1:1.

Neither the diel stations nor all stations considered together provided any evidence of significant diurnal vertical migrations of zoeae or megalops larvae when 40 m or 20 m was used as the depth criterion for migration. About equal numbers of night-time and daytime samples were used, so the resulting data should accurately describe the average vertical distribution of larvae, especially the zoeae, which were well-sampled. The majority of zoea larvae of both species and stages occur in the upper 20 m of the water column (Figure 4.6 and 4.8), and this is where most planktonic interactions involving these larvae can be expected to take place.

The exception to this pattern was the vertical distribution of C. bairdi zoeae on 11 May (Figure 4.7). The sampling location for these data was one of abundant C. bairdi zoeae, and the samples were collected at the time of larval emergence from adult egg masses (see

earlier discussion). There was no diurnal periodicity to the depth distribution pattern within the area of sampling, suggesting that the peculiar distribution may have been the result of sampling at the time of hatchout. Although the results (Figure 4.7) suggest a homogeneous distribution, the large standard deviations show that, in fact, the vertical distribution was highly variable from one sample to the next. The vertical pattern could have resulted from 1) a hatchout which was locally (at least within the advective area of sampling) quite synchronous, and/or 2) a relatively slow upward movement of newly molted zoeae, so that dense patches were found at various depths within the area. There is insufficient information in the existing data to further evaluate these findings, except to point out that the distribution 1) was not common, and 2) was not the result of unusual vertical water column structure, as evidenced by other variables. Hydrographic structure and the distribution of nutrients, chlorophyll and the remainder of the zooplankton community all showed normal vertical patterns at this location (PROBES 1981 consecutive station numbers 2058, 2060, 2061, 2062, 2063).

The megalops larvae do not appear to have been quite as concentrated in the upper 20 m as the zoeae, but they were still found primarily in the upper 40 m during the period of sampling. Neuston samples collected during night-time hours in July 1981 (Armstrong and Incze, unpubl. data) sometimes contained impressive numbers of megalops larvae which rivaled the estimates of abundance (per area of sea surface) obtained from oblique tows taken within the area. Although there are many

difficulties in quantitatively sampling the neuston, the occasionally high abundance of megalops larvae found there suggests that 1) some vertical migrations take place, or 2) many megalops remain at or very near the surface most of the time. However, it is not currently known whether or not surface layer aggregations are common for this species, either temporally or spatially, as they may be for the megalops of other species (cf. Smyth 1980; Rice and Kristensen 1982). When aggregated at the surface, megalops larvae are particularly vulnerable to predation by seabirds (Schneider and Hunt 1982) and to impacts from oil spills.

4.7 Spatial and Interannual Patterns of Larval Abundance

Patterns of distribution and abundance are based on estimates of larval abundance which are highly variable, even on small spatial and temporal scales. Coefficients of variation for data collected in this study were usually around 100%, whether for samples taken in rapid succession or samples collected within a sampling stratum over a period of three to four weeks. This variability is typical of plankton distributions and is a problem which must be dealt with in all zooplankton studies (e.g., Wiebe et al. 1973; Fasham 1978). Despite this variability, however, it was possible in this study to distinguish certain "high abundance" and "low abundance" areas and years using standard statistical methods (Incze 1983).

In this section, spatial patterns of larval abundance are illustrated for selected years and months for each species. These periods were selected to illustrate the general patterns of distribution and abundance with the minimum number of figures requiring interpretation. In

general, spatial patterns of larval abundance do not change much, so a limited number of charts suffice. However, there were major interannual changes in abundance, primarily of C. opilio larvae. The analysis of these changes was based on statistical comparison of estimates of monthly mean abundance for the sampling strata outlined in section 2.8. The data and methods are detailed elsewhere (Incze 1983), but the conclusions are germane to this report and are discussed here. This section focuses on two objectives: (1) the definition of areas where potential impacts on larvae are greatest; and (2) an evaluation of the potential importance of individual larval year-classes to the over-all recruitment process in populations of C. bairdi and C. opilio. Intra-annual patterns of abundance (hatchout and development) were addressed earlier and are not illustrated here.

Figures 4.10 and 4.11 summarize the distribution and abundance data from May and June of 1978 for C. bairdi and C. opilio, respectively. Larvae of both species were abundant in 1978, and a large portion of the southeastern Bering Sea was sampled (cf. Figs. 4.10 and 4.11 and cruise maps in Section 2.0). Figures 4.12 and 4.13 show the data for both species collected in 1980 and 1981. These years were both years of very low larval abundance of C. opilio over most of the study area (the region east and northeast of the Pribilofs excepted). Data for 1980 and 1981 are illustrated to show the low larval abundance of this species and the distribution of C. bairdi larvae in 1981 along the Alaska Peninsula, a region not sampled very much in earlier cruises.

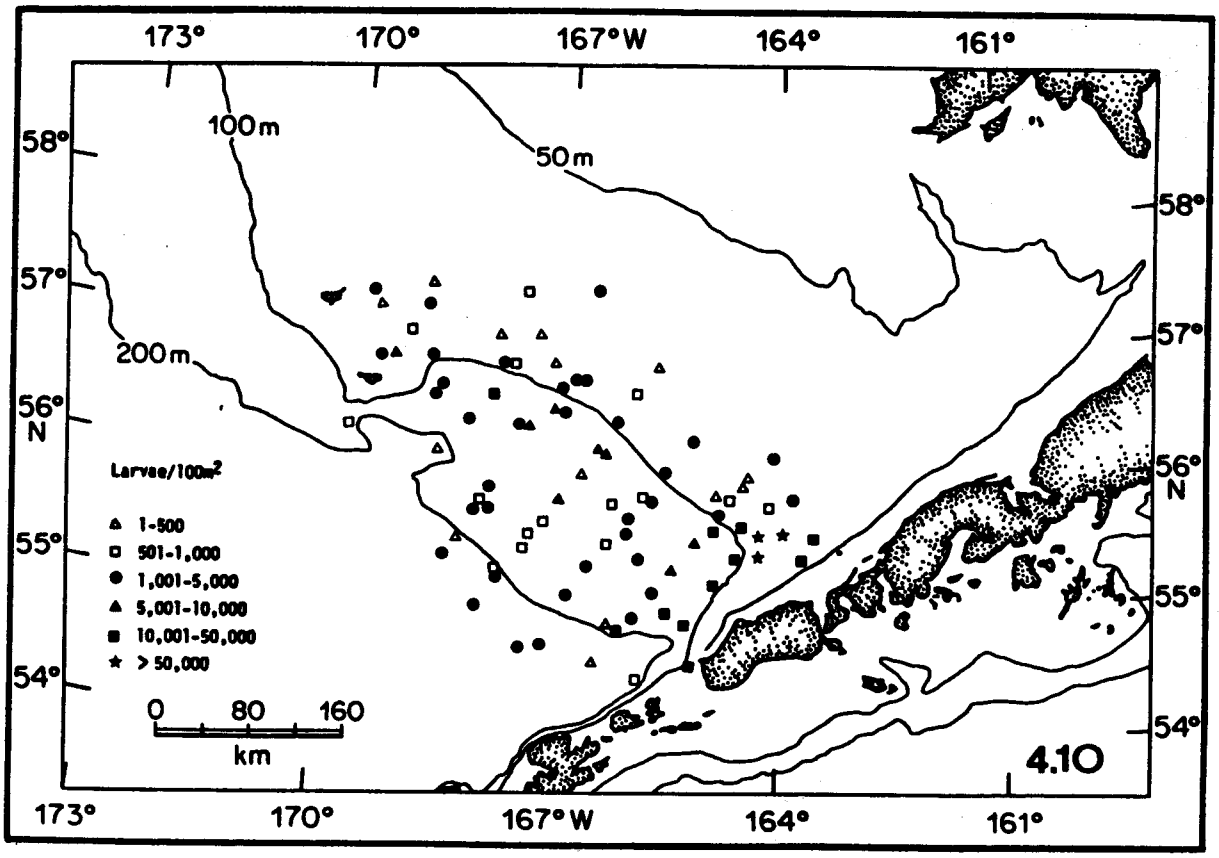


Figure 4.10 Distribution and abundance of C. bairdi larvae in May and June, 1978, PROBES. Zero stations not shown; see Section 2.0 for all sampling locations.

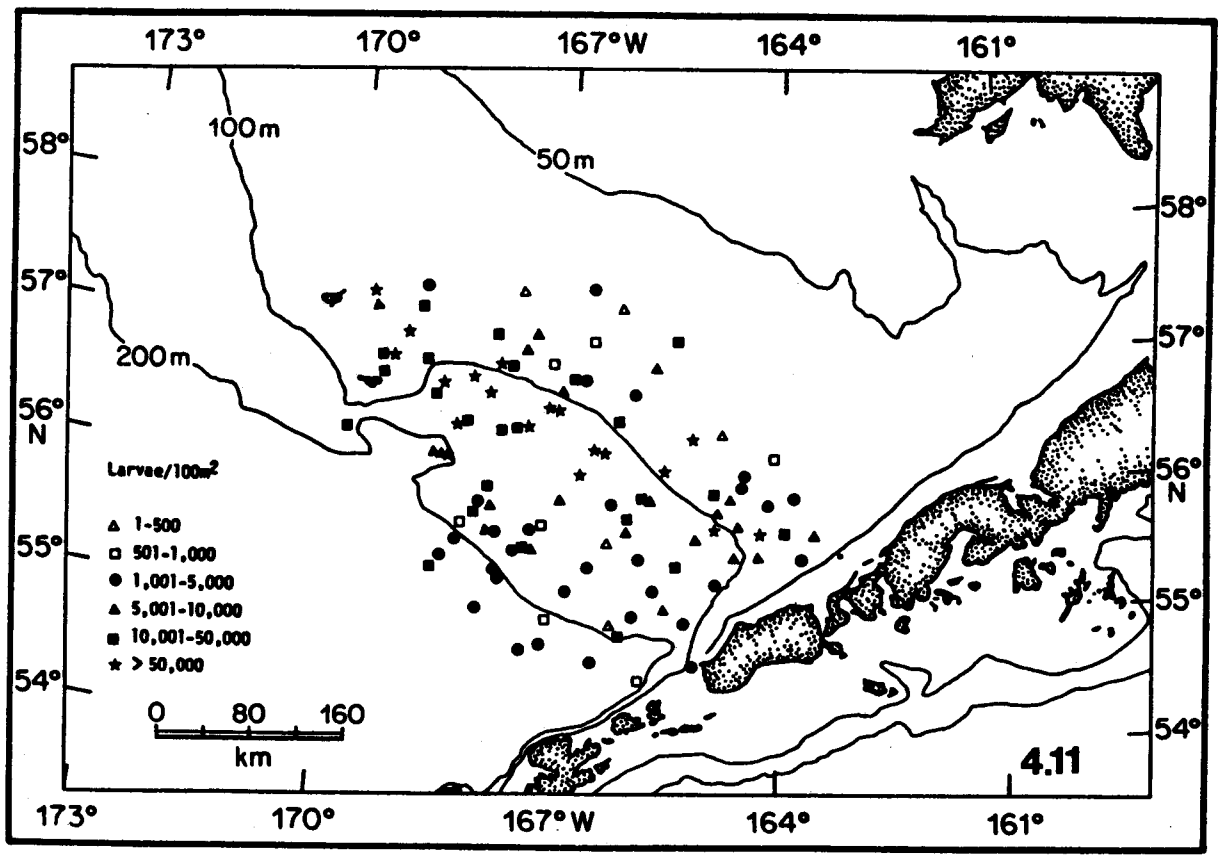


Figure 4.11 Distribution and abundance of C. opilio larvae in May and June, 1978, PROBES. Zero stations not shown.

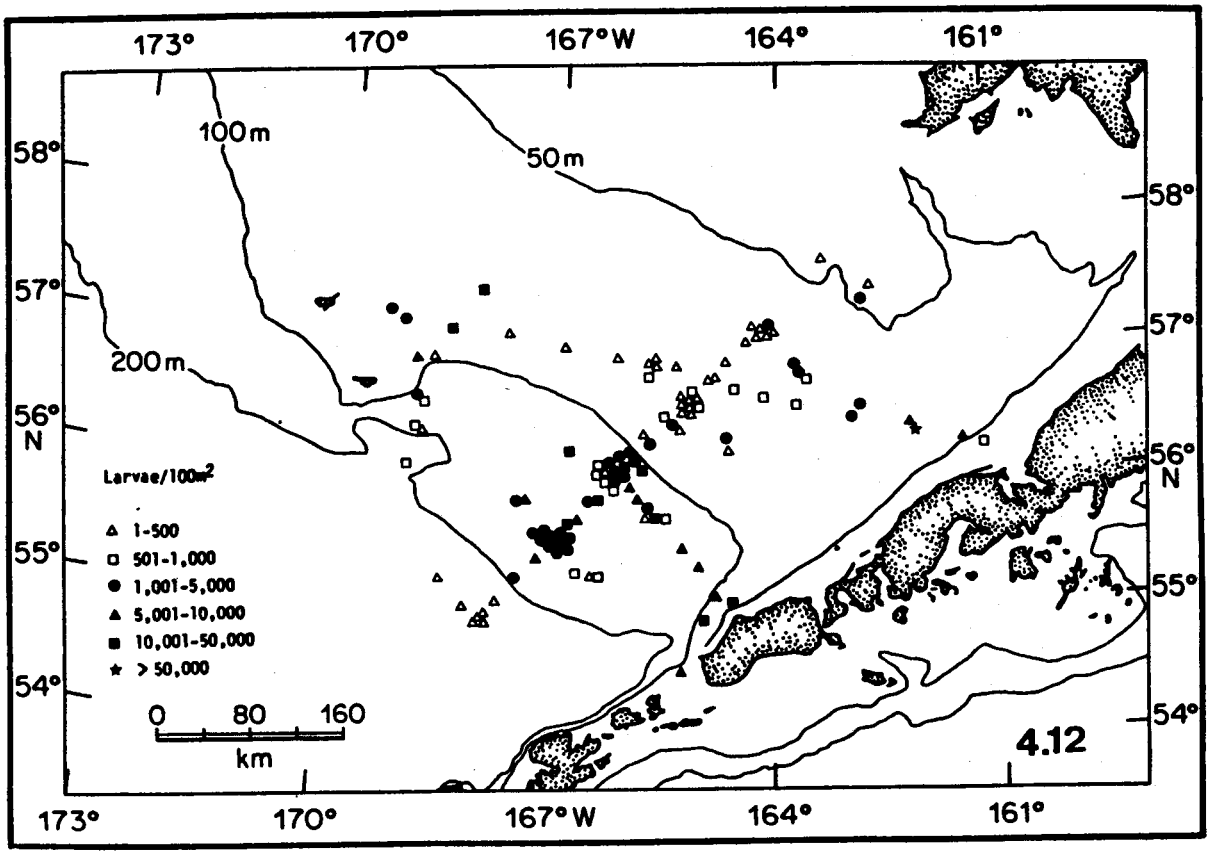


Figure 4.12 Distribution and abundance of C. bairdi larvae in the combined years 1980 and 1981. Zero stations not shown; see Section 2.0 for all sampling locations.

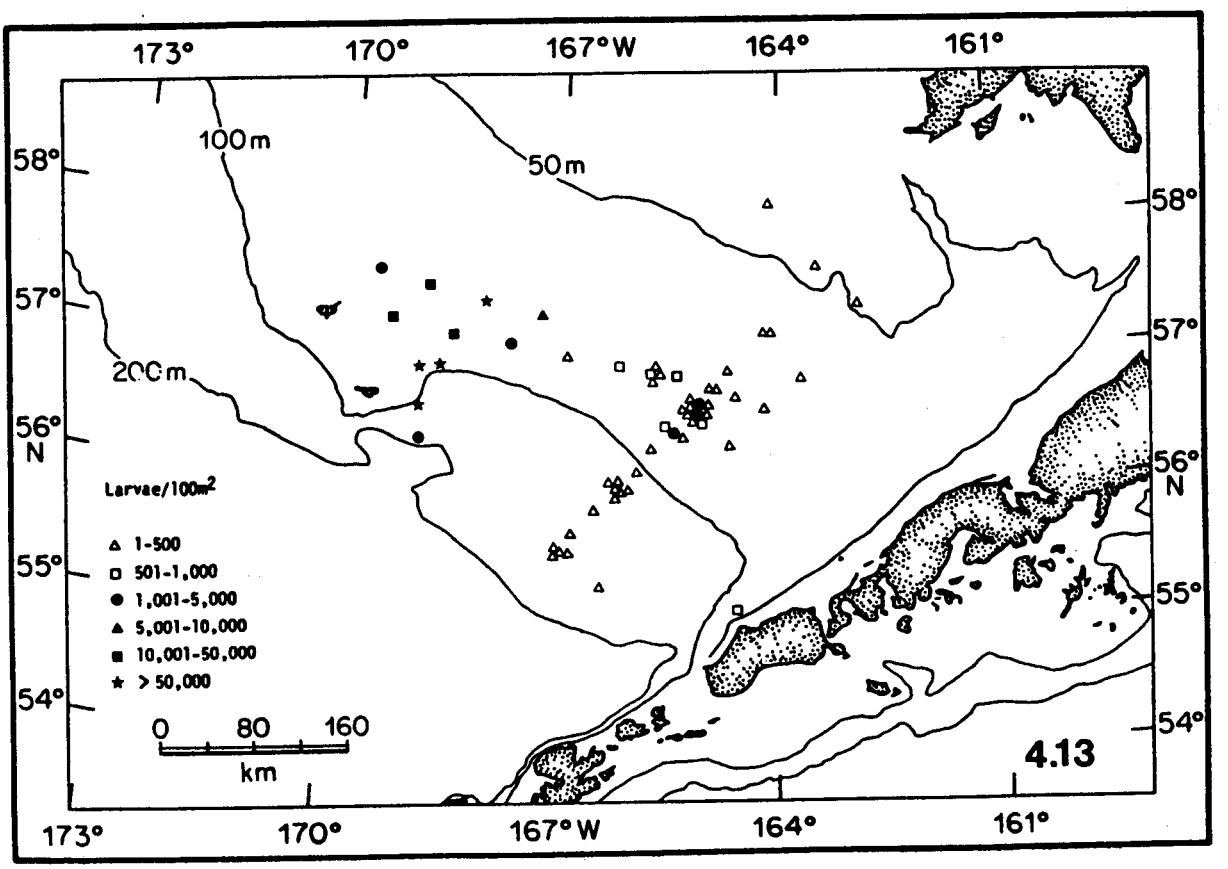


Figure 4.13 Distribution and abundance of C. opilio larvae in the combined years 1980 and 1981. Zero stations not shown.

The distribution patterns for C. bairdi larvae reflect the general pattern anticipated on the basis of the adult spawning populations. Larvae were abundant over the St. George Basin, particularly over shelf depths shallower than 150 m. Larvae were also abundant near the Alaska Peninsula, though the sampling effort in this region was comparatively low in most years. Analysis of data on estimated abundance of larvae in various sampling strata indicated that, over most of the area in this study, large interannual fluctuations in larval abundance of this species did not occur. Furthermore, in areas where adults of C. bairdi dominate, no statistically significant variations in larval year-class strength were observed.

The charted distribution patterns of C. opilio larvae do not correspond closely to the adult populations. The abundance of benthic C. opilio between 70 and 100 m depths over the middle shelf, an area with weak net flows (Kinder and Schumacher 1981), suggests that this is where most larvae of this species should be found. Yet in 1977, 1978 and 1979, an abundance of larvae was found over portions of the St. George Basin (Fig. 4.11 shows the data for 1978 only). This pattern appears to result from three factors. First, sampling effort in years of abundant C. opilio larvae was more concentrated over the outer shelf (especially 1977 and 1979). Second, the most extensive sampling of the middle shelf was conducted in two years (1980, 1981) of very low larval abundance of C. opilio. Finally, the most extensive sampling of an abundant year-class of C. opilio was conducted in a year (1978) in which substantial wind-driven offshore transport occurred in April and early May (Incze

1983). The relative contribution of larvae of C. opilio over the St. George Basin to fishable stocks of Tanner crabs is not currently known, but is an important point to consider since C. opilio contribute substantially to the crab fishery.

Data from the period 1977-1981 clearly show that larval abundance of C. opilio can fluctuate greatly, as much as two orders of magnitude (Incze 1983). Somerton (1981) concluded on the basis of size frequency analysis of benthic populations of C. opilio that recruitment occurs irregularly. While other factors, such as benthic predation, also affect recruitment to juvenile and adult crab populations, success of the larval phase of recruitment is clearly important. The larval abundance data from this study indicate that some years may be much more important than others, and that relative success of larval year-classes may be a significant determinant of adult fisheries recruitment in some years. Impacts on these "key" years might have a much greater effect on adult population dynamics than if year-class strength were more equal each year. Factors potentially contributing to the irregular success of larvae of C. opilio are complex and are presently not well understood (see Incze 1983 for discussion).

4.8 Summary of Principal Findings Relevant to the Assessment of Oil-Related Impacts

1. Most of the larvae of C. opilio hatch during April; a large proportion of the larvae appear to hatch in the first half of this month.

2. Most of the larvae of C. bairdi hatch in late April and the first half of May.

3. Most of the larval hatchout occurs over a period of about two weeks while the total hatchout period may cover 30 or more days.

4. The two zoeal stages last about one month each. The megalops stage lasts at least one month and perhaps considerably longer. Megalops larvae have been collected in considerable numbers over the St. George Basin as late as early October.

5. Eighty-six percent of zoea larvae were found in the upper 20 m of the water column. Megalops larvae showed a more variable depth distribution and were sometimes abundant in the neuston layer.

6. The larvae of C. bairdi were always found in abundance over the St. George Basin, particularly over shelf depths of 100-150 m. Larvae of C. opilio were sometimes, but not always, very abundant in this area.

7. Larval year-class strength of C. opilio fluctuated by almost two orders of magnitude (difference in abundance) during this study. "Strong" larval year-classes may be critical to maintenance of C. opilio stocks at high levels.

8. Larval abundances in excess of 1,000 larvae/100 m^2 sea surface area are common for both species. The maximum mean monthly abundance observed for a single species was 172,124 larvae/100 m^2 (Stage I zoeae of C. opilio, stratum 1, April 1978). Since 86% of zoeae are in the upper 20 m, these values correspond to estimated densities of

over 1 larva/m^3 (common abundance) and 86/m^3 (maximum estimated abundance).

9. Hydrocarbons or other toxicants distributed in the upper, wind-mixed layer would cause direct exposure to most of the larval populations of Tanner crabs. Surface films may impact a substantial portion of the megalops larvae.

5.0 DISTRIBUTION AND ABUNDANCE OF OTHER BRACHYURAN LARVAE IN THE SOUTHEASTERN BERING SEA WITH EMPHASIS ON ERIMACRUS ISENBECKII

Deborah Wencker

5.1 Introduction

There is little detailed literature on the life histories, distribution, and abundance of Brachyura in the southeastern Bering Sea belonging to the families Atelecyclidae (hair crab), Cancridae (Cancer crab), Majidae (spider crabs, other than Chionoecetes bairdi and C. opilio), and Pinnotheridae (pea crab) (see Tables 5.1, 5.2 for summary). Species without commercial value are either little studied and/or are not reported even though they are often caught incidentally during groundfish surveys. From our own experience onboard such cruises we know that noncommercial crabs and shrimp are often caught in high numbers, sorted to species, and logged in data banks. Processed agency reports mention only general listings of total shrimp or noncommercial crab (e.g., Pereyra et al. 1976), or present summary statements on these Crustacea as incidental taxa and therefore, part of communities in which commercial species reside. Some investigators, however, have provided more information on other Brachyura caught, such as catch incidences and biomass (Feder et al. 1981). Inclusion of noncommercial crab among taxa used for analyses of species associations have helped to indicate characteristic biological assemblages in which they are found (Smith and Bakkala 1982; Smith and Walters, 1982).

Sparse coverage in such reports may be due to several factors, including: 1) no commercial value; 2) low abundance; or 3) low

Table 5.1. Size, depth distribution, geographic range and habitat of Brachyura (excluding Chionoecetes bairdi and C. opilio) known to inhabit the S.E. Bering Sea.

Family, species[1]	Adult maximum size	Depth distribution	Geographic distribution	Habitat
Atelecyclidae				
Erimacrus isenbeckii (Korean horsehair crab)	Male: 130 mm. Female: 80 mm.	10 - 360 m.	Bering Sea to Japan Sea	Mud, sand and gravel
Telmessus cheiragonus (Helmet crab)	60 mm.	Shore - 57 m.	Chukchi Sea to California, Siberia to Japan	Mud, sand and gravel
Cancridae				
Cancer magister (Dungeness crab)	Male: 250 mm.[2] Female: 165 mm.[2]	Shore - 90 m.	Aleutians to Baja California	Sand, mud
Cancer oregonensis	40 mm.	Shore - 272 m.	Bering Sea to California	Sand, mud, and empty shell of Balanus nubulus
Majiidae				
Chionoecetes angulatus	Male: 139 mm.	49 - 3000 m.	Pribilof Is. to Kamchatka and Oregon	Mud, sand
Oregonia bifurca	35 mm.	486 m. - 1375 m.	Western Bering Sea	Sand, mud with broken shell
Oregonia gracilis (Decorator crab)	50 mm.	Shore - 382 m.	Bering Sea to Japan and California	Among algae and eel grass
Hyas lyratus (Lyre crab)	50 mm.	Shore - 650 m.	Bering Sea to Washington	Sand, mud with broken shell
Hyas coarctatus alutaceus	70 mm.	Shore - 400 m.	Chukchi Sea to Japan and and northern coast Siberia, Beaufort Sea to West Greenland to Newfoundland	Sand, mud and gravel
Pugettia gracilis (Graceful kelp crab)	30 mm.	Shore - 80 m.	Unalaska to California	Eel grass and kelp
Mimulosa foliatus	30 mm.	Shore - 40 m.	Unalaska to Mexico	No information
Pinnotheridae				
Pinnixa occidentalis	20 mm.[2]	18 - 430 m.	Unalaska to So. California	Commensal in burrows
Pinnixa schmitti	20 mm.[2]	10 - 150 m.	Unalaska to San Francisco	Commensal in burrows and tubes
Fabia subquadrata	20 mm.[2]	Shore to 80 m.	Akutan Pass to California	Commensal on bivalve mollusks

[1]Table compiled from Rathbun 1918, 1925, 1930; Garth 1958; Kozloff 1973 and Otto et al. 1980.

[2]Measurement of width.

Table 5.2. Early life history information on several species of Brachyuran crabs found in the S.E. Bering Sea.

Species	Seasons female ovigerous	Period of hatch	Number of larval stages		Period of larval development[2]	Total length (mm)		Reference[5]
			Zoea	Megalops		Zoea	Megalops	
Erimacrus isenbeckii	NI[1]	Spring	5	1	~5 months	2.7 mm.- 7.2 mm.		1,2,3
Telmessus cheiragonus	June-Oct.	Spring	5	1	~5 months	2.3 mm.- 5.4 mm.		1,2,3,4
Cancer magister	Fall-winter	Early spring	5	1	4-5 months[3]	2.5 mm.- 11 mm.		5,6,7
Cancer oregonensis	NI	Jan., early spring	5	1	4-5 months	2.24 mm. - 7 mm.		6,8
Oregonia gracilis	Mar. - Sept.	Mar., Apr., June and July	2	1	4 weeks	2.5 mm. - 4.3 mm.[4]		2,9
Hyas lyratus	Year round	Apr. - July	2	1	5 weeks	2.5 mm. - 4 mm.[4]		9
Hyas coarctatus alutaceus	Late spring, early summer	May - July	2	1	NI	2.7 mm. - 4.2 mm.[4]		2,4,10
Pugettia gracilis	Year round	May and June	NI	NI	NI	NI		11
Fabia subquadrata	Summer	May - July	4	1	54 days[3]	.75 mm. - 2.1 mm.		12

[1] NI = No information.
[2] Time of development from 1st zoea to megalops.
[3] Time of development from 1st zoea to first benthic instar.
[4] Body length = does not include rostral length.
[5] References: 1) Kurata 1963b, 2) Makarov 1966, 3) Takeuchi 1969, 4) Feder and Jewett 1980, 5) Hoopes 1973, 6) Kendall et al. 1980, 7) Poole 1966, 8) Lough 1975, 9) Hart 1960, 10) Kurata 1963a, 11) Knudsen 1964, 12) Irwin and Coffin 1960.

catchability in survey gear used. Whatever the causes, too little available data on benthic distribution make spatial correlations between larval and adults tenuous. In this section, larval density and distribution will be summarized and related to benthic stocks if possible. The natural history of each species will be presented in taxonomic order. The results and discussion of the larvae of each taxon from our study will be presented with the most commercially important species (Erimacrus isenbeckii), first, followed, in descending order, by those taxa with the highest frequency of occurrence in samples.

5.1.1. Atelecylidae

Erimacrus isenbeckii (Korean horse hair crab), a recent target of an American fishery, occurs from depths of 10-360 m from the Bering Sea to the Japan Sea (Table 5.1). Males reach lengths of at least 128 mm, and the largest recorded by NMFS in the southeastern Bering Sea weighed 1.95 kg (Otto et al. 1980). In 1981, 2.4 million pounds of Erimacrus were taken in the fishery (Otto et al. 1982). In 1982, however, less than a half a million pounds were caught, primarily due to lower market demands for the product (Otto et al. 1982). The fishery is centered around the Pribilof Islands where the majority of the 1980 estimate of 12.9 million sexually mature males with carapace length greater than 80 mm occurred. In years prior to 1980, fairly high concentrations were frequently reported just north of the Alaska Peninsula (Otto et al. 1980). Females, which are rarely larger than 80 mm in carapace length, (Sakurai et al. 1972, cited in Otto et al. 1980) are not part of the fishery, and accurate estimates of abundance and patterns of distribu-

tions are not available for them. During a survey of the epibenthos of the Bering Sea in 1975 and 1976, Feder and Jewett (1980) encountered Erimacrus in 25.6% of trawls made in water between 40 and 100 m deep and 31.7% of trawls made in water between 100 and 200 m. Greatest biomass of Erimacrus occurred between 40-100 m depth and was 1.5% (9.073 g wet weight/m^2) of total epifaunal biomass in the Middle Shelf domain (Jewett and Feder 1981).

Literature on Erimacrus isenbeckii is scarce, but Yoshida (1941) gives the following account of its reproduction. Copulation takes place immediately after the female's first molt to maturity while the carapace is still soft. Eggs are extruded and carried on pleopods under the abdominal flap until zoeae hatch in early spring. Reproduction is inextricably linked to molting in most crabs on an annual basis and likely accounts for large differences in body size between larger sexually mature males and smaller females. Erimacrus females may molt only every other year which slows growth as does the need to put large quantities of energy into egg production (Yoshida 1941).

Telmessus cheiragonus, closely related to Erimacrus but smaller in size (approximately 60 mm in length), occurs in shallow more northerly shelf areas and near river estuaries (Makarov 1966; Table 5.1). It is distributed as far north as the Chukchi Sea. No literature on the reproduction of this species in the southeastern Bering Sea is currently available, but ovigerous females have been found in the Bering Sea from June through September (Feder and Jewett 1980; Lowry et al. 1981). Telmessus cheiragonus is exceedingly abundant in shallow coastal lagoons

of the North Aleutian Shelf, particularly Izenbek Lagoon where it is an important consumer of eelgrass (Zostra marina) production (McRoy 1966; Barsdate et al. 1974).

Erimacrus and Telmessus are food items of secondary importance to other animals of the Bering Sea. Lowry et al. (1981) report that Telmessus is often eaten by the bearded seal and they cite Cunningham's (1969) statement that Erimacrus is occasionally eaten by the red king crab.

Kurata (1963b) described the 5 zoeal stages and megalops stage of both species from the Sea of Japan (Table 5.2). Unfortunatley, most of the text is in Japanese and it is not known if it contains other valuable life history information.

5.1.2 Cancridae

Cancer magister, currently of commercial importance in the Gulf of Alaska, has been reported to inhabit the Bering Sea (Garth 1958), but species lists prepared from more recent surveys of this area (Pereyra et al. 1976; Feder and Jewett 1980) do not include this species. Trawl work aboard the Miller Freeman in June 1982 netted several ovigerous female C. magister north of False Pass (D. Armstrong, personal observation). Dungeness crabs inhabit bays, estuaries, and the open ocean to depths greater than 50 m, from Amchitka Island on the Aleutian chain to Baja California. In British Columbia both males and females reach sexual maturity after twelve molts, two years after metamorphosis from the larval stage. Female growth then becomes slower relative to male, and females rarely attain widths greater than 165 mm, while males may grow

to as wide as 250 mm wide by a maximum age of ten years (Butler 1960, 1961). Mating occurs when adults migrate to shallow water in the spring and the female has molted. Females do not extrude eggs until the following fall. Egg development requires seven to ten months (Hoopes 1973).

Cancer oregonensis is a small crab up to 40 mm carapace that lives on rocky shores and in empty shells of Balanus nubulus at greater depths in the Bering Sea. No information is available in the literature on its growth and reproduction.

Cancer spp. are eaten by the Irish lord (Hemilepidotus jordani) and the rock sole (Lepidopsetta bilineata) (Feder and Jewett 1981).

Poole (1966) describes the five zoeal stages and megalops stage of Cancer magister reared in a laboratory on the coast of California. Lough (1975) discussed larval stages and development of C. oregonensis from the plankton off the coast of Newport, Oregon.

5.1.3 Majidae

The family Majidae includes, in addition to Chionoecetes spp., several small "decorator" crabs of no commercial importance that are distributed widely throughout the southeastern Bering Sea. Hyas coarctatus alutaceus is found from the southern Bering shelf to the Arctic, and Oregonia gracilis and Hyas lyratus occur in more southerly areas (McLoughlin 1963; Feder and Jewett 1980). During epibenthic assessment of the southeastern Bering Sea in 1975 and 1976, H. lyratus occurred in 22.1% of trawls taken between 100 and 200 m, while H. coarctatus

alutaceus was encountered in 47.8% of the trawls made between 40 and 100 m (Feder and Jewett 1980). Wet weight biomass of this last species was 0.028 g/m^2 and comprised only 0.6% of total epifaunal biomass in the Middle Shelf Domain (Jewett and Feder 1981). The kelp crabs Pugettia gracilis and Mimulosa foliatus inhabit the area near Unalaska Island (Rathbun 1925).

Accounts of reproduction of these species are scant or non-existent, but most mating appears to be associated with females molting (Knudsen 1964). Ovigerous females of the species Oregonia gracilis, Hyas coarctatus altaceus and H. lyratus have been reported from the southeastern Bering Sea in the late spring and early summer (Feder and Jewett 1980). Fecundity in Puget Sound was reported by Knudsen (1964) who found that female Oregonia gracilis 17 to 25 mm in carapace length carried 2,800 to 17,400 eggs, and female Pugettia gracilis 20 to 25 mm in length carried 6,200 to 13,300 eggs.

Several of these species have been reported as food items for Pacific cod (Gadus macrocephalus, sculpins, rock sole (Lepidopsetta bilineata), and the sea-stars Asterius amurensis and Pycnopodia helianthodes (Feder and Jewett 1981). Hyas coarctatus alutaceus is an important food item in the Bering Sea bearded seal diet (Lowry and Frost 1981) and of secondary importance for red king crab (Cunningham 1969).

All majid crabs molt through two zoeal stages and a megalops staye (Hart 1971). Hart (1960) described laboratory-reared larvae of Oregonia gracilis and Hyas lyratus from British Columbia. Hyas coarctatus

alutaceus larvae were collected from the Sea of Japan and described by Kurata (1963a). Other species of majid crab larvae have not been described (Table 5.2), but Hart's key (1971) allows easy separation of the sub-families.

Chionoecetes angulatus may attain a carapace length of 139 mm as adults and are distributed on the continental slope and deeper in the southeastern Bering Sea. Several were encountered at depths greater than 140 m during a NWAFC continental shelf groundfish assessment, but abundance estimates were not made (Otto et al. 1979).

5.1.4. Pinnotheridae

Unlike other families discussed thus far, pinnotherids are generally commensal crabs that reside in polychaete tubes and burrows or in mantle cavities of bivalves and gastropods. Data on the distributions of pea crabs in the southeastern Bering Sea are not available. Irwin and Coffin (1960) suggest that the growth of Fabia subquadrata is related to the growth of its host (a bivalve mollusk) and describe the early life history of laboratory-reared larvae from the coast of Washington. The larval stages of Pinnixa occidentalis and P. schmitti have not been described. There is also a conflict in the literature as to the number of zoeal stages for the Pinnotheridae. Irwin and Coffin (1960) report four zoeal stages for Fabia subquadrata, while Lough (1975) reports five for the same species and unidentified species of Pinnixa from the plankton of the Oregon coast.

5.2 Purpose and Scope

The purpose of this section is (1) to both extend and summarize data sets discussed in the annual report of Armstrong et al. (1981) by the inclusion of 1981 data now available, and (2) to examine the spatial patterns of larval distribution and density of the non-Chionoecetes Brachyura in the southeastern Bering Sea. This information should allow a better understanding of where and when larvae of a taxon may be most susceptible to the detrimental effects of oil and it should extend the knowledge of a taxon's early life history and ecology.

5.2.1 Taxonomy

Identification of decapod larvae in this section was made to the taxonomic level listed in the right-hand column of Table 5.3. Because of limited literature on larval descriptions of crab species known to inhabit this region (left-hand column, Table 5.3), only larvae of Erimacrus isenbeckii and Telmessus cheiragonus were identified to species. The literature listed in Table 5.4 was used to identify species to the lowest possible taxonomic level.

5.2.2 Patterns of Larval Distribution Examined

After all data from the years 1976-1981 were summarized for brachyuran larvae, they were analyzed to determine the following patterns of distribution and density: 1) vertical, 2) temporal, and 3) horizontal. However, certain limitations of the data in this study are evident that preclude a thorough analysis of these factors for all taxa, because the plankton samples available are from collections intended for other uses. Periods and regions from which samples were collected varied

Table 5.3. Species list of non-*Chionoecetes* Brachyura known to inhabit the S.E. Bering Sea, and taxonomic level to which they were identified.

Taxa	Level of Identification
Atelecyclidae	
Erimacrus isenbeckii	*E. isenbeckii*
Telmessus cheiragonus	*T. cheiragonus*
Cancridae	
Cancer magister	*Cancer* spp.
C. oregonensis	
Majidae - Subfamily Oregoniinae	
Hyas coarctatus alutaceus	non-*Chionoecetes* Oregoniinae
H. lyratus	
Oregonia gracilis	
Majidae - Subfamilies Acanthonychinae/Pisinae	
Mimulosa foliatus	Acanthonychinae, Pisinae
Pugettia gracilis	
Pinnotheridae	
Fabia subquadiata	Pinnotheridae
Pinnixa occidentalis	
P. schmitti	

Table 5.4. Brachyura taxa identified among larval decapods, larval stages and references used for identifications.

Species/Taxon	Larval Stages	References
Erimacrus isenbeckii	Stages I-V & Meg	Hart 1971, Kurata 1963b, Jewett & Haight 1977
Telmessus cheiragonus	Stages I-V & Meg.	Hart, 1971, Kurata 1963b, Jewett & Haight 1977
Cancer spp.	Stages I-V & Meg	Hart 1971, Poole 1966, Lough 1975
non-*Chionoecetes* *Oregoniinae*	Stages I, II & Meg	Hart 1971, Jewett & Haight 1977
Subfamily Acanthonychinae and/or Pisinae	Stages I, II & Meg	Hart 1971, Lough 1975
Pinnotheridae	Zoea & Meg	Hart 1971, Lough 1975

annually, which resulted in little consistency of spatial and temporal data from which to delineate patterns of distribution and density. These limitations required that the data be analyzed in the following ways: 1) in most cases, data from all years were combined when examining spatial distribution of taxon; 2) intra- and interannual comparisons could only be made for three years for the non-Chionoecetes (Malidae referred to here as Oregoniinae; See Section 4.0 Chionoecetes and for Pinnotheridae; and 3) these two taxa were the only ones analyzed for vertical patterns of larval distribution based on adequate representation in the MOCNESS samples of the years 1980 and 1981.

5.3 Results, Discussion, and Summaries

5.3.1 Vertical Distribution

Vertical distributions of Oregoniinae and Pinnotheridae were examined (1) to assure that bongo net samples collected routinely from 60 m to the surface, or to within 10 m of the bottom in depths less than 60 m, included representative numbers of larvae on which to base abundance estimates, and (2) to determine the vertical location of the majority of these larvae in the water column.

Criteria for the analysis of the vertical distribution of individual taxa were established and applied to 1980 and 1981 MOCNESS stations in order to determine the mean percentages of larvae located at different depth intervals. These criteria are: 1) a total of six larvae of each taxon had to be counted in the subsample examined before an individual MOCNESS station was used as an observation; and 2) at least five

stations had to satisfy criterion No. 1 before the taxon was analyzed for patterns of vertical distribution. After these criteria were met, a taxon was analyzed by calculating the percentage of total larvae that were caught at successive 20 m depth intervals. These percentages were summed by depth intervals for all stations and the mean and standard deviation calculated.

The only two taxa that satisfied the criteria outlined above were Oregoniinae and Pinnotheridae, which were collected respectively at 30 and 7 of the combined 1980 and 1981 MOCNESS stations (all 7 Pinnotherid stations came from 1981 collections). Furthermore, of the 30 stations with adequate Oregoniinae larvae, 63% were sampled from the surface to below 80 m (in 20 m intervals) and 93% were sampled to 80 m depth. All 7 Pinnotheridae stations were sampled below 80 m.

The means and one standard deviation of the percentage of larvae collected at each 20 m depth interval of the 30 Oregoniinae stations are shown in Figure 5.1. The majority of larval Oregoniinae (87%) were caught in the upper 40 m: 58% in the upper 20 m and 29% between 20 and 40 m. Most of the Pinnotheridae larvae (75%) were also located in the upper 40 m of the water column at the 7 stations examined for their vertical distribution (Figure 5.2). The upper 20 m contained 42% of these larvae and 33% occurred between 20 and 40 m.

Although the data for the other taxa that include Erimacrus isenbeckii, Telemessus cheiragonus, Cancer spp. and the subfamilies Acanthonychinae and Pisinae did not satisfy the criteria established for

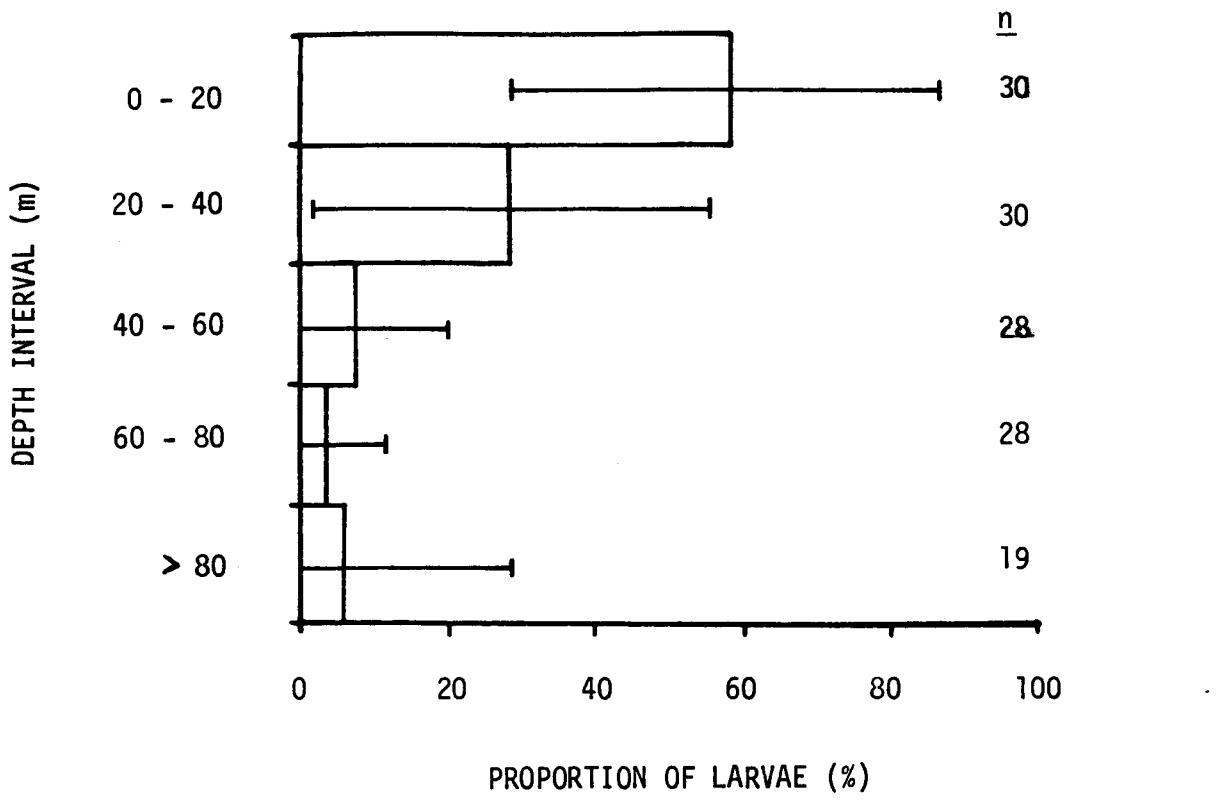


Figure 5.1 Vertical distribution of Oregoniinae brachyuran larvae in 1980, 1981 MOCNESS samples from the southeastern Bering Sea. The bars represent the mean percentage of larvae (±1 standard deviation) collected in 20 m intervals from 0-80 m and deeper than 80 m. N equals the number of stations sampled from which at least six larvae of the taxon were observed and from which the mean of each 20 m interval was calculated.

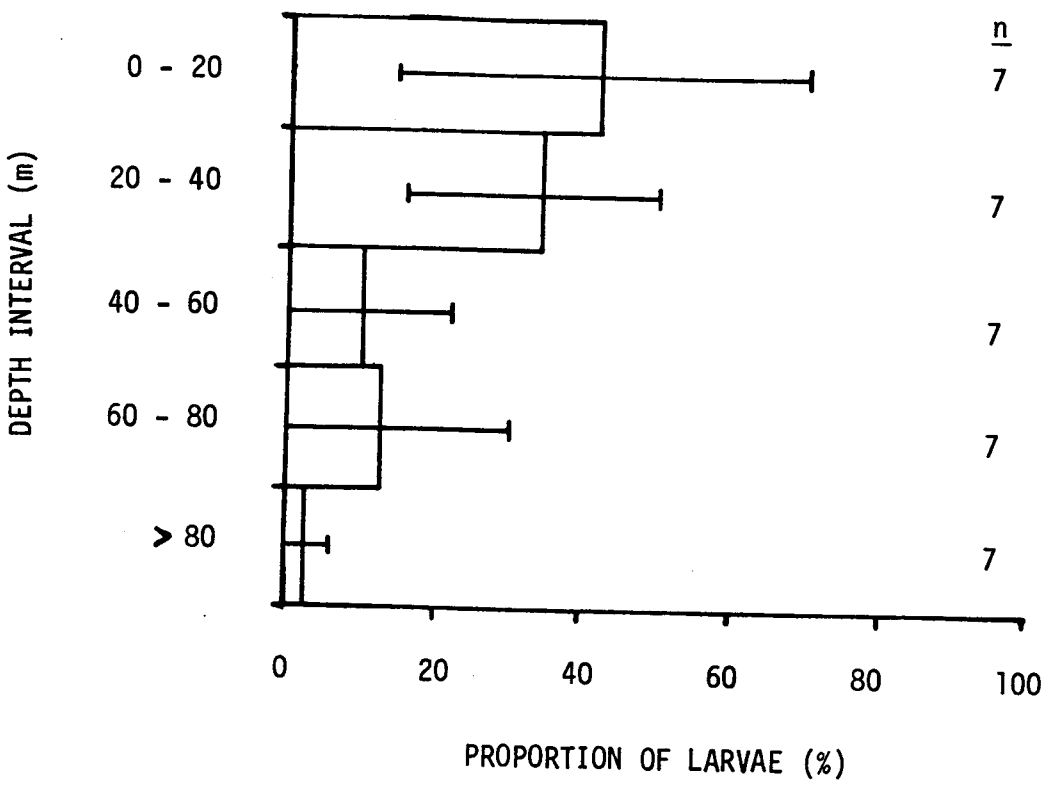


Figure 5.2 Vertical distribution of Pinnotheridae larvae in 1981 MOCNESS samples from the southeastern Bering Sea. The bars represent the mean proportions of larvae (±1 standard deviation) collected in 20 m intervals from 0-80 m and deeper than 80 m. N equals the number of stations from which at least six larvae of the taxon were observed and from which the mean proportion of each 20 m interval was calculated.

examining their vertical larval distribution, a brief examination of vertical distribution of these larvae in the 1980 and 1981 MOCNESS stations suggest that they too were concentrated in the upper 40 m of the water column. Thus, 40 m can be considered a reasonable lower depth limit in calculating density of these taxa in the water column.

Summary

1) The majority of Oregoniinae and Pinnotheridae occurred in the upper 40 m of the water column sampled by the MOCNESS year in 1980, 1981.

2) Although analyses of the larval vertical distribution of the other Brachyura taxa was not possible, that data too (1980 and 1981 MOCNESS) suggest that the majority of these larvae appeared in the upper 40 m.

5.3.2 Temporal and Horizontal Patterns of Larval Distribution and Density

Temporal patterns of larval distribution of the non-Chionoecetes Brachyura during the years 1976-1981 were examined to determine when these larvae were present in the plankton of the southeastern Bering Sea (Fig. 5.3). Criteria were established to assure a conservative approach to examination of the duration of larval stages (molt-frequency). These criteria were: 1) $n \geq 6$, where n is the number of larvae of an individual taxon observed in a sample, and 2) at least three samples were used to calculate the mean percent of each larval stage during each one-week interval. Consequently, only one taxon, Oregoniinae, was examined for molt-freqency patterns and only in the year 1981 because all other

taxa were collected too sporadically in time and space to satisfy the criteria above.

Horizontal patterns of distribution and density were determined for zoeae and megalopae from the spring and summer months of the years 1976-1981 combined in the cases of Erimacrus isenbeckii, Cancer spp., Telemessus cheiragonus and the subfamilies Acanthonychinae and/or Pisinae. Most larvae were present in May and June; therefore this was the time period used to calculate their frequency of occurrence by stratum. These taxa were relatively uncommon and too little data were available from separate years for interannual comparisons. However, Oregoniinae and Pinnotheridae were well represented (over 20% of all annual stations produced zoeae and/or megalopae) in the years 1978, 1980 and 1981, which allowed both intraannual comparisons between sub-areas or strata (see Section 2.8), and interannual comparisons between the three years. Samples from February and March 1978 and October 1980 were excluded from such analyses because they were collected only in a single year.

Mean densities, standard deviations, and ranges of values for Erimacrus isenbeckii, Cancer spp., Telemessus cheiragonus and Acanthonychinae and/or Pisinae larvae were calculated for each stratum by using densities only from stations at which these larvae occurred. While interannual differences in timing of hatch and density of larvae would make such averaging quantitatively inaccurate, these relatively rare taxa were each grouped over 1976-1981 for a qualitative sense of where larvae predominated. Mean densities of Oregoniinae and Pinnotheridae were calculated for April, May, and June of 1978, 1980, and 1981, and

also July of 1981. Within strata, both positive values (stations where larvae were caught) and zero stations were averaged for comparisons and contrasts of intra- and interannual density and distribution along or across the shelf.

5.3.2.1 Erimacrus isenbeckii

Seasonal Occurrence: Larvae of this species were generally uncommon but were collected in the plankton from mid-April to late-June when data from all the sampling periods of the years 1976-1981 were combined (Fig. 5.3). Individual larval stages were present as follows: Stage I (SI), from late-April to mid-June; SII, from mid-April to mid-June; SIII, from mid-May to mid-June; SIV in mid-April and June; SV, in June; and megalops larvae in June.

Because the seasonal occurrence of SI and IV larvae did not overlap from year to year, gaps appear in the bars representing occurrence of these stages over the sampling periods of all years combined in Figure 5.3

Distribution: Larvae of E. isenbeckii were collected at only 9% of the stations analyzed from the years 1976-81. Of the samples with larvae, 85% were collected in May and June, which was therefore the time frame selected in which to examine frequency of occurrence. Frequency of occurrence (percent) of Erimacrus larvae is listed by stratum in Table 5.5 and the locations of stations at which Erimacrus larvae were collected are plotted on a map of the study area in Figure 5.4. These results show that larvae were collected throughout the study area, but were most

Table 5.5. Frequency of occurrence of Erimacrus isenbeckii within each stratum in May and June of the combined years 1976-1981. Percentages were derived from the proportion of all stations within each stratum at which E. isenbeckii were found (see Fig. 2.21). As noted in the text, only 9% of the total stations analyzed in all years contained larvae of this species.

Stratum number	Frequency of occurrence (percent) of larvae within strata
1	7
2	10
3	11
4	18
5	19
6	31
7	6
8	3
9	6
10	14
11	38
12	50

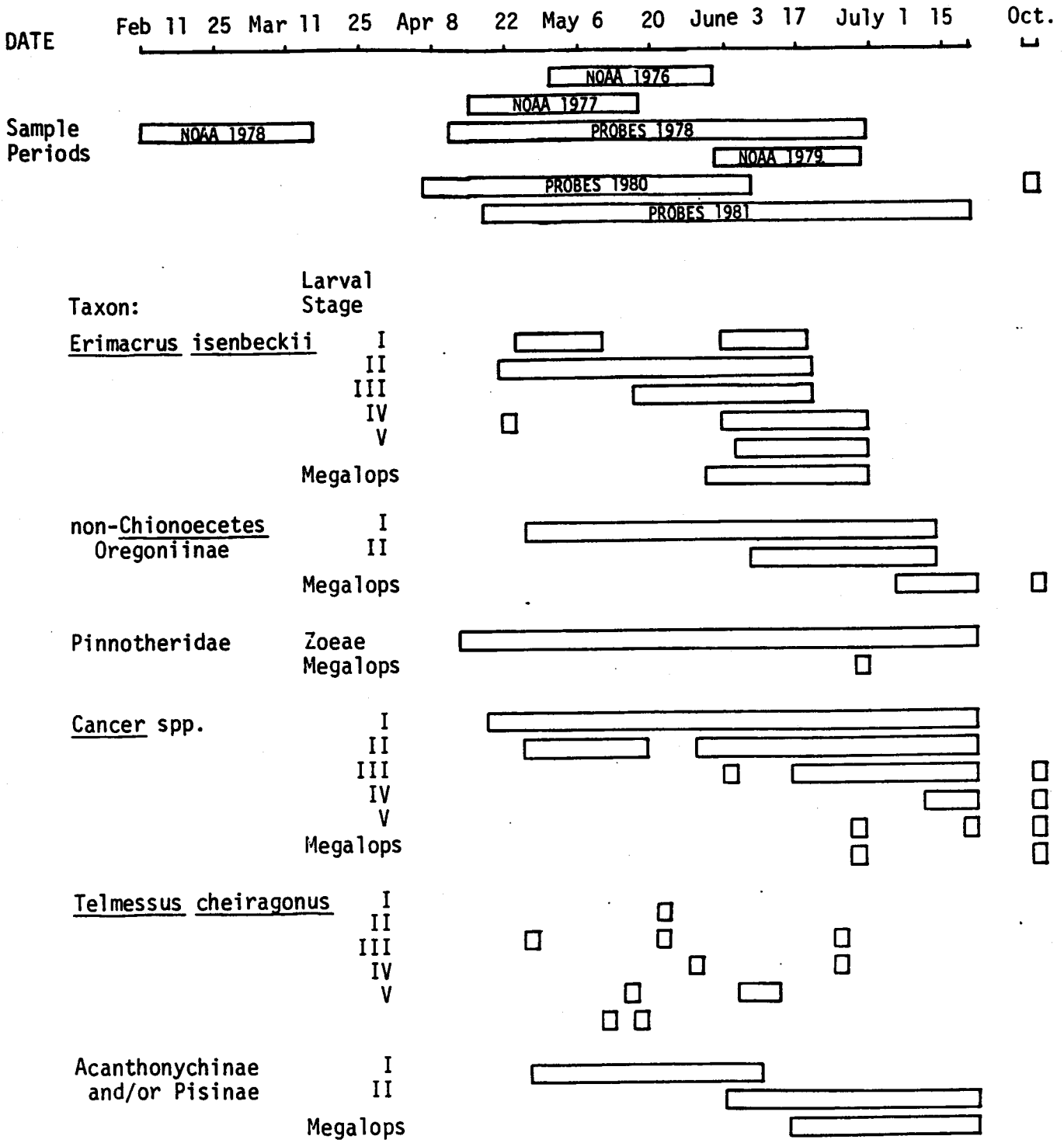


Figure 5.3 Seasonal occurrence of larval stages of selected beachyuran taxa in the southeastern Bering Sea in the years 1976-1981. Also depicted are the seasons and durations of cruises that collected zooplankton samples from which these data are derived (see Section 2.0 for more details). Gaps in bars showing duration of larval stages are due to relative scarcity over much of the total sampling period.

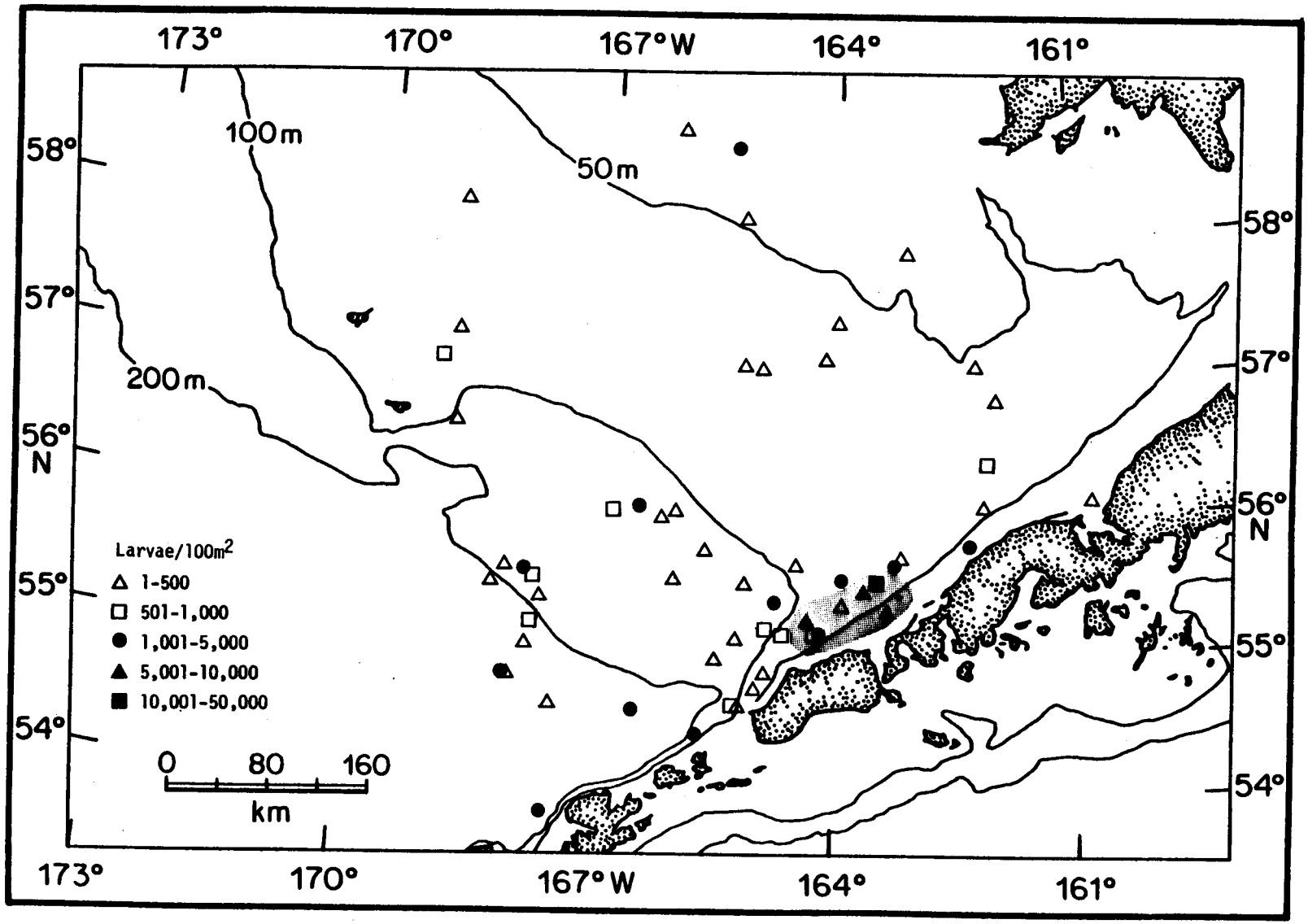


Figure 5.4 Locations and densities of Erimacrus isenbeckii larvae collected in the southeastern Bering Sea in the years 1976-1981. Locations where no larvae were found are omitted, but all station locations for these years are illustrated in Figures 2.1 - 2.18.

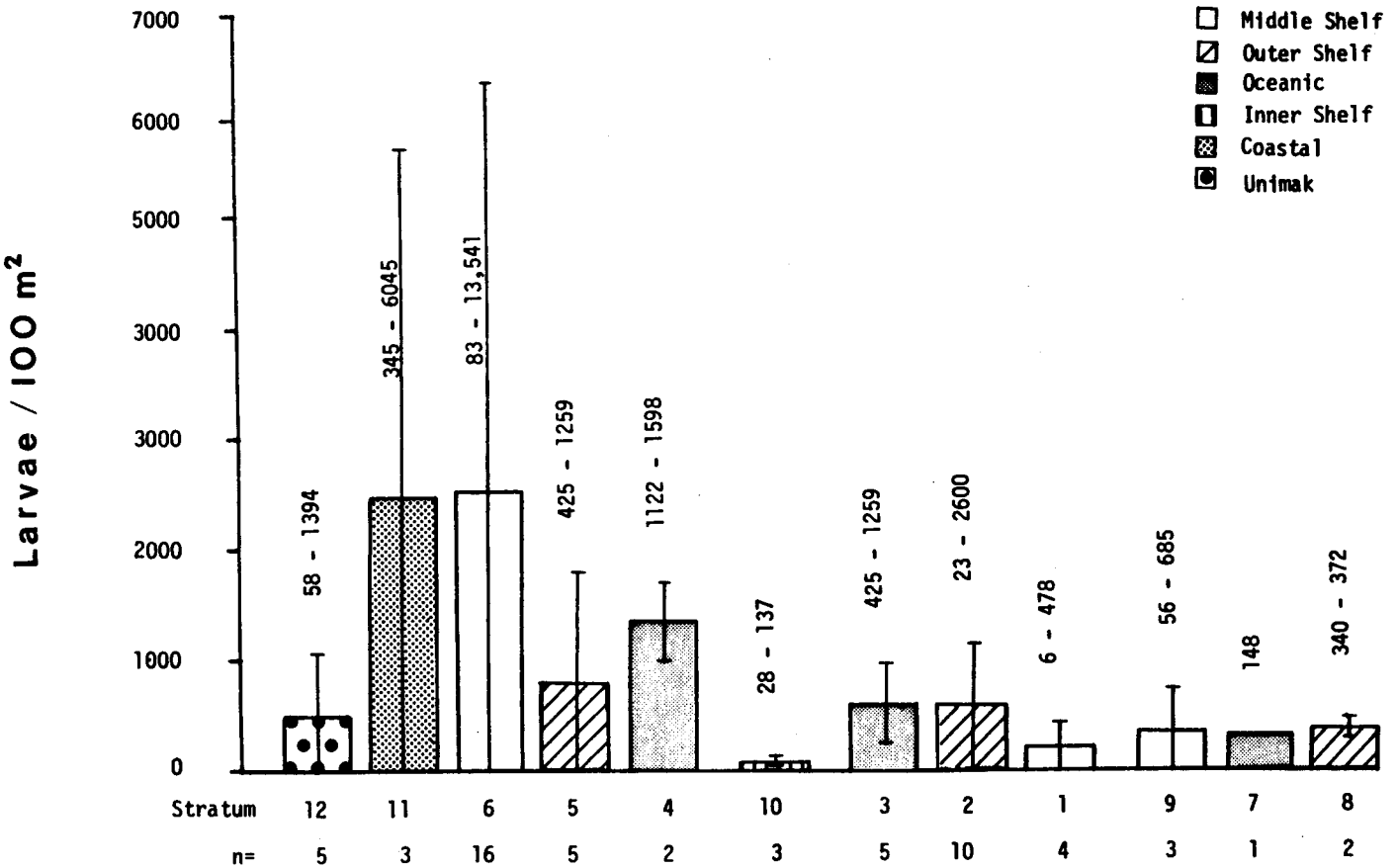


Figure 5.5 Mean density and one standard deviation of Erimacrus isenbeckii larvae in the southeastern Bering Sea for all years, 1976-1981, combined. The range of densities from which these means were calculated are listed above each corresponding bar; while the number of samples used to calculate each mean, n, are listed on the lower axis. Stations at which no larvae were found were not used in calculating the mean density of Erimacrus isenbeckii larvae within each stratum (see Fig. 2.8).

abundant in strata 6, 11, and 12 in an area near their junction at eastern Unimak Island and Bechevin Bay (Figure 5.4). This pattern is somewhat in accord with NMFS groundfish survey data that shows relatively low density of female E. isenbeckii throughout the southeastern Bering Sea, with somewhat greater numbers near Unimak Island and at the Pribilof Islands (Otto et al. 1982). Perhaps because few samples were collected in this latter location the density of larvae at the Pribilofs was very low (Fig. 5.4). However, to date there is no definitive information to indicate important regions of female abundance or larval hatch but nearshore areas are suspected.

Density: Mean density ± 1 standard deviation, the range of densities and the number of stations at which larvae were present for each stratum are shown in Figure 5.5. Strata are labeled as to the regime (inner, middle, and outer shelf; oceanic zone; Alaska coastal and Unimak Island) in which they are located. Individual stations sometimes contained fairly high densities of larvae (in excess of 5,000/100m^2), but commonly numbers were very low, often less than 500/100m^2 (Figure 5.4). Average densities were highest in strata 6 and 11 with over 2,000/100 m^2. But the enormous range (83-13,541 larvae/100 m^2 in stratum 6) and standard deviations associated with the data reflect the vagaries of interannual differences in seasonal occurrence and densities of larvae. Stations from other strata usually lacked E. isenbeckii larvae or contained them in low densities of a few hundred/100 m^2 (Figs. 5.4, 5.5; in comparison with values in excess of 100,000/100 m^2 for Tanner larvae in Sec. 4.0).

Long-shelf density of Erimacrus larvae seemed to be greatest along the 100 m and 200 m isobaths of the middle shelf and oceanic regimes. Again the confluence of 50 m and 100 m isobaths just north of Unimak Island was the area of greatest occurrence and density (Fig. 5.4).

Summary

1) Erimacrus isenbeckii larvae were collected at 9% of all stations sampled during 1976-1981.

2) These larvae were generally distributed throughout the study area but their frequency of occurrence was higher near the Alaska Peninsula in the coastal, middle shelf and Unimak Is. regimes.

3) Mean densities of larvae were appreciably higher in the eastern region of the southeastern Bering Sea than in the central and western regions, while larval densities were very low at the Pribilofs which may reflect the fact that few samples were collected there.

4) Zoeal stages were found in April through June and megalops larvae in June only.

5.3.2.2 Oregoniinae (Hyas spp., Oregonia spp.)

Seasonal Occurrence: Larvae of this taxon were present in the plankton from mid-April to early-October when all data were combined for years 1976-1981 (Fig. 5.3). Each larval stage appeared as follows: SI, from mid-April to mid-July; SII, from early-June to mid-July and megalops larvae from early to mid-July and October. This time sequence was re-

fined somewhat based on data from 1981 that was used for molt-frequency analysis (Fig. 5.6). The samples used for this analysis, late May through about June 10, showed all larvae were SI zoeae (90-99%). From June 13 to July 4 SII were dominant, and after July 11 megalopae were the most abundant stage. Assuming that megalopae require about one month for development (similar to Tanner larvae, Section 4.0), the majority of the population would have metamorphosed in mid- to late-August in 1981. Add to this time about one month for SI zoeal development, and total planktonic time for this taxon would be about 3.5 months.

Distribution: Larvae of this taxon were found at 42% of all stations sampled in 1976-1981. Of these stations, 77% were collected in May and June, which was therefore used as the time frame for analyses of interannual densities between strata. During May and June, larval Oregoniinae were most frequently (> 60% of stations) collected in strata 1, 4, 5, 9, 10 and 12, and least frequently (< 30% of stations) in strata 7, 8, and 11 (Table 5.6; See Fig. 2.8 for strata). This May/June distribution and density are shown in Figures 5.7, 5.8, and 5.9 for the years 1978, 1980 and 1981, respectively. There tend to be fewer larvae over the middle and inner shelf to the extent they were collected, and more along the 100 m isobath and outer shelf. High densities are shown near western Unimak Island in all years (Figs. 5.7-5.9) which is likely due to the presence of Oregonia gracilis spp. that were found in high abundance nearshore in 1982 (Armstrong, unpublished data).

Density: Because sampling within all strata in each year was not consistent, it is somewhat difficult to compare larval densities between

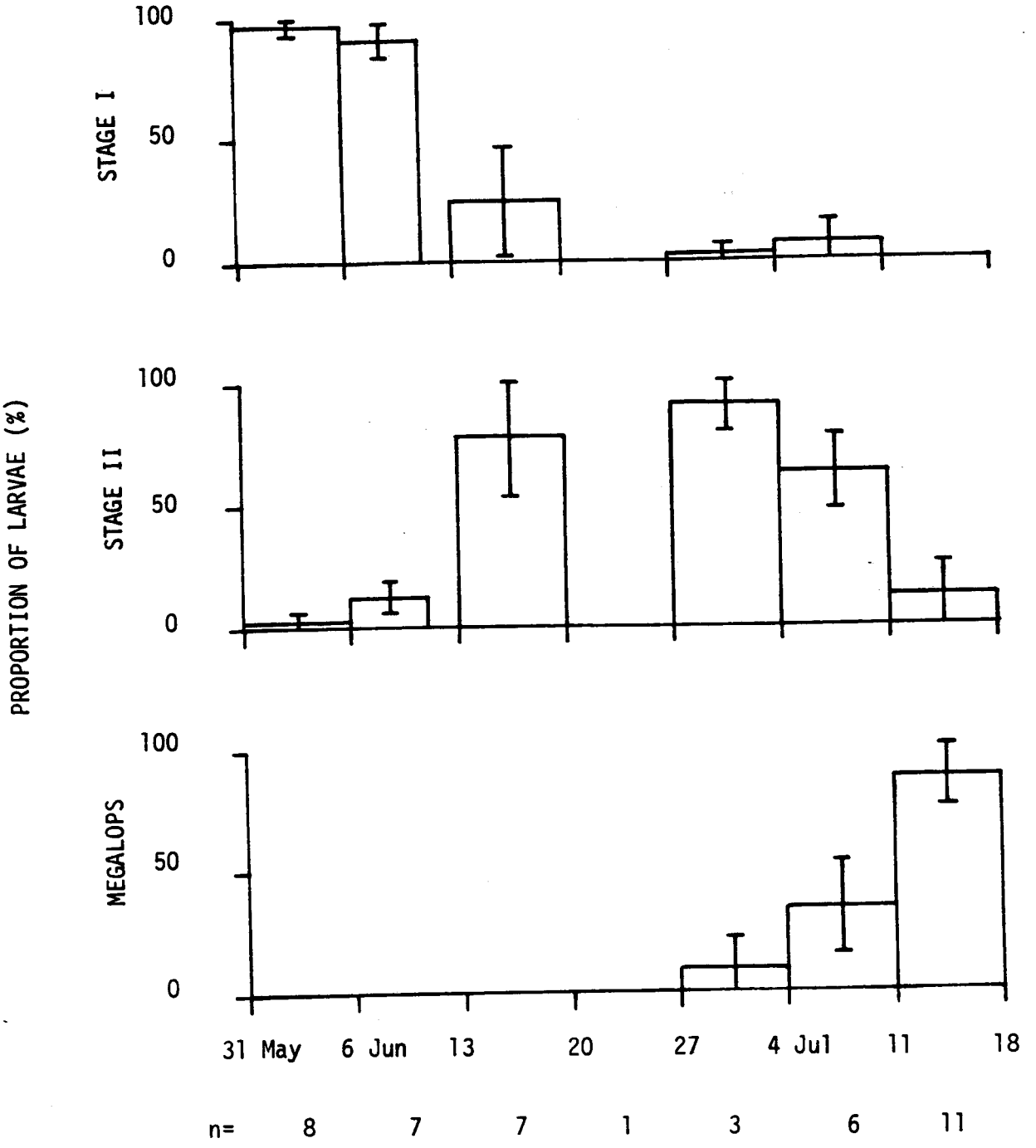


Figure 5.6 Frequency-of-occurrence of larval stages of Oregoniinae during weekly intervals from 31 May to 18 July 1981. The number of samples used to calculate the mean percent and one standard deviation of each stage for each week is equal to n. Molt frequency from stage I to stage II to megalopae is about 30-35 days.

Table 5.6. Frequency of occurrence (as percent) within each stratum of Oregoniinae in May and June of the combined years 1976-1981. Percentages were derived from the proportion of all stations each stratum at which Oregoniinae were found.

Stratum number	Frequency of larval occurrence within each stratum (percent)
1	60
2	53
3	44
4	82
5	62
6	33
7	25
8	28
9	65
10	71
11	25
12	100

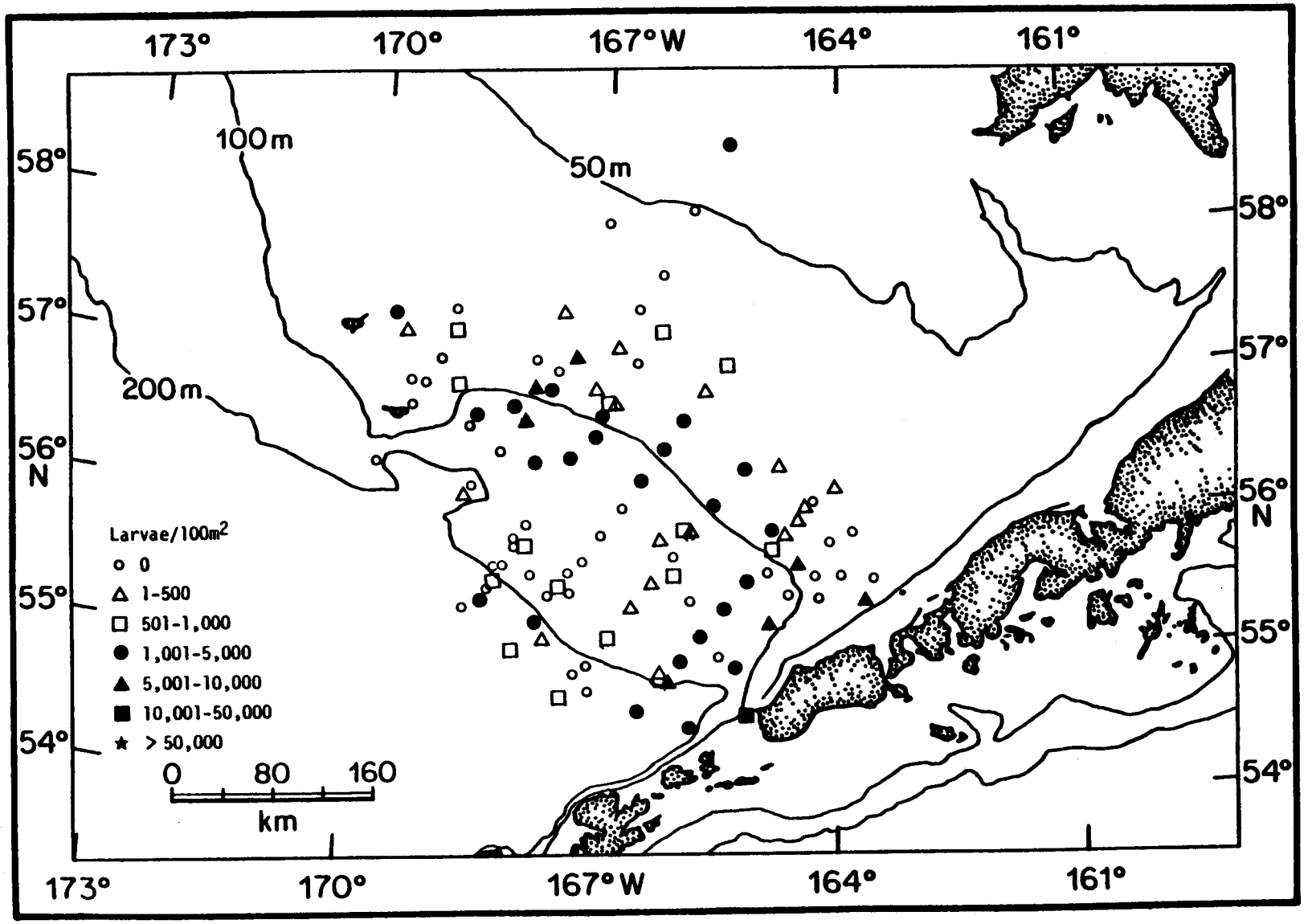


Figure 5.7 Distribution and abundance of Oregoniinae larvae in May/June 1978.

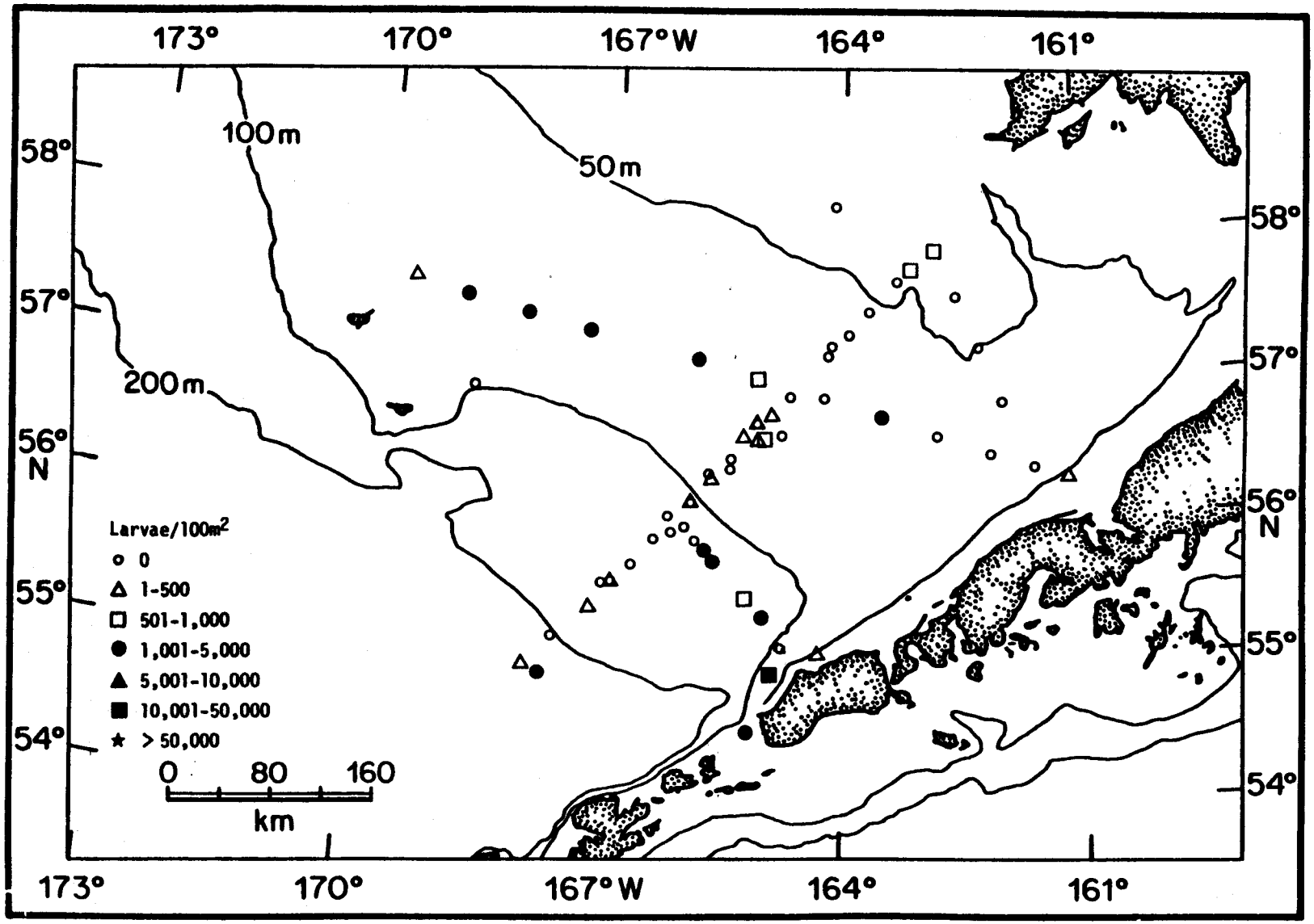


Figure 5.8 Distribution and abundance of Oregoniinae larvae in May/June 1980.

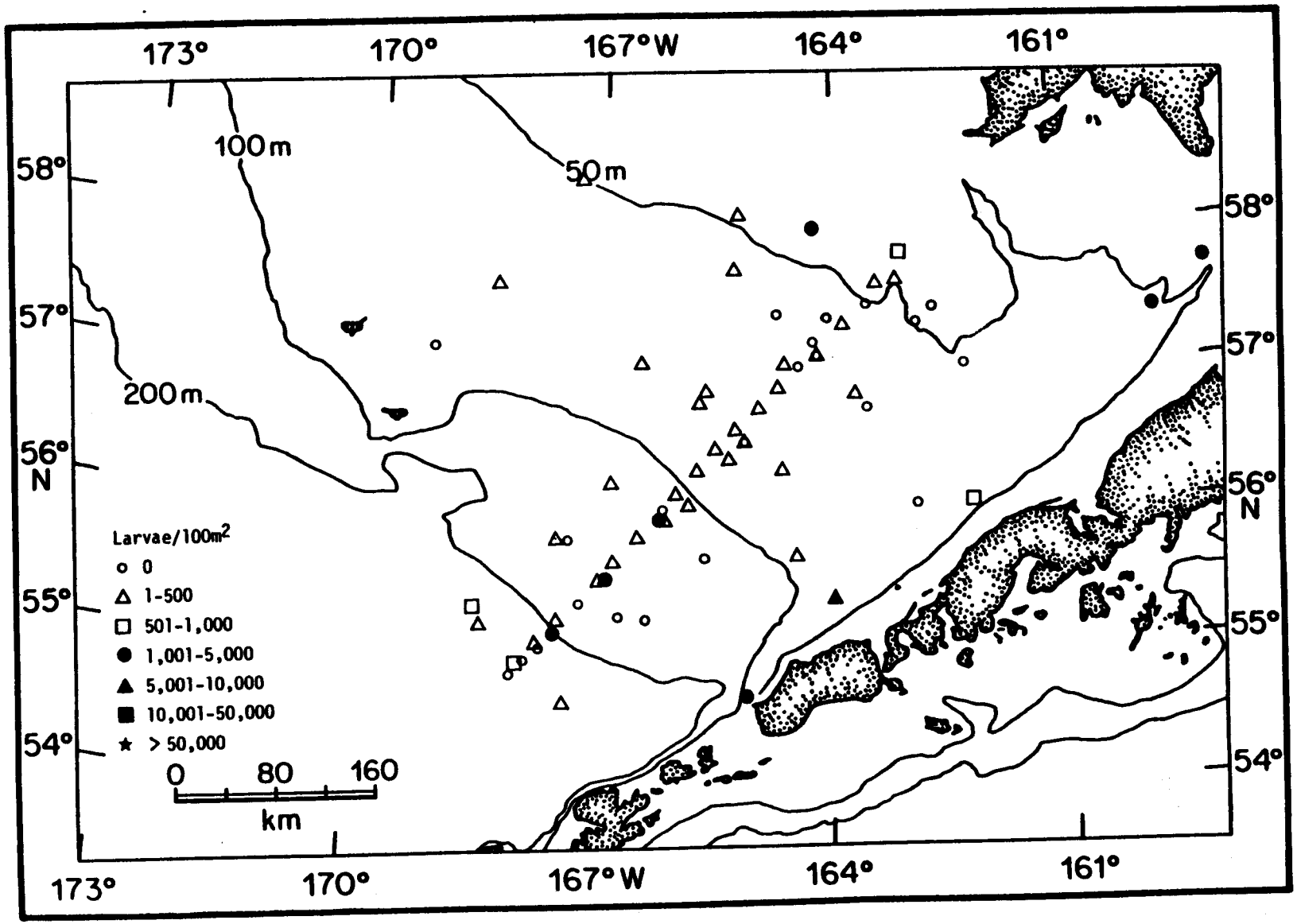
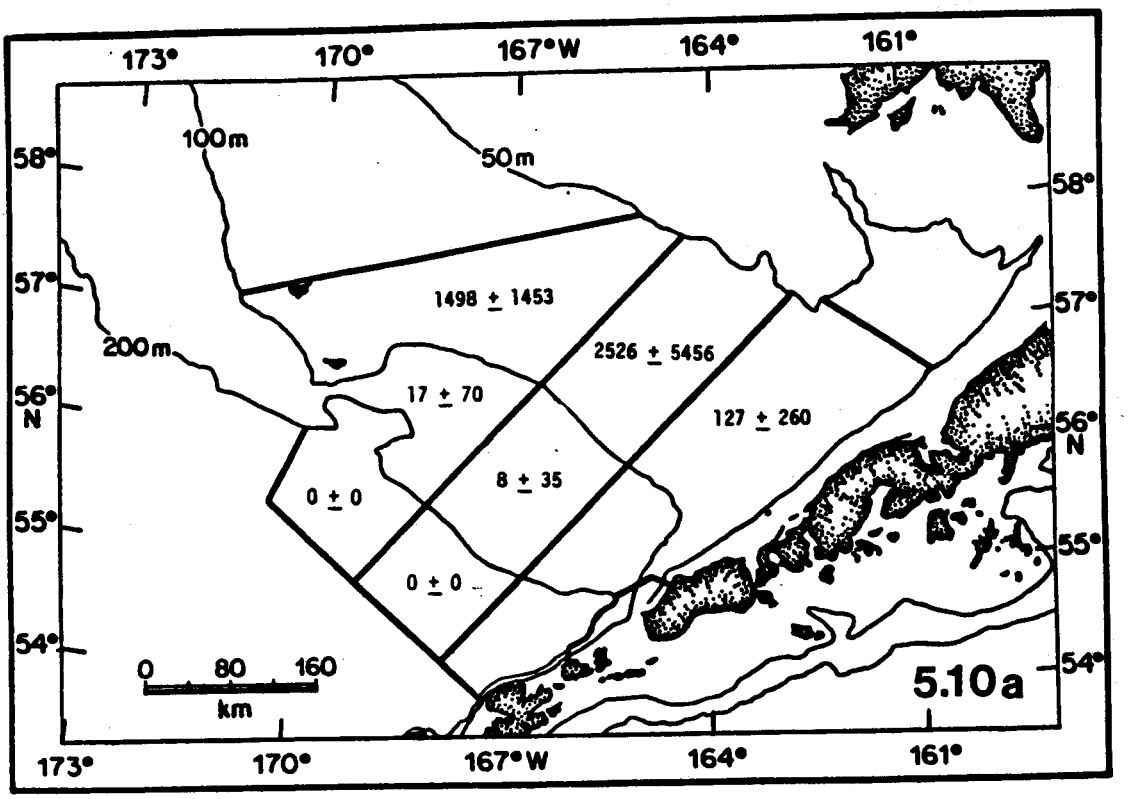


Figure 5.9 Distribution and abundance of Oregoniinae larvae in May/June 1981.

them. Contrasts can be made to highlight seasonal, regional and annual differences in densities (Figs. 5.10-5.12). These mean larval densities were only calculated when the number of stations sampled in each stratum during the time period indicated was $\geq$ 5; consequently, densities for some strata are not given.

Some seasonal changes in regional densities were found when April was compared to May/June (Fig. 5.10 a & b) in 1978. There was apparently an earlier hatch over the middle shelf than over the outer shelf. Strata 1 and 9 had mean densities of about 1500-2500 larvae/100 m^2 while strata 2 and 8 had virtually none (Fig. 5.10a). In May/June larvae were widely distributed over the shelf but more abundant over the outer (1142-2222 larvae/100 m^2) than the middle shelf (922-1845/100 m^2). It is not known to what extent this shift in regional density represents differences in timing of species hatch across the shelf (Hyas spp. vs. Oregonia spp.) and/or intraspecific variability between regions (i.e. strata).

For interannual comparison of larval densities, May/June samples were available from strata 1, 2, and 6 in 1978, 1980 and 1981 (Figs. 5.10b, 5.11, 5.12a). Although standard deviations about mean densities of each stratum are large, larval density was higher in 1978 than in either 1980 or 1981. The latter two years showed very low abundance of larvae in the plankton; densities were 2-18 times less than those found in 1978. The nature of spawner-recruit relationships for this taxon are unknown, and so the extent to which more or less pelagic larvae indicate good or poor year-classes cannot be assessed. Still low larval abundance



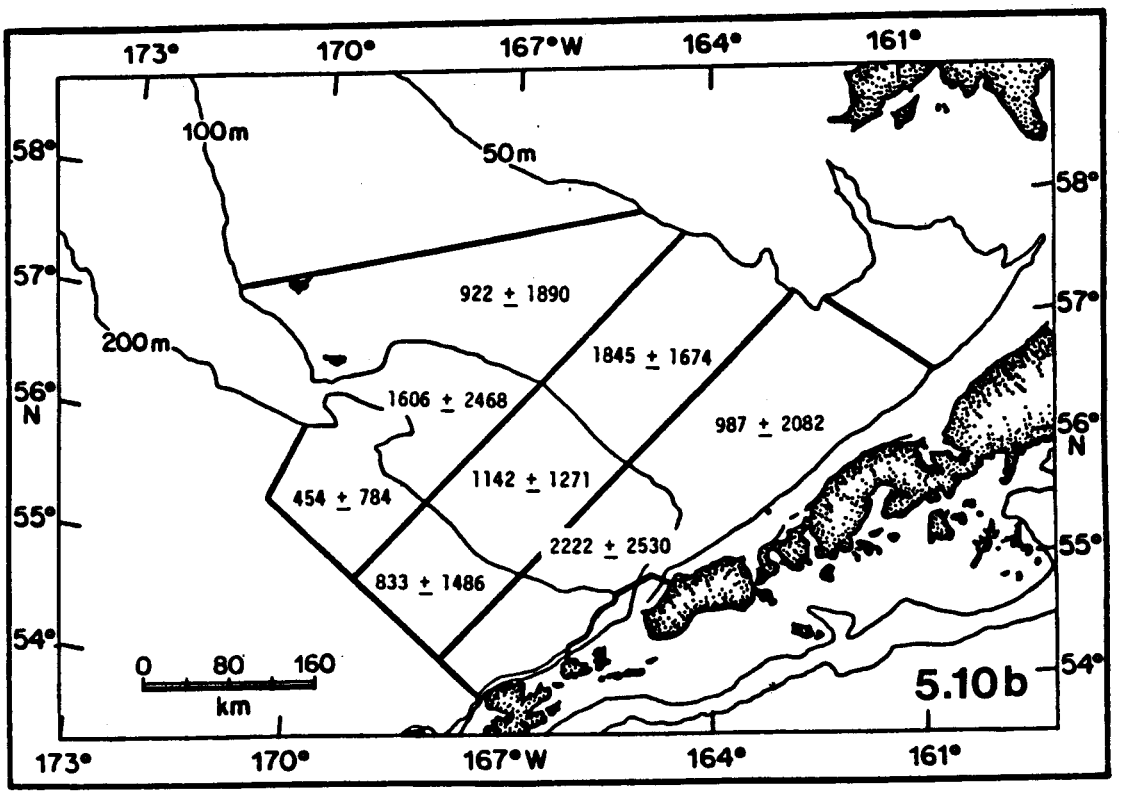
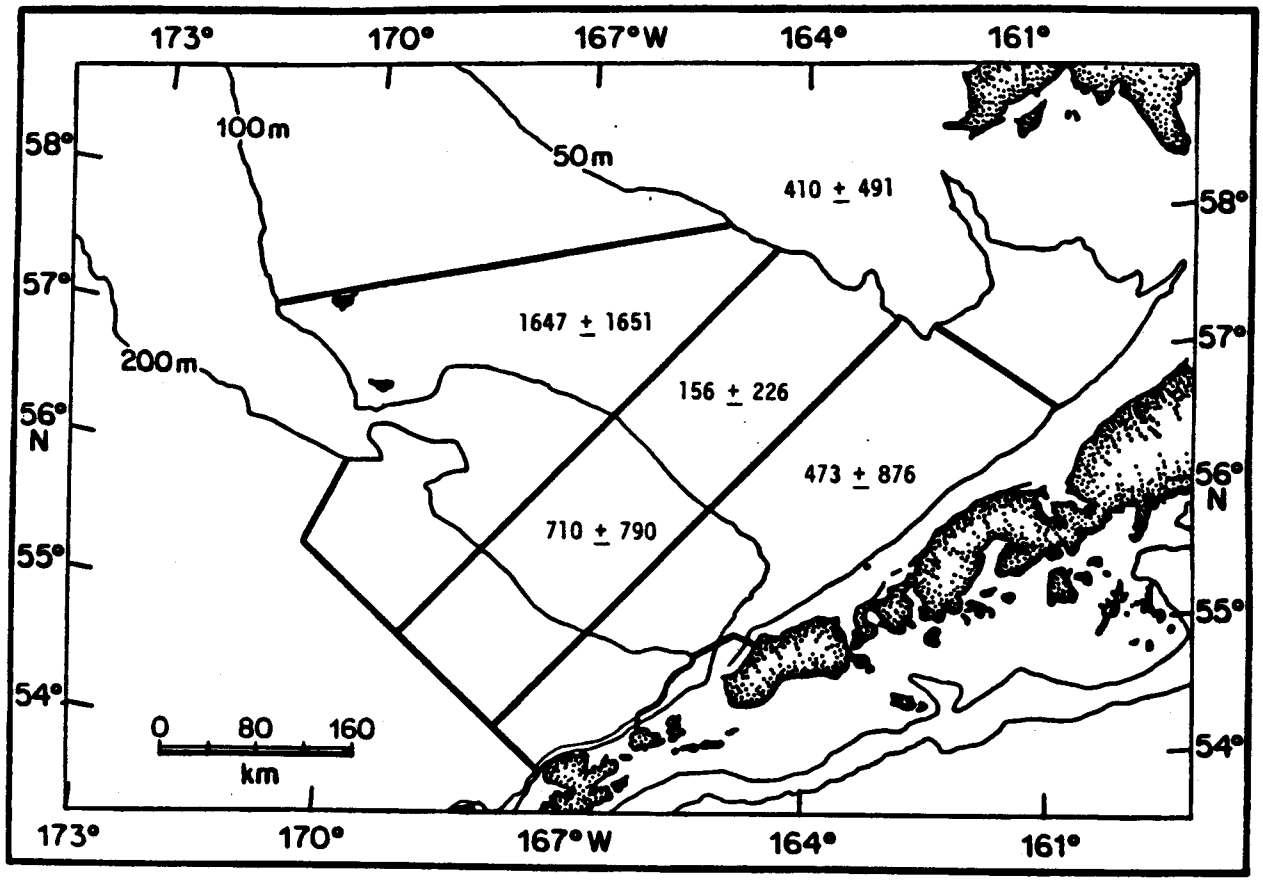
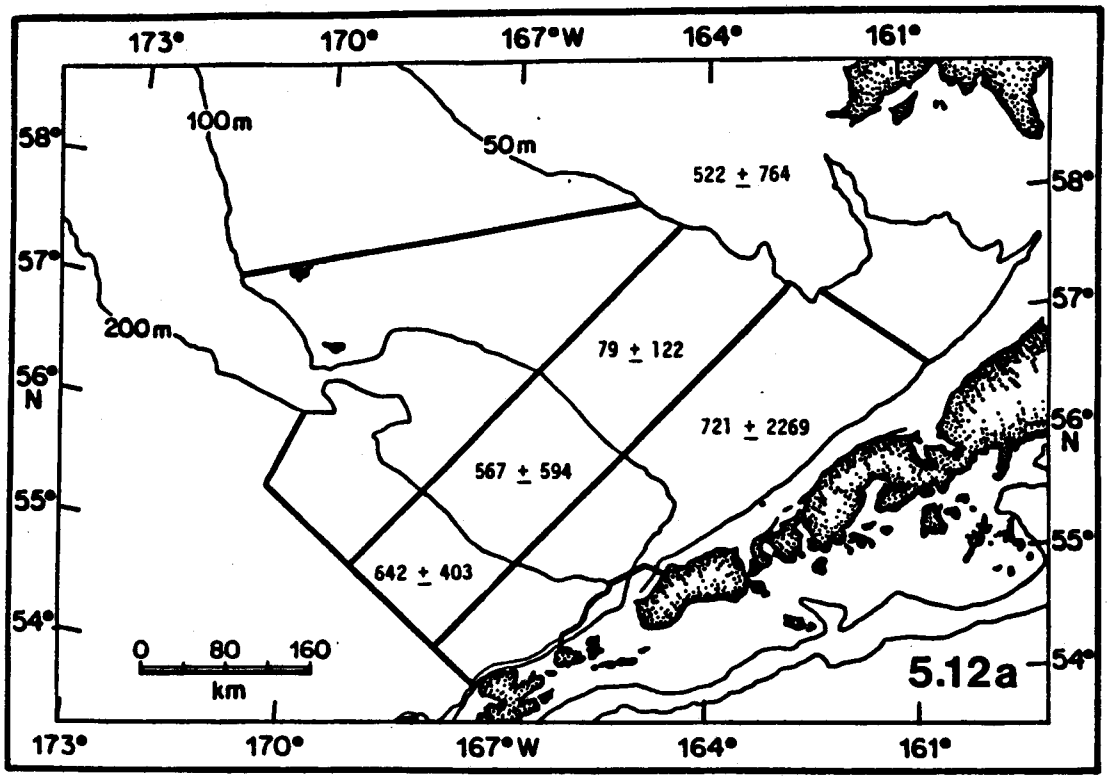


Figure 5.10 Distribution of mean density with one standard deviation of non-Chionoecetes Oregoniinae larvae/100m^2 in the S.E. Bering Sea in April. (a) and May and June (b) of 1978. Means were calculated with zeros for stations at which no larvae were found and for only those strata in which the number of samples collected during these time periods was ≥ 5.



5.11 Distribution of mean density with one standard deviation of non-Chionoecetes Oregoniinae larvae/100m^2 in the southeastern Bering Sea in May and June of 1980. Means were calculated with zeros for stations at which no larvae were found and for only those strata in which the number of samples collected during this time period was $\geq$ 5.



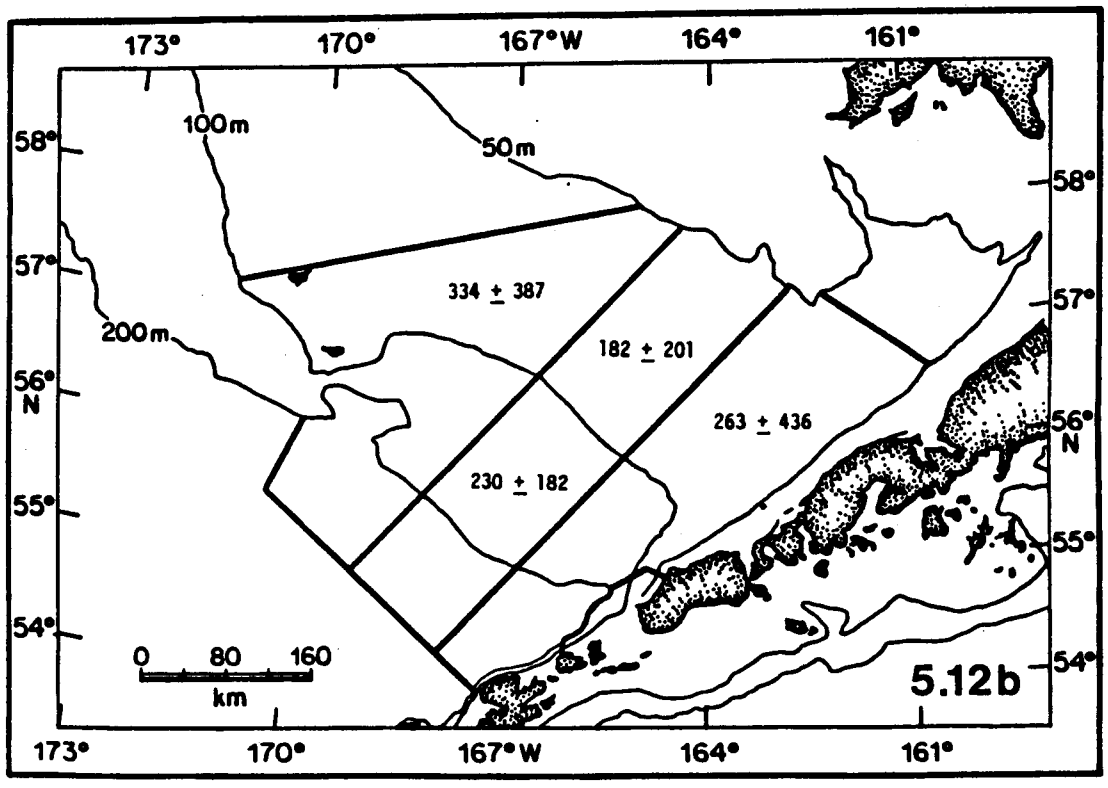


Figure 5.12 Distribution of mean density with one standard deviation of non-Chionoecetes Oregoniinae larvae/100m^2 in the S.E. Bering Sea in May and June (a) and July (b) of 1981. Means were calculated with zeros for stations at which no larvae were found and for only those strata in which the number of samples collected during these time periods was $\geq$ 5.

hints at the species' response to adverse conditions that might be exacerbated by oil pollution.

Summary

1) Oregoniinae larvae were encountered at 42% of the stations sampled during this study.

2) The taxon is widely distributed over the southeastern Bering Sea, although densities appear to be greater seaward of the 100 m isobath over the outer shelf regime and shoreward near Unimak Island.

3) Densities varied between areas within a year. Hatching may occur earlier in April over strata of the middle shelf and in May over the outer shelf.

4) Interannual comparisons showed that larval density was similar in 1980 and 1981, which were both low years compared to 1978.

5.3.2.3 Pinnotheridae

Seasonal Occurrence: Zoeae of this family were present for the total length of the spring-summer sampling periods of the years 1976 to 1981, which was a period of 14 weeks (Fig. 5.3). Because individual zoeal stages of the Pinnotheridae could not be identified, the seasonal occurrence of all zoeal stages combined is represented. Megalops larvae of this taxon appeared one year in late-June.

Distribution and Density: Considering the wide geographic range over which zooplankton samples were collected between 1976-1981, Pinnotheridae are more narrowly distributed than some other taxa. They were found

at 21% of all stations sampled and greatest densities were found on both sides of the 100 m isobath from St. George to Unimak islands (Fig. 5.13). Densities were also high near Amak Island between Bechevin Bay and Izenbek Lagoon. Considering the relationship between this family of crab and bivalve molluscs, larval crab distribution is somewhat in accord with infaunal distribution and abundance of bivalves in the southeastern Bering Sea (McDonald et al. 1981). The frequency-of-occurrence of pinnotherid larvae within strata is shown in Table 5.7 and reflects high abundance in strata 2, 5, and 6.

The pattern of larval distribution shown in Figure 5.13 was further analyzed by averaging larval densities within depth intervals of 50-74 m, 75-125 m, 126-200 m and > 200 m for the years 1978, 1980 and 1981 (Figs. 5.14 a, b, c). Most larvae occurred between 75-125 m where mean densities in 1978 ranged from 2178 to 10,603 larvae/100 m^2 (Fig. 5.14a). There was an obvious drop in larval density both shallower and deeper than this depth interval in all years analyzed (Figs. 5.14 a, b, c), where densities were zero to a few hundred larvae/100 m^2. Interannual differences in density during May/June were difficult to assess but there is an indication of reduced density in the 75-125 m interval of strata 1 and 2 in 1980 and 1981 (about 200 larvae/100 m^2; Figs. 5.14 b and c) compared to 1978 (2178/100 m^2).

Summary

1) Pinnotheridae larvae were collected at 21% of all the stations sampled during 1976-1981.

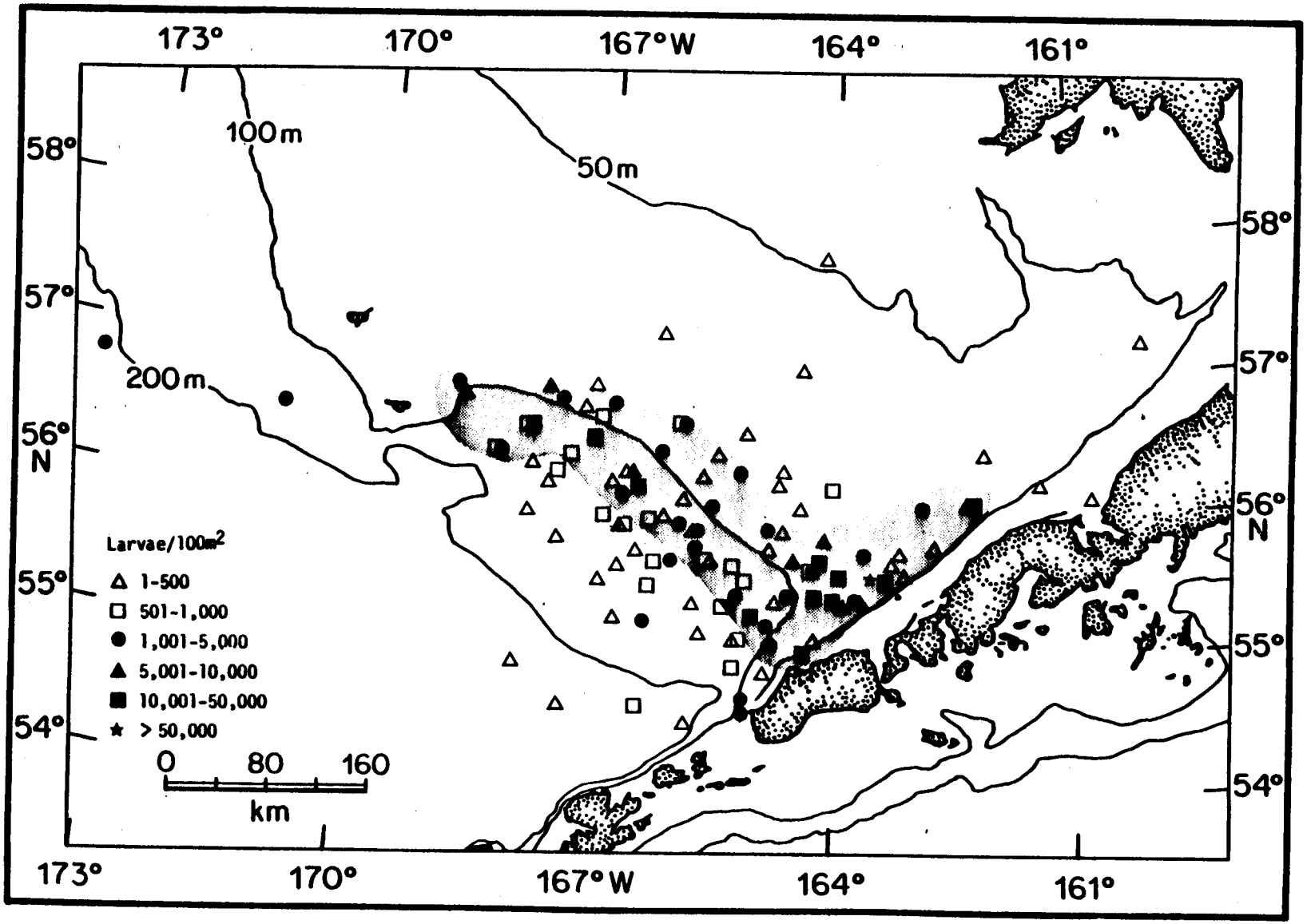
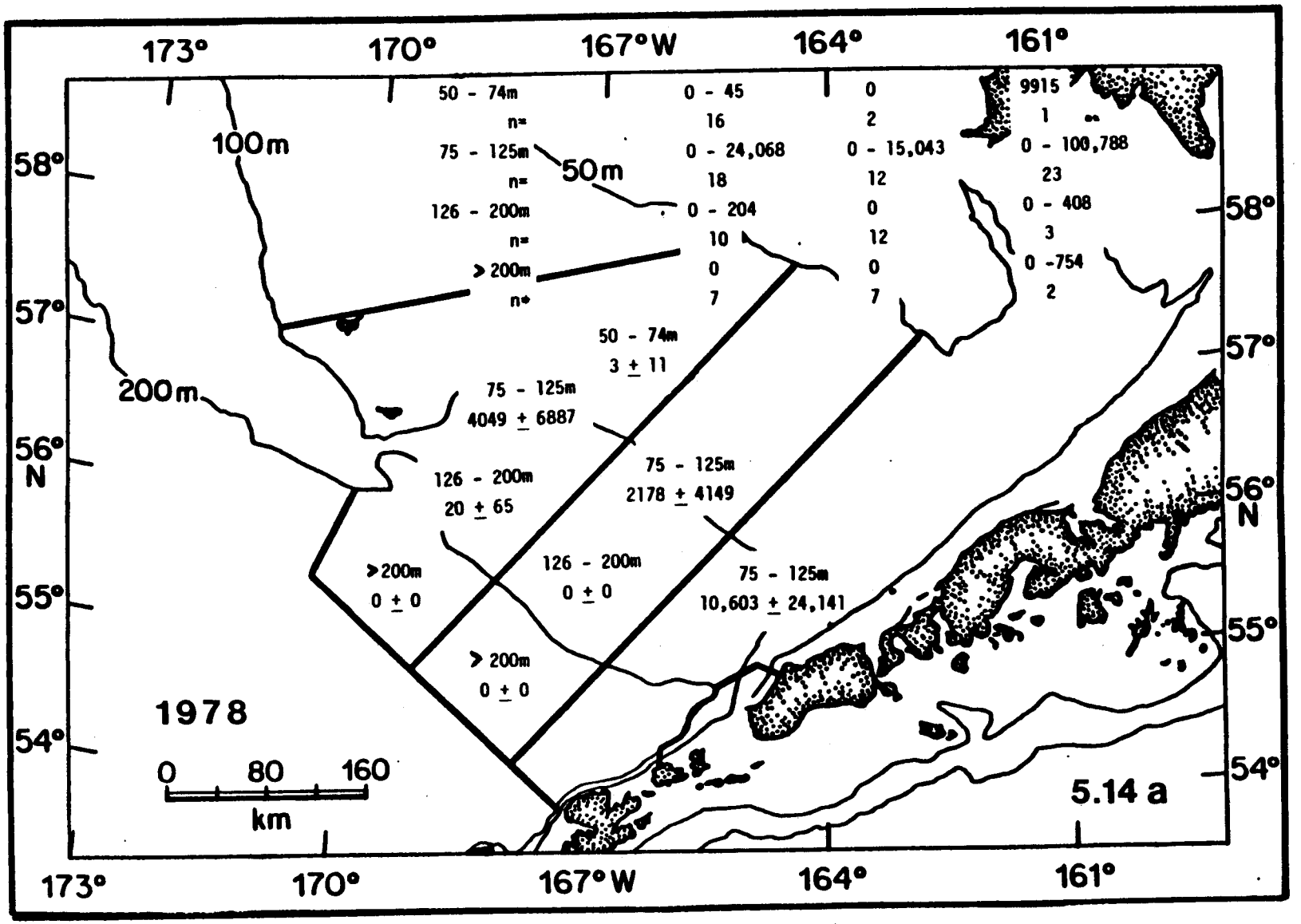


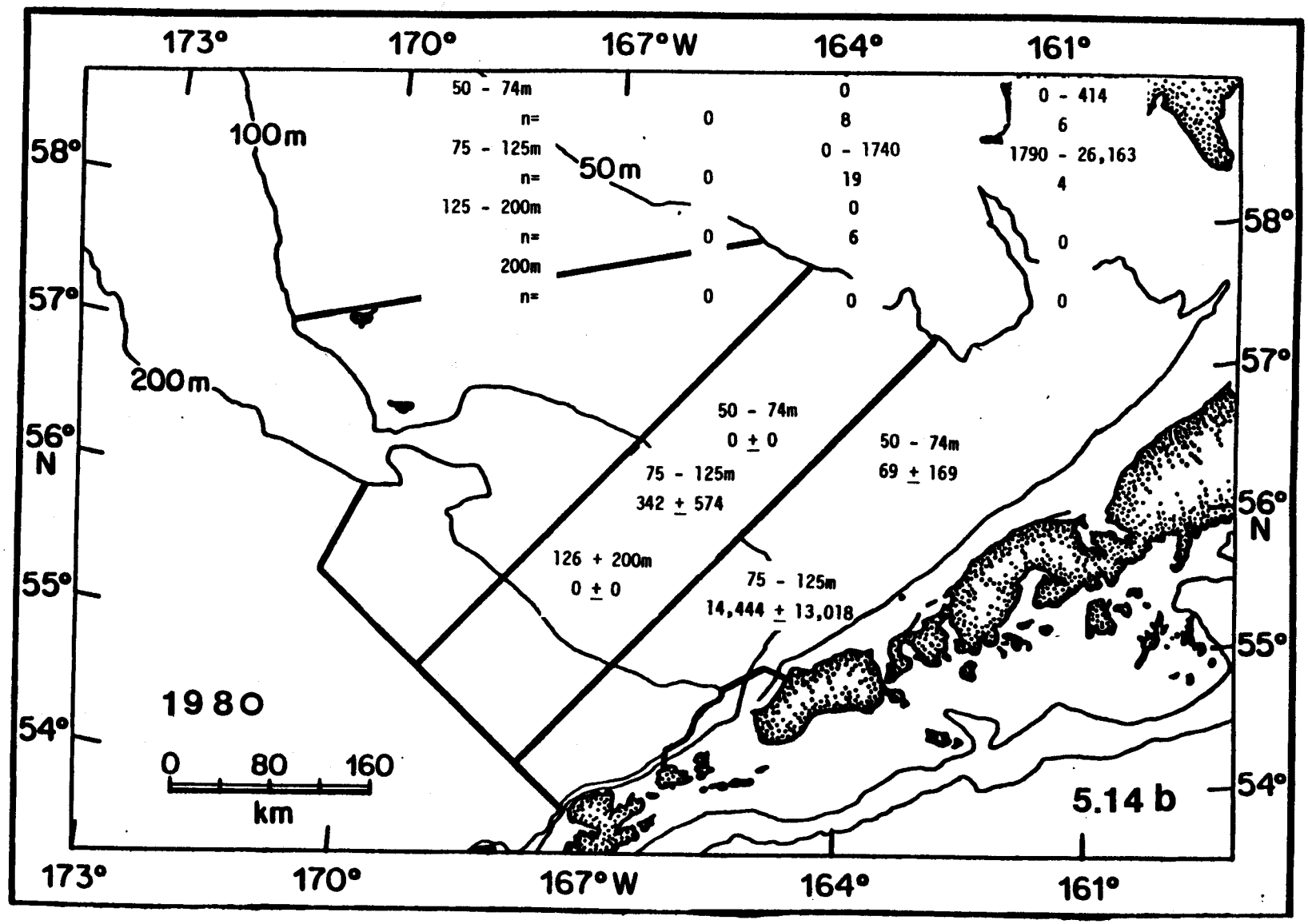
Figure 5.13 Locations and densities of Pinnotheridae larvae collected in the southeastern Bering Sea in the years 1976-1981. Locations where no larvae were found were omitted, but all station locations for these years are illustrated in Figures of Section 2.0.

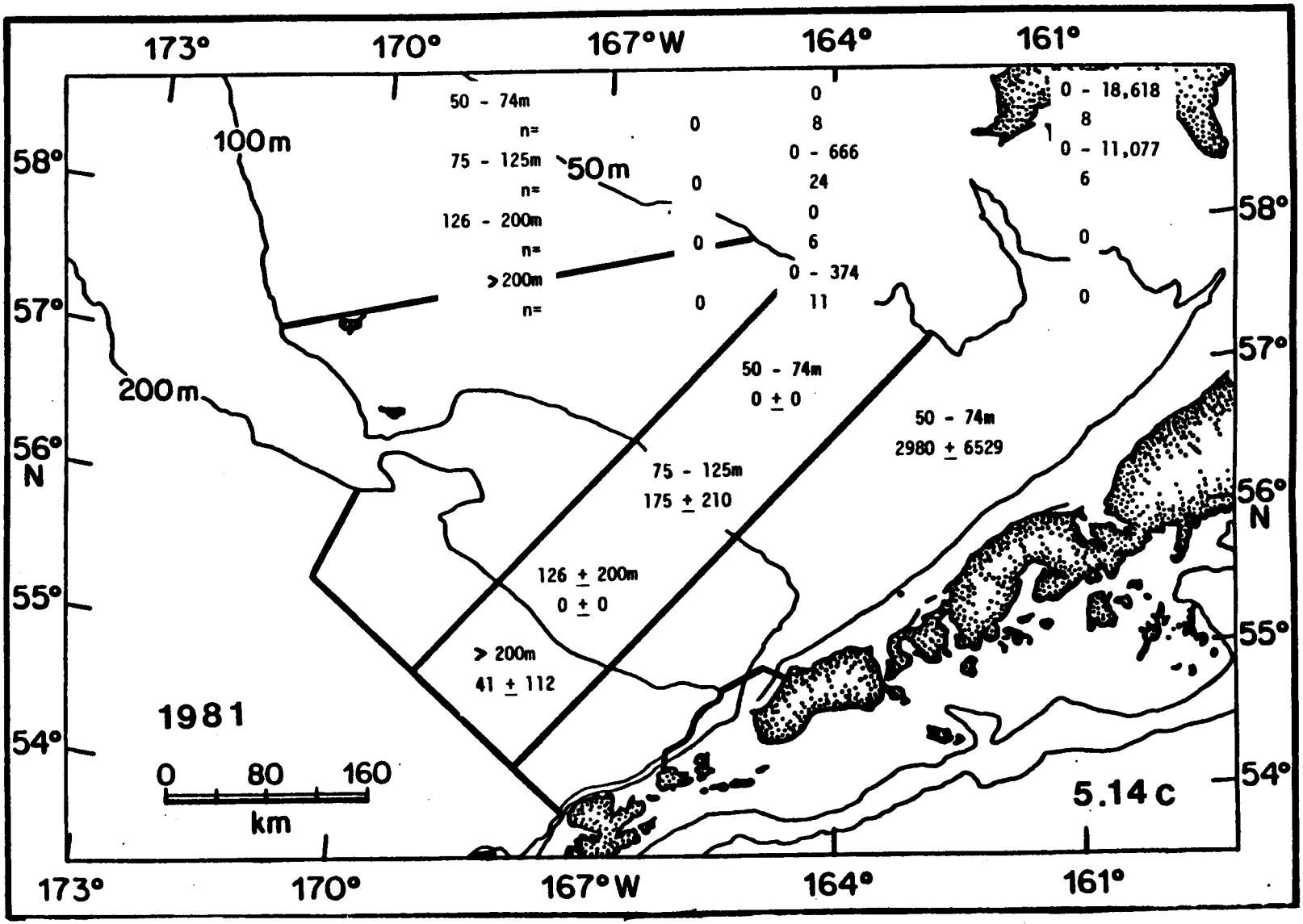
Table 5.7. Frequency of occurrence (percent) within a stratum of Pinnotheridae larvae in May and June of the years 1977-1981 combined.

Stratum number	Frequency of occurrence within each stratum (percent)
1	25
2	38
3	8
4	18
5	57
6	67
7	8
8	20
9	18
10	5
11	25
12	33

Figure 5.14 Cross and long-shelf pattern of mean density with $\pm$ one standard deviation of Pinnotheridae larvae/100 m^2 in the southeastern Bering Sea in May and June of 1978(a), 1980(b) and 1981(c). The depth interval for which means were calculated are listed above each mean in the general vicinity of their occurrence; while the range of density and the number of samples, n, collected at each interval are listed above each region. Means include both zero and positive stations. Only those depth intervals in which the number of positive samples collected is $\geq$ 4 (n) are included.


173°
170°
167°W
164°
161°
58°
57°
56°
N
55°
54°
100m
50m
200m
50 - 74m
n=
75 - 125m
n=
126 - 200m
n=
> 200m
n=
0 - 45
16
0 - 24,068
18
0 - 204
10
0
7
0
2
0 - 15,043
12
0
12
0
7
9915
1
∞
0 - 100,788
23
0 - 408
3
0 -754
2
50 - 74m
3 ± 11
75 - 125m
4049 ± 6887
126 - 200m
20 ± 65
>200m
0 ± 0
75 - 125m
2178 ± 4149
126 - 200m
0 ± 0
75 - 125m
10,603 ± 24,141
> 200m
0 ± 0
1978
0 80 160
km
5.14 a


173°
170°
167°W
164°
161°
58°
57°
56°
N
55°
54°
100m
50m
200m
50 - 74m
n=
0
0 - 1740
0 - 414
6
75 - 125m
n=
0
19
1790 - 26,163
4
125 - 200m
n=
0
0
6
0
200m
n=
0
0
0
50 - 74m
0 ± 0
75 - 125m
342 ± 574
126 + 200m
0 ± 0
50 - 74m
69 ± 169
75 - 125m
14,444 ± 13,018
1980
0
80
160
km
5.14 b


173°
170°
167°W
164°
161°
58°
57°
56° N
55°
54°
100m
200m
50m
50 - 74m
n=
75 - 125m
n=
126 - 200m
n=
>200m
n=
0
0
0
0
0
8
0 - 666
24
0
6
0 - 374
11
0 - 18,618
8
0 - 11,077
6
0
0
50 - 74m
0 ± 0
75 - 125m
175 ± 210
126 ± 200m
0 ± 0
> 200m
41 ± 112
50 - 74m
2980 ± 6529
1981
0 80 160
km
5.14c

2) In May and June of all years combined, the majority of these larvae were distributed between the 75 and 125 m depth interval.

3) A significantly higher mean density of larvae was found in water 75-100 m deep in the eastern region of the southeastern Bering Sea during May and June of the year 1978 than in 1980 or 1981.

4) High densities ranging from 13,675 to 100,788 were found in May and June throughout the major area of distribution in the years 1978, 1980, and 1981.

5.3.2.4 Cancer spp.

Seasonal Occurrence: The six larval stages of Cancer spp. appeared in the plankton samples collected in the years 1976 to 1981 combined from mid-April to early-October, which is a period of 24 weeks (Fig. 5.3). Individual larval stages were collected during this time period as follows: SI, from mid-April to mid-July; SII, from late-April to mid-July; SIII from early June to mid-July and October; SIV in mid-July; SV in late-June, mid-July and October, and megalops larvae in late-June and October.

Distribution and Density: Larvae were found in 13% of all samples sorted from 1976-1981. The frequency-of-occurrence was highest in strata 4, 5, and 12 (73%, 57%, and 67%, respectively) and was low in all others (Table 5.8). Cancer larvae were most abundant near Unimak Island and over the shelf break west of Unimak Pass (Fig. 5.15). High densities along western Unimak Island was likely due to larvae of Cancer oregonensis where adults are common in rocky cobble substrate, and larvae in

Table 5.8. Frequency of occurrence (percent) within each stratum of *Cancer* spp. larvae in May and June of the years 1976-1981. Depicted is the percent of all stations within each stratum at which *Cancer* spp. were found.

Stratum number	Frequency of occurrence within each stratum (percent)
1	2
2	25
3	19
4	73
5	57
6	18
7	0
8	3
9	0
10	5
11	13
12	67

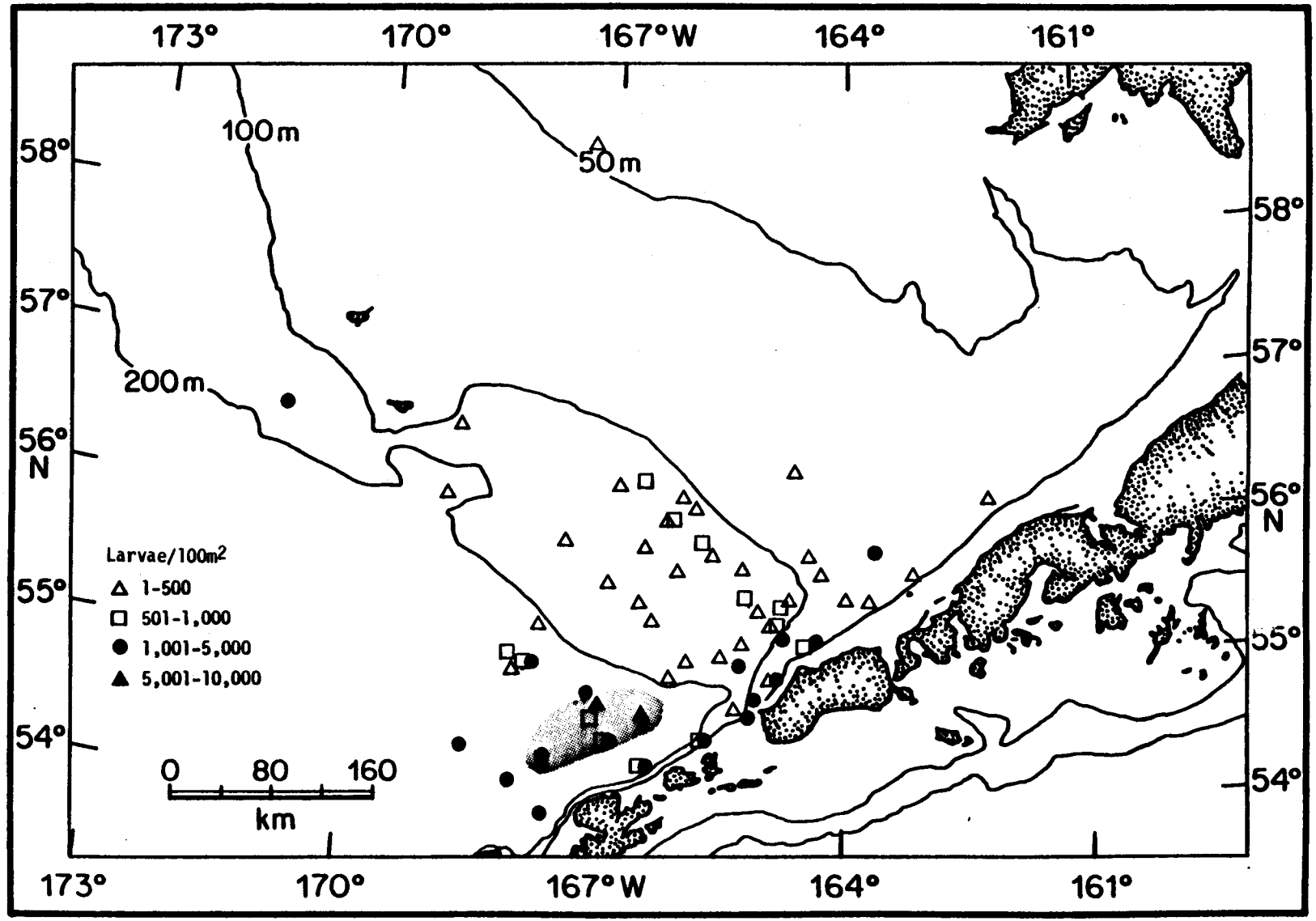


Figure 5.15 Locations and densities of Cancer spp. larvae collected in the southeastern Bering Sea in the years 1977-1981. Locations where no larvae were found were omitted, but all station locations for these years are illustrated in Figures of Section 2.0.

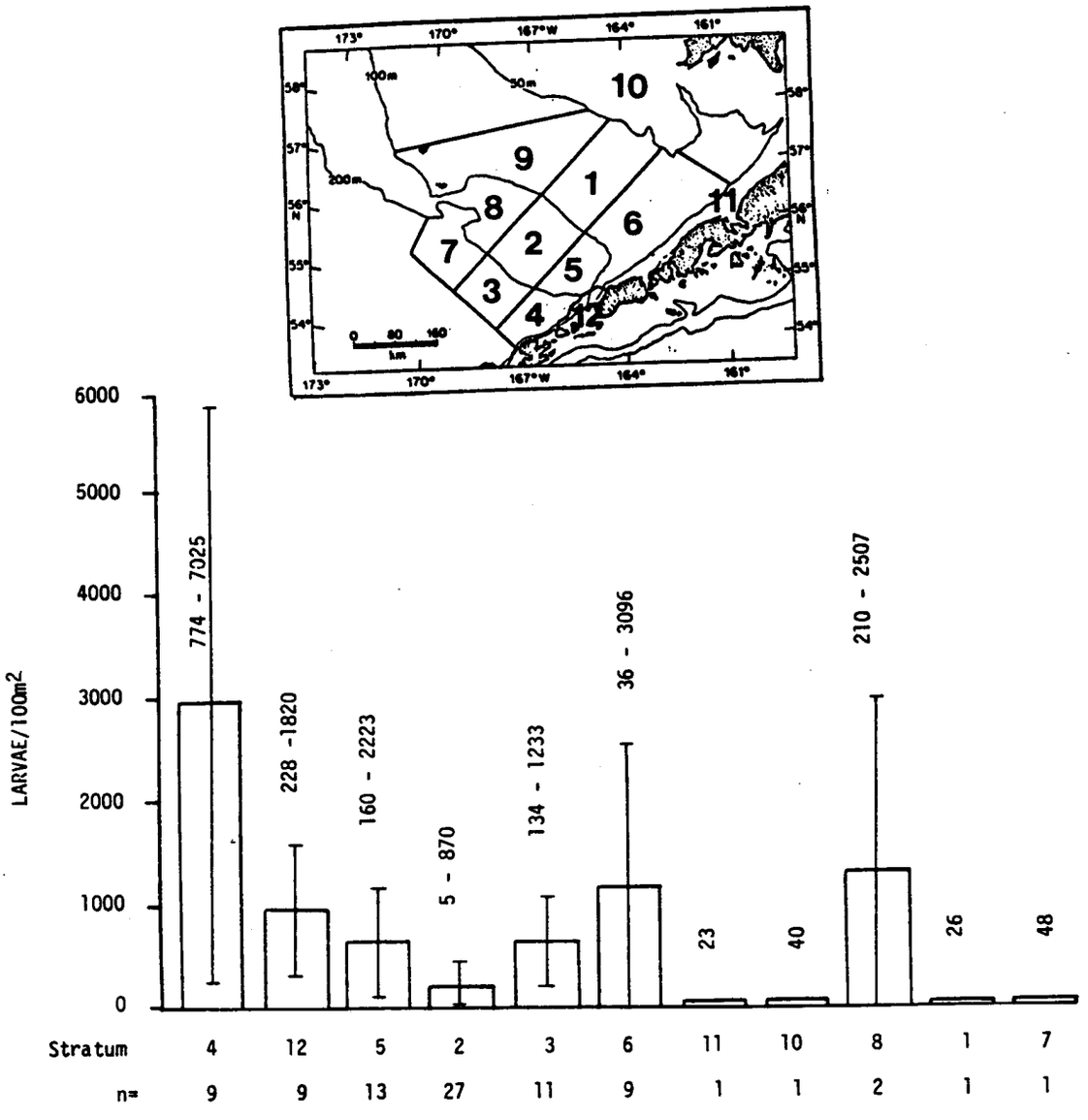


Figure 5.16 Mean density and one standard deviation of Cancer spp. larvae in the southeastern Bering Sea for all years, 1977-1981, combined. The range of densities from which these means were calculated are listed above each corresponding bar; while the number of samples used to calculate each mean, n, are listed on the lower axis.

excess of 100,000/100 m^2 were found in 1982 (Armstrong, unpublished data).

Mean densities calculated by stratum were highest in stratum 4 (about 3000/100 m^2) and less, but comparable, in strata 3, 5, 6, 8, and 12 (about 500-1100 m^2) (Fig. 5.16). The highest single density of 7025 larvae/100 m^2 occurred in stratum 4.

Summary

1) Cancer spp. larvae were collected at 13% of all stations sampled during this study.

2) Larvae were generally most abundant nearshore of Unimak Island and west over the shelf break.

3) The highest density found was over 7000/100 m^2 but means between 1000-3000/100 m^2 were more typical of high abundance areas.

5.3.2.5 Telemessus cheiragonus

Seasonal Occurrence: These larvae were collected in the plankton from late-April to late June, a total period of 10 weeks, when data were combined from the years 1977-1981 (Fig. 5.3). Individual larval stages were present during these sampling periods as follows: SI in mid-May; SII in mid-April, mid-May, and late-June; SIII in late-May and late June; SIV in mid-May and early-June; and SV in early and mid-May. Megalops larvae were never observed in the plankton samples of this study.

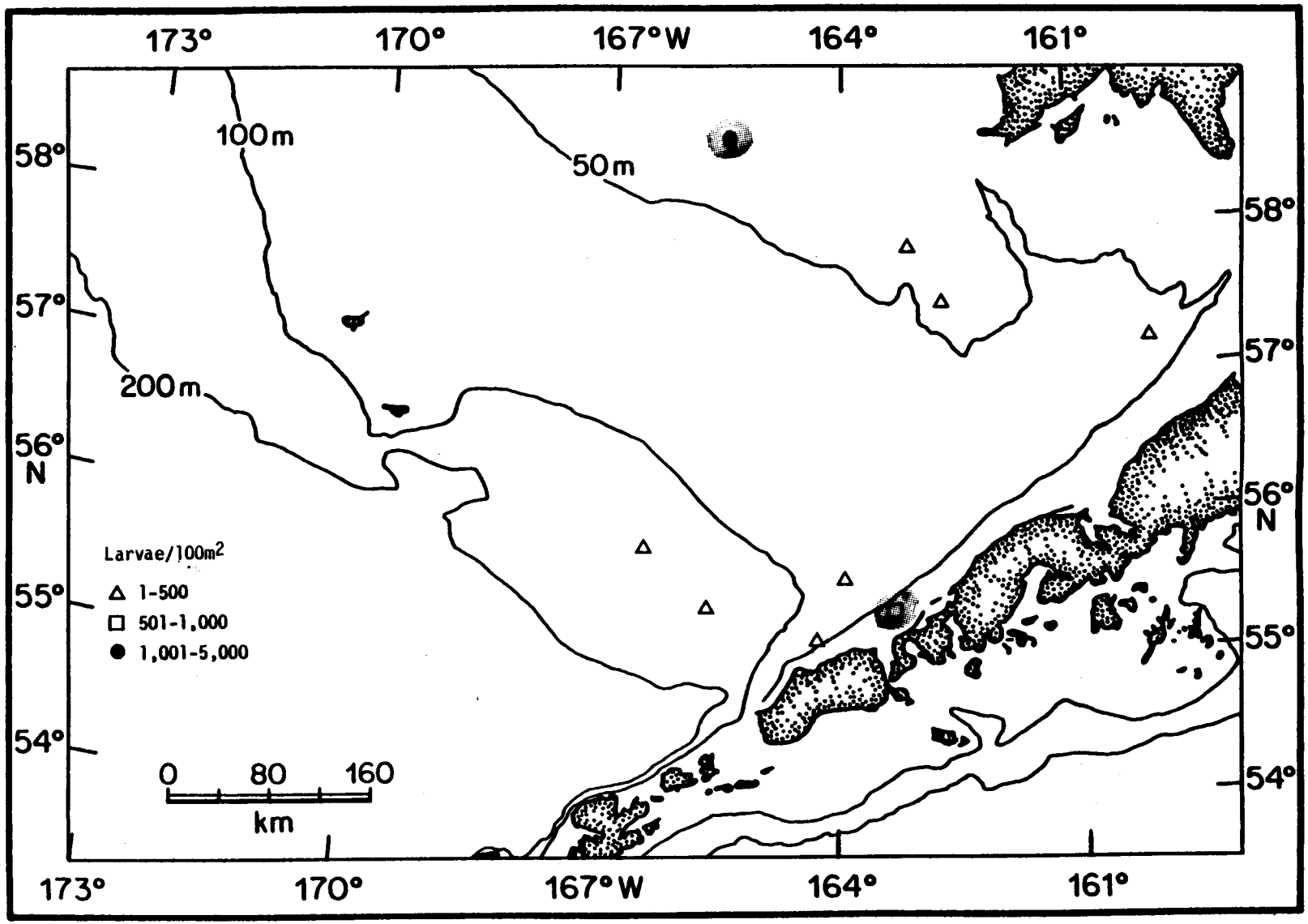


Figure 5.17 Locations and densities of Telmessus cheiragonus larvae collected in the southeastern Bering Sea in the years 1976-1978 and 1981. Locations where no larvae were found were omitted, but all station locations for these years are illustrated in Figures of Section 2.0.

Table 5.9. Frequency of occurrence (percent) of Telmessus cheiragonus larvae within each stratum in May and June of the years 1976-1981 combined.

Stratum number	Frequency of occurrence within each stratum (percent)
1	0
2	1
3	0
4	0
5	5
6	7
7	0
8	0
9	0
10	14
11	13
12	0

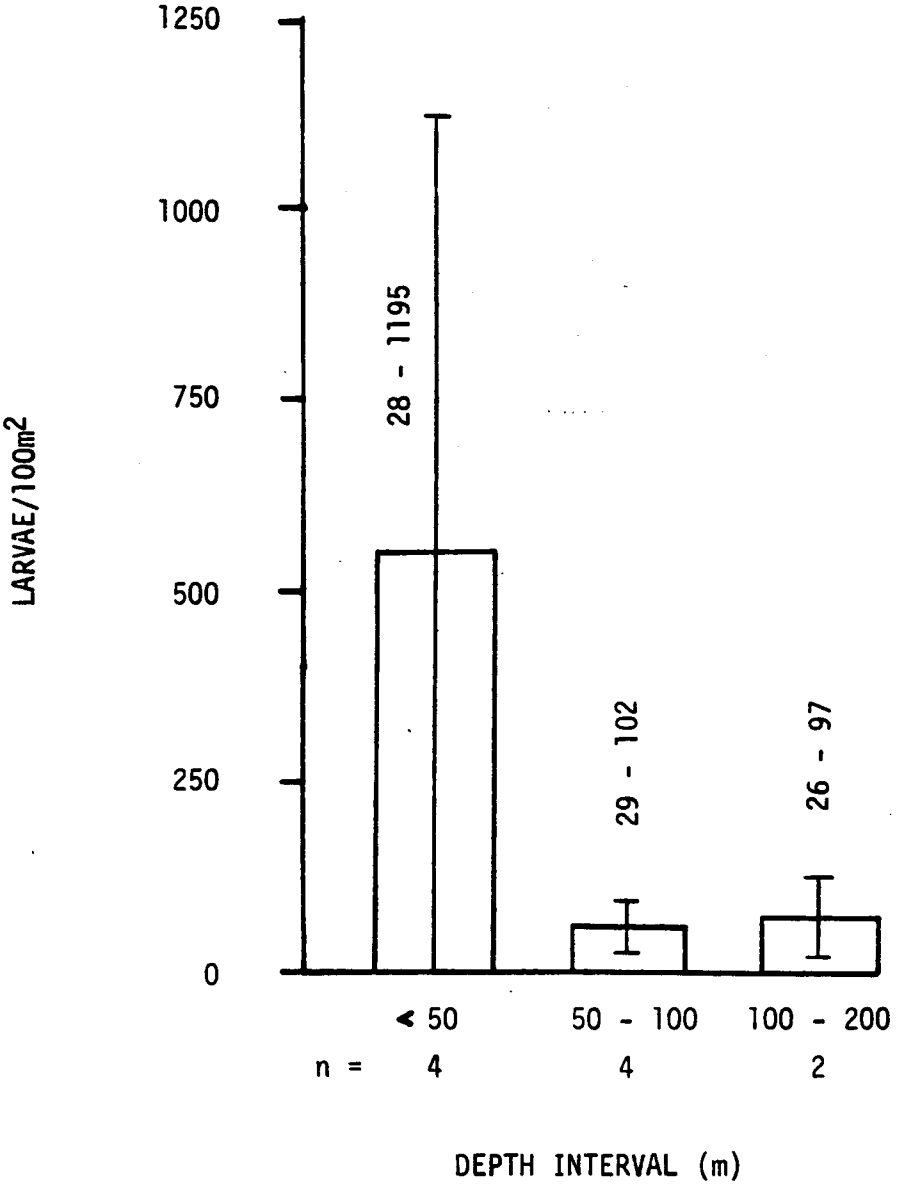


Figure 5.18 Mean density and one standard deviation of Telmessus cheiragonus larvae collected at stations with water depths ranging from <50-200 m in the southeastern Bering Sea for all years, 1976-1981, combined. The range of densities from which these means were calculated are listed above each corresponding bar; while the number of samples used to calculate each mean, n, are listed on the lower axis. Stations at which no larvae were found were not used in calculating the mean density of Telmessus cheiragonus.

Distribution and Abundance: Larvae of the species were found in only 2% of all stations, the lowest percentage of all non-Chionoecetes Brachyura taxa studied. This is reflected by the low frequency-of-occurrence within each stratum that never exceeded 14% (Table 5.9). Little can be said of their distribution other than the surprising scarcity (Fig. 5.17). Since Izembek Lagoon is known to support large populations of adults (McRoy 1966), higher larval densities in that area were expected. However, the majority of all larvae found were at stations less than 50 m deep nearshore (Fig. 5.18), where the mean density was 552/100 m^2. The highest single density found was 1195 larvae/100 m^2.

Summary

1) Larvae were only collected at 2% of all stations sampled during 1976-1981.

2) No larvae were collected in water deeper than 200 m, near the Pribilof Islands or in the central region of the middle shelf.

3) Distribution and density appear related to depth since the highest relative frequency-of-occurrence and the highest relative mean density of these larvae were found in water shallower than 50 m.

5.3.2.6 Acanthonychinae and Pisinae

Seasonal Occurrence: Larval stages of these subfamilies were found in the plankton from late-April to mid-July, a total period of 12 weeks, when their appearance in all the sampling periods of the years 1976 to 1981 were combined (Fig. 5.3). Individual larval stages were present during these sampling periods as follows: SI, from late-April to

early-June; SII from early-June to mid-July and the megalops larvae from mid-June to mid-July.

Distribution and Density: Larvae were collected in 5% of all samples, most in stratum 12 at the western tip of Unimak Island (Table 5.10 and Fig. 5.19). Larvae of the taxa were rarely found in the water deeper than 200 m and never near the Pribilof Islands. Mean densities were low, less than 500 larvae/100 m^2 in all of the eight strata where they were found (Fig. 5.20). The highest density found was 1536/100 m^2 in stratum 12 and the lowest was 13/100 m^2 in stratum 2.

Summary

1) Larvae were only collected at 5% of all stations sampled during this study.

2) No larvae were collected near the Pribilof Islands.

3) The stratum with the highest relative frequency of occurrence of larvae and at their greatest density was stratum 12, Unimak Pass.

Table 5.10. Frequency of occurrence (percent) of larvae of the subfamilies Acanthonychinae and/or Pisinae within a stratum in May and June of the years 1976-1981.

Stratum number	Frequency of occurrence within each stratum (percent of total stations)
1	0
2	11
3	3
4	18
5	19
6	4
7	8
8	0
9	0
10	5
11	0
12	83

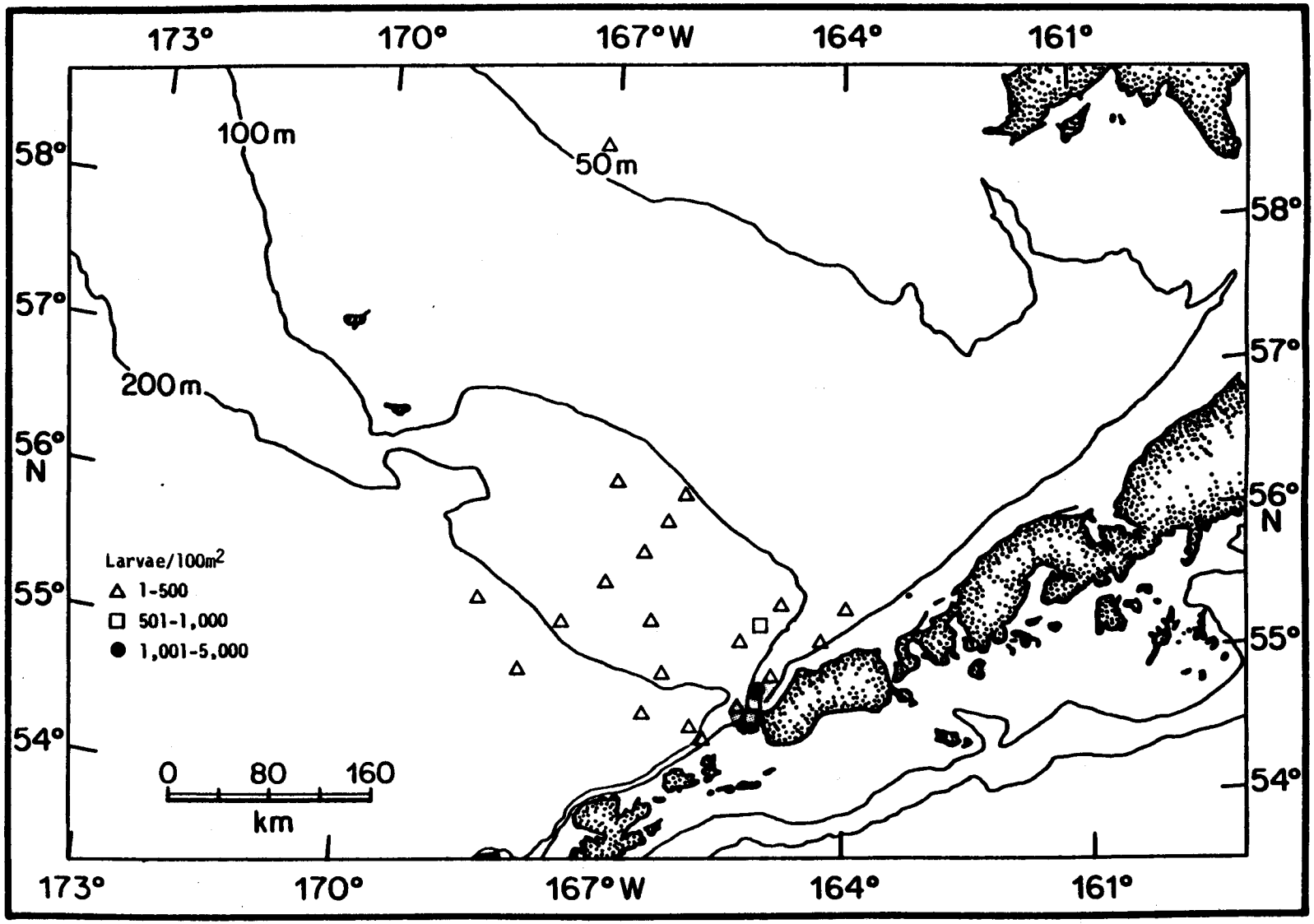


Figure 5.19 Locations and densities of Acanthonychinae and/or Pisinae larvae collected in the southeastern Bering Sea in the years 1976-1981. Locations where no larvae were found were omitted, but all station locations for these years are illustrated in Figures of Section 2.0.

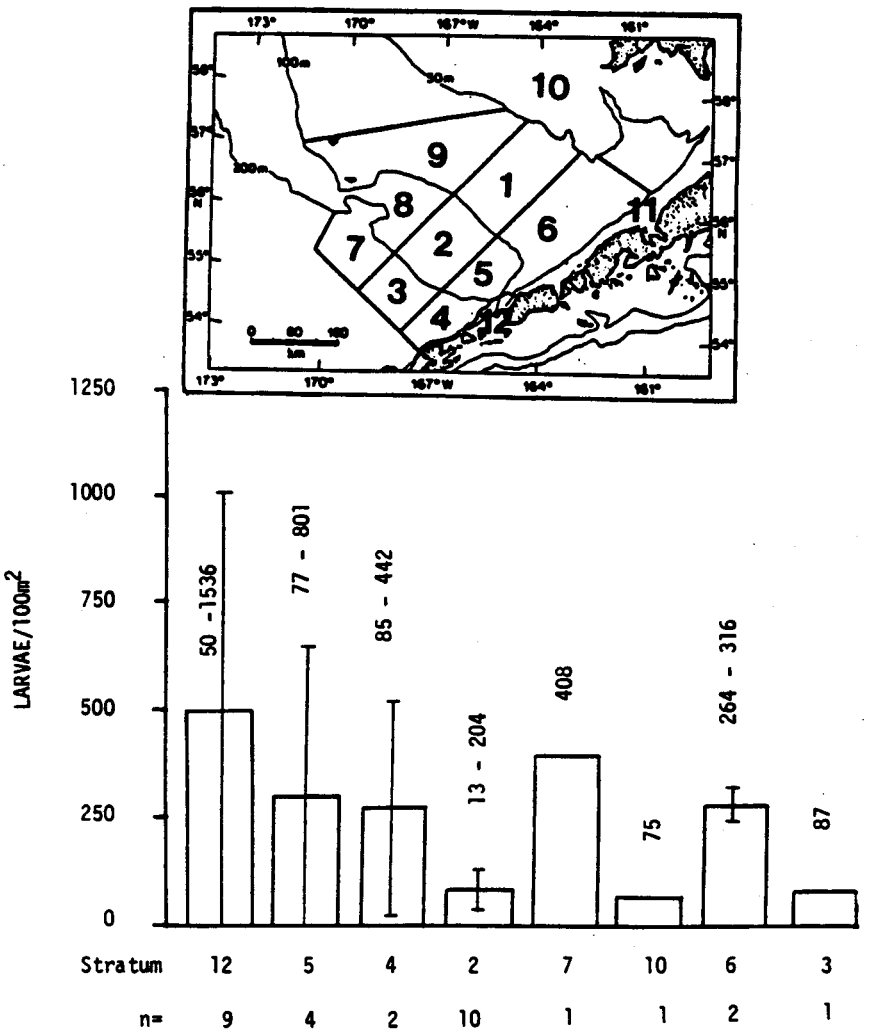


Figure 5.20. Mean density and one standard deviation of Acanthonychinae and/or Pisinae larvae in the southeastern Bering Sea for all years, 1976-1981, combined. The range of densities from which these means were calculated are listed above each corresponding bar; while the number of samples used to calculate each mean, n, are listed on the lower axis. Stations at which no larvae were found were not used in calculating the mean density of Acanthonychinae and/or Pisinae larvae.

6.0 DISTRIBUTION AND ABUNDANCE OF SHRIMP LARVAE IN THE SOUTHEASTERN BERING SEA WITH EMPHASIS ON PANDALID SPECIES

Janet Armstrong

6.1 Introduction

Bering Sea shrimps, suborder Natantia, belong to at least six families of decapod crustaceans. In addition to the commercially important family Pandalidae, represented by 5 species in the southeastern Bering Sea, other families are Hippolytidae and Crangonidae (Butler 1980), and possibly a species of the family Penaeidae (K. Coyle, U. of Alaska, IMS - personal communication). Feder and Jewett (1980) give an extensive list of the adult species found in this area that includes members of the families Oplophoridae and Pasiphaeidae. (From all samples sorted to date only a single oplophorid larva was found and these families are thus of no consequence in this report.) Butler's monograph (1980) on Pacific Coast shrimp gives ranges for many adults which were added to Feder's list (see Appendix A).

Pandalidae are the only shrimp of direct commercial importance and have thus received most attention in the literature. Thorough larval descriptions for pandalid populations of different geographic locations are given by Berkeley (1930) for British Columbia, Pike and Williamson (1962) for the North Sea, Kurata (1964c) for Hokkaido, Japan, and Rothlisberg (1980) for the Pacific northwest coast (see Appendix B for complete list of references on larval shrimp). For identification of Bering Sea pandalid larvae the following comprehensive species descriptions were used:

Pandalus borealis - Haynes 1979
Pandalus goniurus - Haynes 1978a
Pandalus montagui tridens - Haynes 1980
Pandalus stenolepis - Needler 1938
Pandalopsis dispar - Berkeley 1930

6.2 Pandalidae

6.2.1 Pandalus borealis: Life History and General Biology

Distribution: P. borealis, an amphiboreal species, ranges from Point Barrow, Chukchi Sea southwest through the Okhotsk Sea to the Sea of Japan and Korea, and southeast throughout the Bering Sea and Gulf of Alaska to the mouth of the Columbia River. In addition it is found in the Barents Sea, the North Sea, and from the Gulf of Maine to western Greenland in 16-1380 m depths (Butler 1980). P. borealis is thought to be the bridge species between the Atlantic and Pacific Ocean pandalid groups (Rasmussen 1967). Fishable populations occur between 54-400 m depths (Ronholt 1963), but the species is often dominant between 70-150 m at the outer edge of the continental shelf where bottom temperatures range between 1.8°-3.8°C (Ivanov 1969). Post-larval stages can tolerate a wide temperature range from -1.68° to 11.13°C (Allen 1959) while larvae can survive an upper limit of 14°C (Poulsen 1946 in Butler 1971). Haynes and Wigley (1969) describe P. borealis preference for soft mud, sand and silty substrates with relatively high organic content (0.5-1.5% organic carbon) in the Gulf of Maine. Survival is optimal at salinities from 25.9 to 35.7°/$_{oo}$ (Allen 1959; Butler 1964).

Reproduction: Like all Alaskan pandalid shrimp, P. borealis are protandric hemaphrodites (Berkeley 1930). Animals first achieve sexual

maturity as males at age 3.5 years in the Bering Sea and remain breeding males for two seasons. After a transitional period they subsequently develop female characteristics by 5.5 years (Ivanov 1969; Butler 1971). Females can mature early and circumvent the male phase entirely in populations found in southern parts of the range (Allen 1959; Butler 1964), but this event has not been recorded in the Bering Sea (Ivanov 1969). Rasmussen (1967) gives comparative reproductive data for Norwegian populations and Haynes and Wigley (1969) summarize this information, adding data on ovigery for Maine shrimp. Sexual development is hormonally controlled and has been studied by Carlisle (1959). Table 6.1 compares life history data of P. borealis and other pandalid species.

Colder water temperatures of the Bering Sea slow growth and development, extend the ovigerous period, and greatly determine the seasons of spawning and hatching (Butler 1971). The normal life span for P. borealis in the S.E. Bering Sea can be up to 6 1/2 years (Ivanov 1969) compared to 3 1/2-4 years for populations in the warmer water (North Sea, Allen 1959; British Columbia, Butler 1964).

Ovarian development occurs in mature females (age 5 years) in the summer, followed by spawning from August to mid-September in the southeastern Bering Sea. Eggs are extruded, fertilized and carried on the pleopods through the winter and hatch from April through mid-May (NPFMC 1978). The average ovigerous period lasts from 7.5 to 9.5 months. Females from Kachemak Bay, Alaska carry approximately 914 eggs per clutch (Haynes and Wigley 1969), but a range of 300-3400 eggs, has been noted for different P. borealis populations world-wide (Allen 1959; Haynes and

Table 6.1. Comparison of life history and reproductive information for pandalid species.

	Depth preference (m)	Sexual maturity[1] Male (mm) Size	Age	Female (mm) Size	Age	Maximum age year	Reproduction Fecundity Eggs/clutch	Ovigerous period	Larval hatch
P. borealis[2,3]	90-120	120 TL 19.5 CL	3 1/2	150 TL 25 CL	5 1/2	6 1/2	914 1631 2150	Nov.-Mar.	Apr., May
P. goniurus[4,5]	38-124	62 TL 13 CL	1	78 TL 16.5 CL	2	2 1/2	2000	Nov.-Apr.	
P. tridens[4]	200-470	83 TL 15 CL	1 1/2	123 TL 22 CL	2 1/2-3	4		Nov.-Apr.	Apr.
P. stenolepis[4]		76 TL 14 CL		82 TL 18 CL				Nov.-Apr.	
Pandalopsis dispar[2,3,6]	>200	182 TL 31 CL	1 1/2	208 TL 36 CL	2-4	4	1129, 4150	All year	Mar. Apr.

References:
[1]Data represent average length and age.
[2]NPFMC: Fishery Management Plan and E.I.S. for the shrimp fishery in the Bering Sea, November 1978.
[3]McBride 1974 - Kachemak Bay Ak. stocks (unpublished).
[4]Butler, T. 1980 - Strait of Georgia, B.C. stocks.
[5]McLaughlin, P. 1963 - S.E. Bering Sea stocks.
[6]Hynes, F. 1930 - S.E. Alaska stocks.

Wigley 1969; Rasmussen 1953 from Butler 1971). No fecundity data are available for the southeastern Bering Sea. Stickney and Perkins (1980) are currently studying the fluctuating fecundity of Maine stocks of P. borealis which, after declining in the early 1970's, seem to be rebuilding. Horsted and Smidt (1956 from Butler 1980) report that a parasite Hemiarthrus abdominalis can cause as much as 50% reduction in the number of eggs carried by P. borealis females in the North Atlantic Ocean.

Larval Development: P. borealis has 5 planktonic zoeal stages and one megalops stage (often referred to as a "mysid" stage) before molting to a juvenile (Haynes 1979). Larvae grow from 6.7 mm mean total length at Stage I to 18.5 mm at the megalops stage. The average mean growth increment per molt is 2.36 $\pm$ 1.04 mm total length. Duration of planktonic life is approximately 3 months according to Berkeley (1930). In the North Sea, Allen (1959) found P. borealis molts as many as 14 times from larval metamorphosis to the male phase (from 21 to 93 mm total body length). At age 1.5 years, the Pribilof stocks are all immature males with a carpace length (CL) of 12-13 mm (Ivanov 1969). At age 2.5 years (CL = 18-19 mm) some shrimps become sexually mature males and participate in autumn breeding for the first time. Allen (1959) found that 5 molts are necessary before males exhibit mature sex characteristics. Most shrimp in the 3+ and 4+ age classes (CL = 22 mm and 25 mm, respectively) are breeding males with a small proportion as females. By 5.5 years of age (max CL = 27-32 mm) all shrimp are females. Few shrimp survive to 6.5 years and according to Ivanov (from NPFMC 1978), all at

this age are non-reproducing or sterile females. Usually females undergo 3 molts between ovigerous periods (if they produce more than one brood) but do not molt from the time the eggs are extruded until 2 weeks after the zoeae hatch. The majority of Bering Sea P. borealis have only one brood (Ivanov 1969) and it is this last age class (5.5-6.5 yr) that supports the fishery.

Food Habits: Food habits of zoeae were studied by Stickney and Perkins (1980). Preliminary findings indicate that diatoms may be a major food source for newly hatched zoeae in Maine and the timing of phytoplankton blooms may be crucial for early stage survival. Older larvae rely more on a zooplankton diet. Paul et al. (1978) performed prey density and feeding response experiments with Stage I (SI) P. borealis. Juvenile food habits received little attention. Adult diets consist of both benthic mollusks, detritus, small crustaceans, polychaetes, echinoderms, and protozoans, and pelagic copepods, euphausiids, mysids and other shrimp and crab larvae (Barr 1970; Butler 1971). Pelagic organisms are caught during diel vertical migrations when shrimp leave the bottom at dusk, disperse throughout the water column, and return to the bottom by dawn (Barr 1970).

Ontogenetic Migrations: Life stage and seasonal migrations of southeastern Bering Sea stocks are also assumed to occur. Stage I-III zoeae remain generally within the area of hatch but thereafter migrate to shallower water (46-64 m) where metamorphosis occurs and they spend their first summer as juveniles (Berkeley 1930, for Canadian stocks); thereafter they move to deeper water to join the adults. Ovigerous females in the

Gulf of Maine were found to move into shallower water as eggs developed (Haynes and Wigley 1969). Pribilof populations affected by winter cooling migrate 30-40 miles toward the outer shelf from 85-100 m depths to 95-120 m depths where temperature is warmer and more stable (Ivanov 1969).

Predators: Principal predators include many commercial fish species: Pacific cod, white pollock (Feder 1978), sand sole (Miller 1967), silver and white hake, halibut and dogfish (Butler 1980). Grey and humpback whales, marine birds (NPFMC 1978) and harbor seals (Lowry et al. 1978) also prey on pandalid shrimp.

Competitors for the same habitat include Pandalus tridens and Eualus macilentus. It was theorized in "A Review of the First Northern Hemisphere Pandalid Shrimp Workshop" held in Kodiak, Alaska (Frady 1981), that after depletion by commercial fisheries (i.e., Japanese overfishing the Pribilof area stocks 1961-63) or by predators, P. borealis shrimp stocks may have been replaced by other competitor species of fish and shrimp.

6.2.2 Commercial Fishery

Historically the southeastern Bering Sea fishery has been dominated by Japan and the USSR. After catches of Japanese flounder trawlers indicated large populations of P. borealis in 1960, the Japanese targeted on shrimp stocks northwest of the Pribilof Islands and in 1961 took 14,000 metric tons (MT). Catches peaked in 1963 at 30,000 MT and declined thereafter until the area was abandoned in 1969 (NPFMC 1978). Overfishing of

Bering Sea stocks during the early 1960's caused severe depression and slow recovery of stocks and there has been no significant fishery since 1966 (Paul Anderson - NOAA Cruise Results, Cruise No. 79-02, R/V Sunset Bay). In 1975 and 1976 3,500 and 1,700 MT of shrimp were taken by the Japanese from along the 100 m isobath on the continental shelf edge. Biomass estimates in 1978 stood at 30,600 MT (69 million lb) for an area of 24,000 square nautical miles (nm^2) northwest of the Pribilofs (NPFMC 1978). The maximum sustainable yield (MSY) from this population was estimated to be 11,000 MT but the current Allowable Biological Catch (ABC) has been set at 1,000 MT. This low quota reflects the current management goals of giving these stocks time to rebuild, and encouraging the maintenance of a healthy resource at historic levels which then could promote the development of a strong domestic shrimp fishery. The current ABC level will allow the management agency to assess annual catch-per-unit-effort and collect biological specimens to construct age-class structure of the population.

Stock estimates for P. borealis surveyed in 1979 over an extended area of 30,400 nm^2 (Pribilofs to St. Matthew Island and out to the U.S.-U.S.S.R. convention line) indicate a mean biomass estimated at 63.56 x 10^6 kilograms (140 million lb with an 80% confidence interval of 120.5 - 159 million lb; P. Anderson, NMFS, Kodiak AK correspondence, Oct. 1981).

The above biomass estimates are based on an area northwest of the St. George Basin. Other estimates close to the St. George Basin come from 1979 NOAA/NMFS Cruise Results (Cruise No. OR-79-03 R/V Oregon) of a

shrimp survey conducted in Unalaska, Makushin and Pavlof Bays. Biomass estimates for Unalaska Bay for 1979 were 0.95 million lbs for P. borealis compared to 8.1 million lbs in 1978. Population estimates for 1979 were only 10-35% of 1978 estimates indicating a substantial decline.

No biomass estimates have appeared in the literature recently for the St. George Basin shrimp populations, and no commercial shrimp fishery is presently centered in that area.

6.2.3. Other Pandalus spp.

Other pandalids in the southeastern Bering Sea include P. goniurus, P. tridens, P. stenolepis and Pandalopsis dispar. The range of P. goniurus, the flexed pandalid, is from the Chukchi Sea and Bering Sea to Puget Sound in 5-450 m (Butler 1980). In southeastern Bering Sea this shrimp prefers depths of 38-124 m and a mud to coarse sand bottom habitat at -.3° to 6.4°C (McLaughlin 1963). Very few P. goniurus zoeae have been found in our samples (see Section 6.6.1, Results and Discussion).

P. tridens, the yellow leg pandalid, ranges from the Bering Sea to San Nicholas Island, California, in 5-1984 m (from Butler 1980). Adults prefer depths of 200-470 m and rocky habitats. The reproductive biology for P. tridens, also a protandric hemaphrodite, has been studied for Canadian populations (Butler 1964) but remains fragmentary for the Bering Sea. Haynes' (1980) study of P. tridens larvae show growth from 3.2 mm Total Length (TL) for SI to 13.0 mm TL for SVII and megalops. No data are available for age and size at maturation for males and females

in the Bering Sea but Butler (1980) gives this information for a Canadian population (see Table 6.1). P. tridens was caught incidentally at only one station during the 1979 pandalid survey cruise in the southeastern Bering Sea from the Pribilof to St. Mathew Island group and out to the U.S. - U.S.S.R. convention line (NOAA 1979, Cruise Results No. 79-02, R/V Sunset Bay).

The rough patch shrimp, P. stenolepis, is known to occur from Unalaska Island to Hecata Bank, Oregon in 49-229 m depths over muddy bottoms (Butler 1980). Reproductive biology is poorly known for Canadian populations (Butler 1964) and unstudied for the southeastern Bering Sea but it is assumed to follow a typical pandalid pattern. Needler (1938) gives descriptions of 6 larval stages plus a first postlarva. Larvae grow from 5 mm TL at SI to 14 mm TL at SVI in British Columbia. The ovigerous period lasts from November until April in Canadian waters (Butler 1980). No commercial concentrations of this species are known to occur in the North Pacific.

The side-stripe pandalid, Pandalopsis dispar, prefers greater depths (>200 m according to Butler 1980) than P. borealis, and ranges from the Pribilof Is. to Manhattan Beach, Oregon (Butler 1980). Growth and reproduction were studied for Canadian populations (Berkeley 1930; Butler 1964) but no information is available for Bering Sea stocks. Berkeley (1930) describes 5 or 6 larval stages of P. dispar growing from 10 mm TL at SI to 30 mm TL at SV. In Canadian populations males matured at 18 months and were reproductively active for two seasons. Transition to females occurred by age 3 yr and death followed the hatching of a

single brood (Berkeley 1930). It is assumed that the colder waters of the southeastern Bering Sea retard growth and maturation and prolong the life span. Harris et al. (1972) studied the relationship between carapace length and egg number. Puget Sound P. dispar were found to have a mean egg count of 904 eggs/clutch versus 4,150 eggs/clutch found by Hynes (1930) in a southeastern Alaskan population (Table 6.1). Also, P. dispar females were found to be smaller at the same age in Puget Sound than in Southeastern Alaska. Commercial quantities of P. dispar have been taken by trawlers off the British Columbia coast but usually P. dispar occurs in mixed catches with P. borealis in Alaska.

Comments on Bering Sea Pandalids: The ecological and potential commercial importance of pandalids in the southeastern Bering Sea is difficult to ascertain and the following points should be stressed.

1. NMFS groundfish trawl surveys routinely underestimate sizes of shrimp stocks due to the large mesh size of their nets.

2. Little attention has been given these families in studies of benthic ecology since they are not found in commercially exploitable quantities or sizes.

3. An underestimation of the importance of these groups has resulted and scant attention has been given to the crucial trophic role they may play in the diet of commercial fish and marine mammals.

6.3 Hippolytidae

The Hippolytidae are the largest family of shrimp with respect to number of species in the North Pacific Ocean (Butler 1980) and are represented by 17 or more species in the southeastern Bering Sea (see Appendix A). As a group they are generally small to medium sized shrimp dominating the 40-80 m depths of the continental shelf (Ivanov 1969; Table 6.2). Larval descriptions appear in the literature for five species (Williamson 1957; Haynes 1978b; Pike and Williamson 1960; Appendix B) while mention of the others is either incomplete or totally lacking. There is a wide range in number of hippolytid zoeal stages from 2 in lebbeids to 5-9 in eualids (Table 6.3). No complete larval series is available for Heptacarpus.

Adult descriptions are given by Butler (1980) for Eualus avinus, E. barbatus, E. fabricii, E. pusiolus, E. townsendi, Heptacarpus camtschatica, H. moseri, Lebbeus grandimanus, L. groenlandicus, Spirontocaris arcuata, S. lamellicornis, S. ochotensis, S. prionata, and S. snyderi. Additional species of hippolytids may have been overlooked in compiling the list in the appendix. The most abundant of these species are probably E. gaimardii belcheri, E. macilentus, and one of the spirontocarids in our study area.

The crucial role these species play in the food web of the Bering Sea is reflected in such studies as Lowry et al. (OCS 1981 report). They showed that Eualus gaimardii belcheri feeds upon ostracods, euphausids, copepods and benthic phytoplankton. In turn, E. belcheri comprised 20-38% by volume of the total diet of ringed seal pups and was the major

Table 6.2. Life history information for hippolytid species.

	Depth (m)	Range	Total length Male (mm)	Total length Female (mm)	Number of larval stages
Eualus avinus	46-642	Pribilofs - Oregon	29	44	I-V or I-IX then megalopa
E. barbatus	82-507	" "	76	95	
E. fabricii	4-255	Circumboreal	27	42	
E. g. belcheri[1]	5-55	" northern form			
E. macilentus[2]	50-100	No data			
E. pusiolus	0-1381	Circumboreal			
E. stoneyi[1]	No data	-			
E. suckleyi[1]	No data				
E. townsendi	38-630	Pribilof < Sea of Japan Puget Sound	35	44	
Heptacarpus moseri	0-1100	Pribilof - Wash.		43	No data
H. camtschatica	0-108	Chukchi < Sea of Japan Str. of St. George	32	45	
Lebbeus grandimanus	6-180	Bering Sea - Sea of Japan San Juan Is.	36	45	I, II and megalopa
L. gröenlandicus	11-518	Bering Sea - Sea of Japan + N. Atl., Wash.	58	107	
Spirontocaris arcuata	5-641	Chukchi - Sea of Japan Wash.	22	46	I - V and megalopa
S. lamellicornis	3-192	Commander Is. - Pt. Arena, CA.	42	63	
S. murdocki	No data	-	-	-	
S. ochotensis	0-247	Bering Sea < Sea of Japan Vancouver Is. WA.	22	31	
S. prionata	4-163	Bering Sea < Sea of Japan Monterrey. CA	19	28	
S. snyderi	4-141	Bering Sea - Cedros Is., CA	18	24	

References: Butler, T. 1980.
[1]Anderson, P. (personal communication) - common in St. George Basin.
[2]Ivanov, B. 1969 - common in S.E. Bering Sea.

summer food for spotted seals. Feder and Jewett (1981) depict small, miscellaneous shrimp as food items for several species of fish (cod, starry flounder) in the southeastern Bering Sea, but quantification of use is not given.

6.4 Crangonidae

Crangonid shrimp are represented by eight or more species in the southeastern Bering Sea (see Appendix A), of which four are common (Crangon dalli, C. communis, Sclerocrangon boreas and Argis dentata). As a group they are generally medium-sized shrimp dominating the 0-50 m depths of the continental shelf (Ivanov 1969; Table 6.3). They are an important food source for demersal fish and invertebrates although they do not support a direct commercial fishery in Alaska. Crangonids eat benthic diatoms, detritus, polychaetes, small crustaceans, crustacean eggs and larvae, gastropods, foraminiferans and ophiuroids (Squires 1967), and mysids captured during diel vertical migrations (Sitts and Knight 1979). They are preyed upon by sand sole (Miller 1967), starry flounder (Feder and Jewett 1978), Pacific cod (Feder 1978), yellowfin sole (Feder and Jewett 1981), Beluga whales and phocid seals (Lowry et al. 1981), and Dungeness crabs, tomcod, and sculpin (Stevens et al. 1982).

Very little literature exists on the relative abundance of crangonid stocks. Their shallow, in-shore habitat has not been extensively sampled by suitable methods. These species bury in the sand during the day and thus dredging rather than trawling might yield more complete data. Crangon dalli and A. dentata appeared in 34 and 31% of the OCSEAP 1975 tows and C. communis, A. dentata and A. ovifer appeared in 24, 29, and

Table 6.3. Life history information for crangonid species.

	Depth (m)	Range	Max. T.L. (mm) Male	Max. T.L. (mm) Female	Number of larval stages	Fecundity eggs/clutch
Crangon dalli[2,3]	38-110	Chukchi - WA. and Sea of Japan	50	80	I - V and megalopa	4290
C. communis	16-1537	Chukchi - CA. and Sea of Japan	61	80		2200
C. alaskensis	5-50	Bering Sea - WA. and Kurile Is. Japan	52	65	I - V and megalopa	
Sclerocrangon[2] boreas	0-366	Circumboreal	110	108	Direct development	448
Argis alaskensis	18-221	Pribilof - Ore.	44	67		
A. crassa	4-125	Northern Bering Sea - WA. and Sea of Japan	40	56		448
A. dentata[2]	0-2090	Circumboreal	46	83	I - II and megalopa	
A. lar[2]	10-280	Chukchi - Str. of St. George and Sea of Japan	56	79	Larval life <1 month	980
A. ovifer	102-673	Pribilof	38	67		

[1]Data compiled from Butler, T. 1980.
[2]Anderson, P. - personal communication - most common crangonid species in the St. George Basin NMFS surveys.
[3]Ivanov, B. 1969. Most common crangonid specie.

21% of the 1976 tows (Feder 1978). Crangon communis is abundant where Pandalus borealis and Pandalopsis dispar are found (Butler 1980), and is commonly found on mixed mud and sand bottoms at depths of 62-95 m and temperatures of 0.5-3.6°C (McLaughlin 1963). Population estimates of crangonids in the southeastern Bering Sea have not been made. Estimates made from trawl surveys in Grays Harbor, Washington, were as high as 38,million shrimp for the bay during summer months, and even this figure was thought to be low because of gear inefficiency (Hoeman and Armstrong 1981). Crangonid populations in the Bering Sea may be substantial. Their ecological and community role both as detrital processors (Rice 1981) and predators, and as prey for commercial fish and crustaceans make them an important group to consider in scenarios of oil impact.

Larval descriptions are complete for 3 species; C. dalli (Makarov 1966), C. alaskensis (Loveland 1968) and A. dentata (Squires 1965). Five larval stages and one megalops are known for C. dalli and C. alaskensis, while A. dentata had only 2 zoeae before the post-larval stage and Sclerocrangon boreas undergoes direct development in which larvae hatch as juveniles (Table 6.3). No information appears in the literature describing the reproductive biology of these species in the southeastern Bering Sea. Allen (1960) reported that hatching occurs from May through August in Crangon dalli from North Sea stocks. On the Kamchatkan shelf, Makarov (1967) noted that argids hatched from May to the end of June.

6.5 Penaeidae

Among the plankton collected in the southeastern Bering Sea and sorted in our project is a series of four larval stages from a very

distinctive group. Most notable characteristics of this group are long dorsal and lateral spines on the dorsal margins of each abdominal segment and five spines above each eye. Makarov (1967) assigned this spiny larva to the family Crangonidae, Paracrangon echinata, while Kurata (1964) relegated them to the family Glyphocrangonidae, Glyphocrangon spp. Ken Coyle from the University of Alaska (personal communication) disagrees with both designations and has assigned these larvae to the family Penaeidae since Glyphocrangon sp. do not range to the Bering Sea. These larvae will appear in our summaries as a deep-water penaeid until further clarification reveals otherwise.

6.6 Results and Discussion

6.6.1 Pandalidae

Frequencies of Occurrence of Pandalus borealis. Larvae of this species were consistently the most prevalent pandalid in samples from 1976-1981. The percent frequency of larval occurrence by month from PROBES 1981 for the 5 pandalid species is given in Figure 6.1. P. borealis larvae were present at 37% of the stations in April, 30% in May, 42% in June, and 65% in July. A very dramatic rise in P. tridens larval occurrence was seen from a low of 5% in April to 37% in June. P. stenolepis larvae did not appear in samples before June but were abundant thereafter, taken at 36% and 28% of the stations from June and July. P. goniurus larvae and Pandalopsis dispar larvae were rarely taken - never at > 5% of the stations per month. As an average between April and July, P. borealis larvae were found at 45% of stations analyzed (Fig. 6.1). This frequency of occurrence is comparable to values from PROBES 1978 and 1980 when

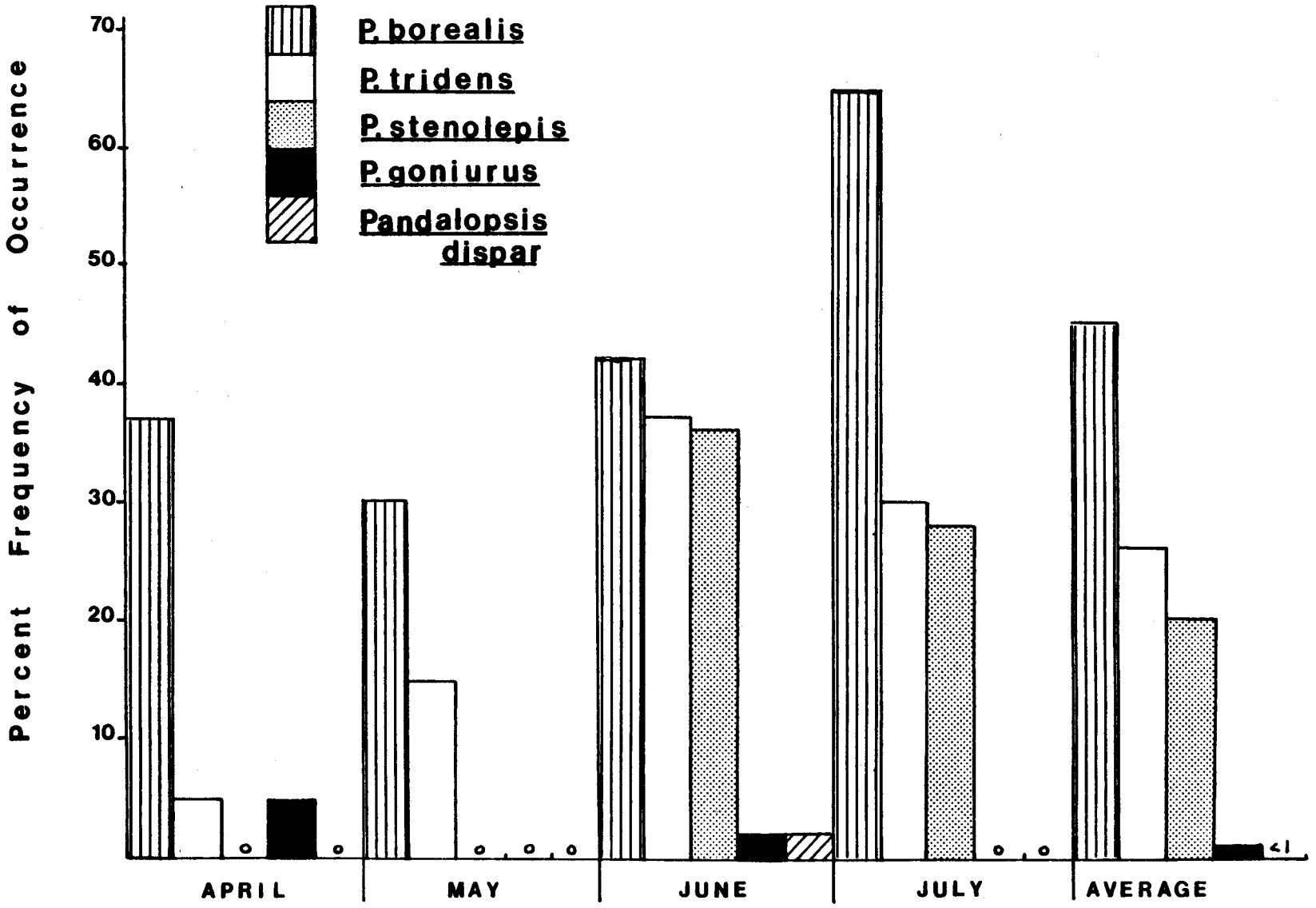


Figure 6.1 Frequency of occurrence of pandalid shrimp larvae at PROBES stations collected in 1981 by months April - July.

sampling patterns within the St. George Basin covered similar areas (Table 6.4). Frequency of occurrence of pandalids in 1981 (PROBES) was relatively high compared to values from 1980 samples. P. borealis was taken at 38-45% of the stations from 1978, 1980, and 1981. P. stenolepis consistently showed the most variability in frequency of occurrence from a low of 2% in 1980 to a high of 20% in 1981. P. goniurus and Pandalopsis dispar larvae were taken rarely during 1980 and 1981 and not at all in 1978.

Larval Duration. Zooplankton samples collected in February and March 1978 contained no pandalid zoeae and thus first hatch was assumed to occur about April 1st. Stage I zoeae of P. borealis were present throughout the St. George Basin in early April during the first sampling days of the NOAA 1977, PROBES 1978, 1980 and 1981 cruises and continued to be taken as late as mid-May in 1978 and 1981. Figure 6.2 shows the duration of each stage during the PROBES 1981 cruise for P. borealis, P. tridens and P. stenolepis larvae. The intermolt period for P. borealis was calculated by taking the midpoints of each larval stage duration and figuring the difference between adjacent midpoints. Thus 12-20 days (2-3 weeks) seems to be the average intermolt period for P. borealis larvae. These zoeae would require approximately 3 months of planktonic life to accomplish the 5 molts to the megalops stage (VI) and to settle to the benthos. Although the sampling periods of cruises from 1978-1981 did not extend past mid-July, P. borealis larvae would apparently settle out by mid-August. Future examination of samples from the NOAA 1982 summer cruise will help substantiate the exact length of the larval period.

Table 6.4. Frequency of occurrence (percent) of Pandalid shrimp larvae from PROBES stations collected in 1978, 1980 and 1981.

	1978	1980	1981	Years
P. borealis	42	38	45	
P. tridens	22	11	26	
P. stenolepis	5	2	20	
P. goniurus	0	1	1	
P. dispar	0	1	<1	

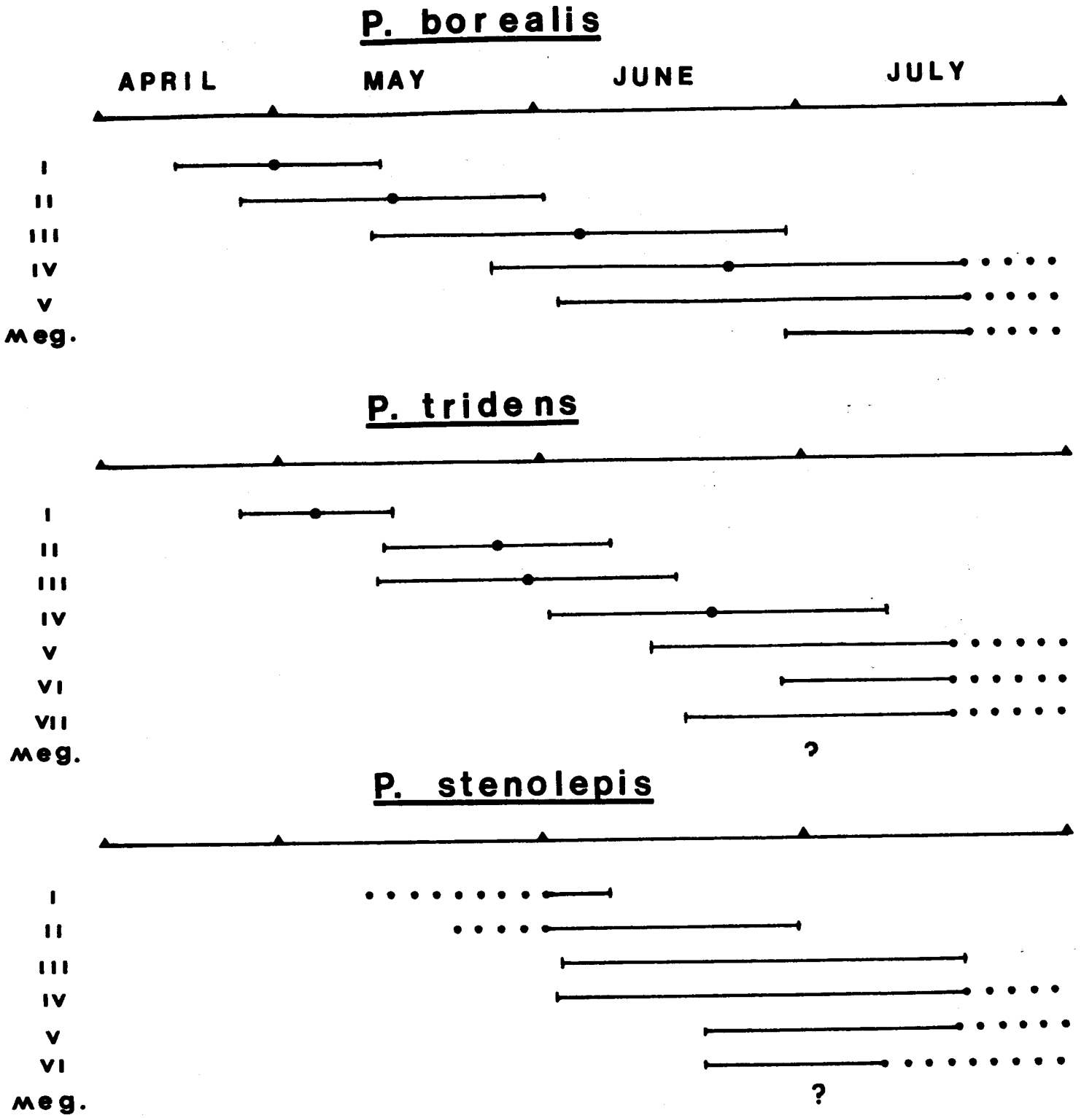


Figure 6.2 Duration of larval stages of three pandalid shrimp species collected at PROBES stations in 1981. Megalops stages of P. tridens and P. stenolepis were not taken. Dots represent hypothetical time periods for which there are no data.

A stage frequency histogram for P. borealis (Fig. 6.3) shows a slightly later or a more protracted hatchout period for larvae in 1978 as compared with 1981. In May, fifty percent of the larvae were still SI in 1978 as compared to 1% of the larvae in 1981. By June 1978, only 10% of the larvae had reached SIV or megalops compared with 31% in 1981.

P. tridens seemed to follow the same pattern of emergence, appearing first in mid-April in 1977 (NOAA) and by late April in 1978 (PROBES). No P. tridens larvae were collected until the end of April in 1980 and 1981 since sampling did not occur until late April at stations > 200 m preferred by the P. tridens adults.

Duration of the larval stages of P. tridens and P. stenolepis, as given in Figure 6.2, are less clear cut than seen for P. borealis larvae. P. tridens and P. stenolepis larvae were less abundant and sampled less frequently thereby giving only an incomplete representation of larval stage durations. Two to three weeks is still probably the average intermolt period for P. tridens and P. stenolepis larvae. Since these two species have 7 and 6 larval stages before metamorphosis, respectively, and since no megalops of either species were ever found, larvae may be in the water column until late August or early September, a planktonic life of approximately four months is thus indicated.

A stage frequency histogram for P. tridens larvae, Figure 6.4, compares data of 1978 and 1981. Only one Stage I larva was found in 1981 April samples due to sparse sampling beyond the shelf break. The P. tridens larval population seemed to lag about one stage behind during

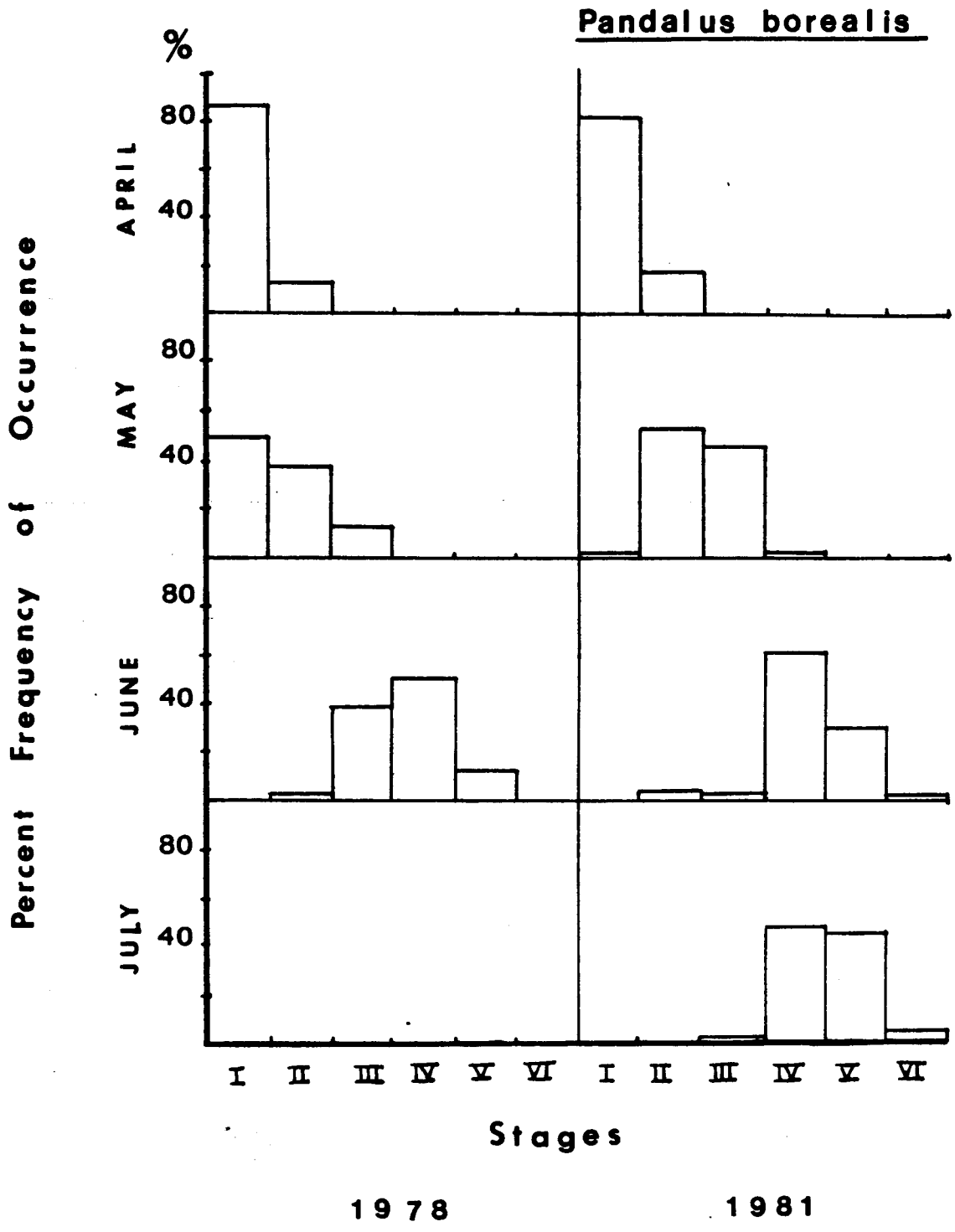


Figure 6.3 Pandalus borealis stage frequency histograms by month from PROBES 1978 and 1981. No samples were taken in July 1978.

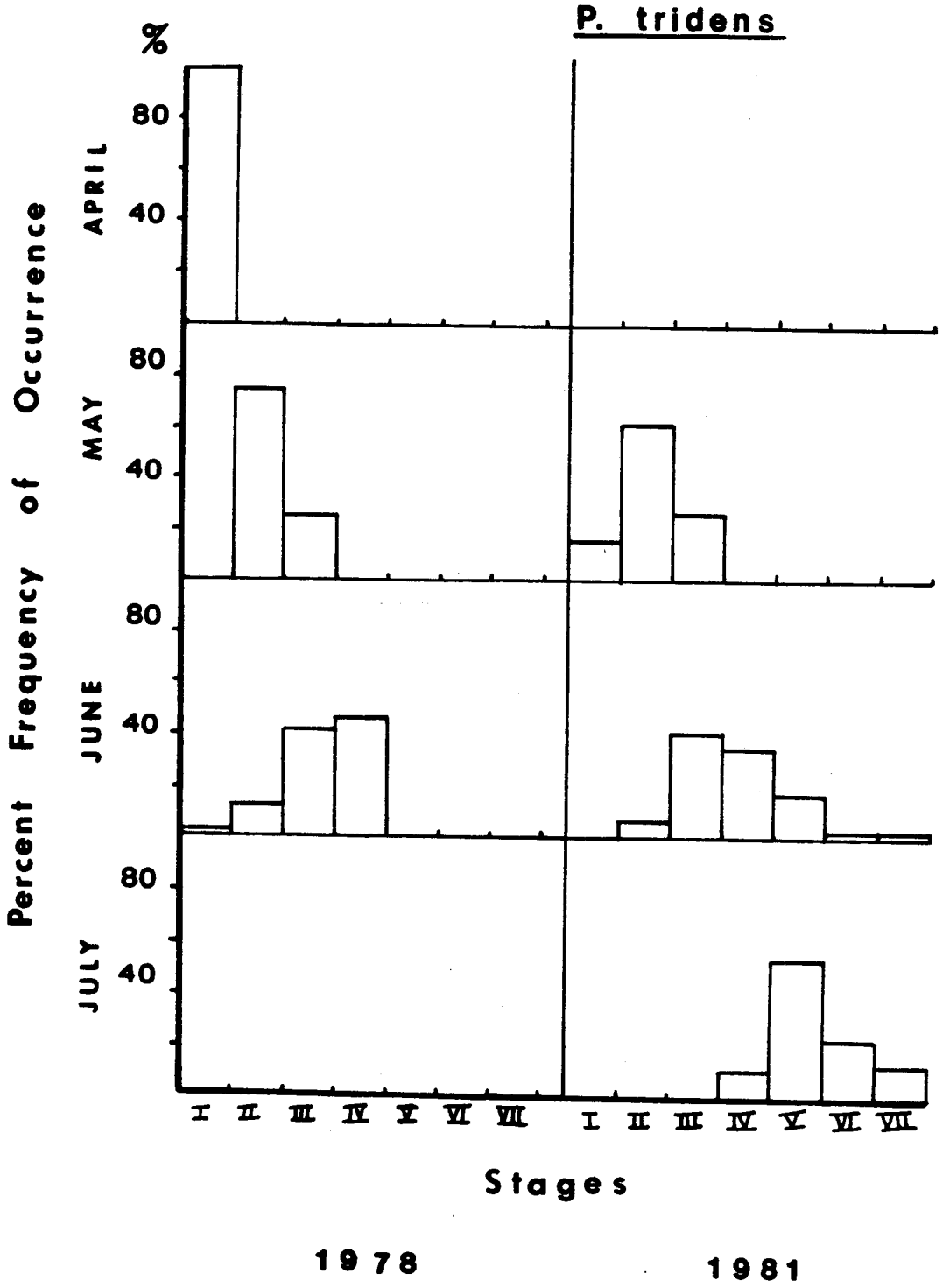


Figure 6.4 Pandalus tridens stage frequency histograms by month from PROBES 1978 and 1981. No samples were taken in July of 1978.

June 1978 compared to June 1981. Contrasting P. tridens with P. borealis larval development (Figs. 6.3 and 6.4), P. tridens larvae were generally one stage or one molt behind P. borealis larvae by June of both years. For example, in June 1978, 60% of P borealis larvae were SIV or greater compared to 46% of P. tridens larvae, while in June 1981, 93% of P. borealis larvae were SIV or greater versus 54% of P. tridens larvae.

The northernmost extent of the range of P. stenolepis is given by Butler (1980) as Unalaska Island. The NOAA 1977 cruise first took P. stenolepis SI in mid-April just west of Unimak Pass. No other cruises sampled this area during April. All other cruises took SI zoeae from mid-May until early June. The frequency of P. stenolepis occurrence was so low it is not possible to make definitive statements regarding this long SI duration (except possibly asynchronous hatch-out within the population). Figure 6.2 shows duration of stages from April until July for PROBES 1981. Since early sampling was not done near Unimak Pass, first hatch-out and the duration of SI and SII is not well-documented. Sampling in May and June over central St. George Basin took later S of P. stenolepis (II-VI), but no megalopae were found. With respect to staging, P. stenolepis larvae were mostly stages I and II during late April-early May (NOAA 1977), stages III and IV during early-mid June (PROBES 1981), and stages IV and V from late June to early July. These larvae would probably not complete metamorphosis before late August.

Pandalus goniurus adults are commonly taken from the St. George Basin (Feder 1978) in the 38-124 m depths on a mud to coarse sand

bottom. A pandalid larval type that was smaller and had fewer setae on the antennal scale than the P. borealis larvae (as described by Haynes 1978) was found sporadically at scattered locations over the mid-shelf domain in samples from 1976-1981. While this larval type agreed with a description of P. borealis SI larvae from Hokkaido, Japan (Kurata 1964), it seemed significantly smaller and with different setal counts than the majority of P. borealis larvae. At the same time, it had a larger body size than the SI P. goniurus described by Haynes (1978) from Kachemak Bay, Alaska. The colder water temperatures of the Bering Sea may cause significant size differences in larvae compared to populations from the Gulf of Alaska, and thus size alone cannot be used as a definitive characteristic for the species. Size of Bering Sea larvae were consistently larger and had consistently different numbers of antennal setae, maxillule spines, and maxilla setae counts than Haynes' Kachemak Bay. Larval specimens were sent to Dr. Evan Haynes of the NMFS Auke Bay Laboratory to confirm identifications of P. goniurus. All P. borealis SI larvae from 40-120 m stations were re-examined and re-assigned to P. goniurus if they proved to be < 5.0 mm from rostrum to telson, with less than 19 setae on the antenna, less than 9 spines on the basipodite of the maxillule, and less than 11 setae on the scaphognathite of the maxilla. Relatively few P. goniurus larvae were found following this extensive review of 1976-1980 samples. Only 2.4% of the PROBES stations sampled in 1981, and 0% and 4.5% of the NOAA 1981 stations (two cruises) contained P. goniurus larvae. Figure 6.5 illustrates station locations of P. goniurus larvae from all years combined.

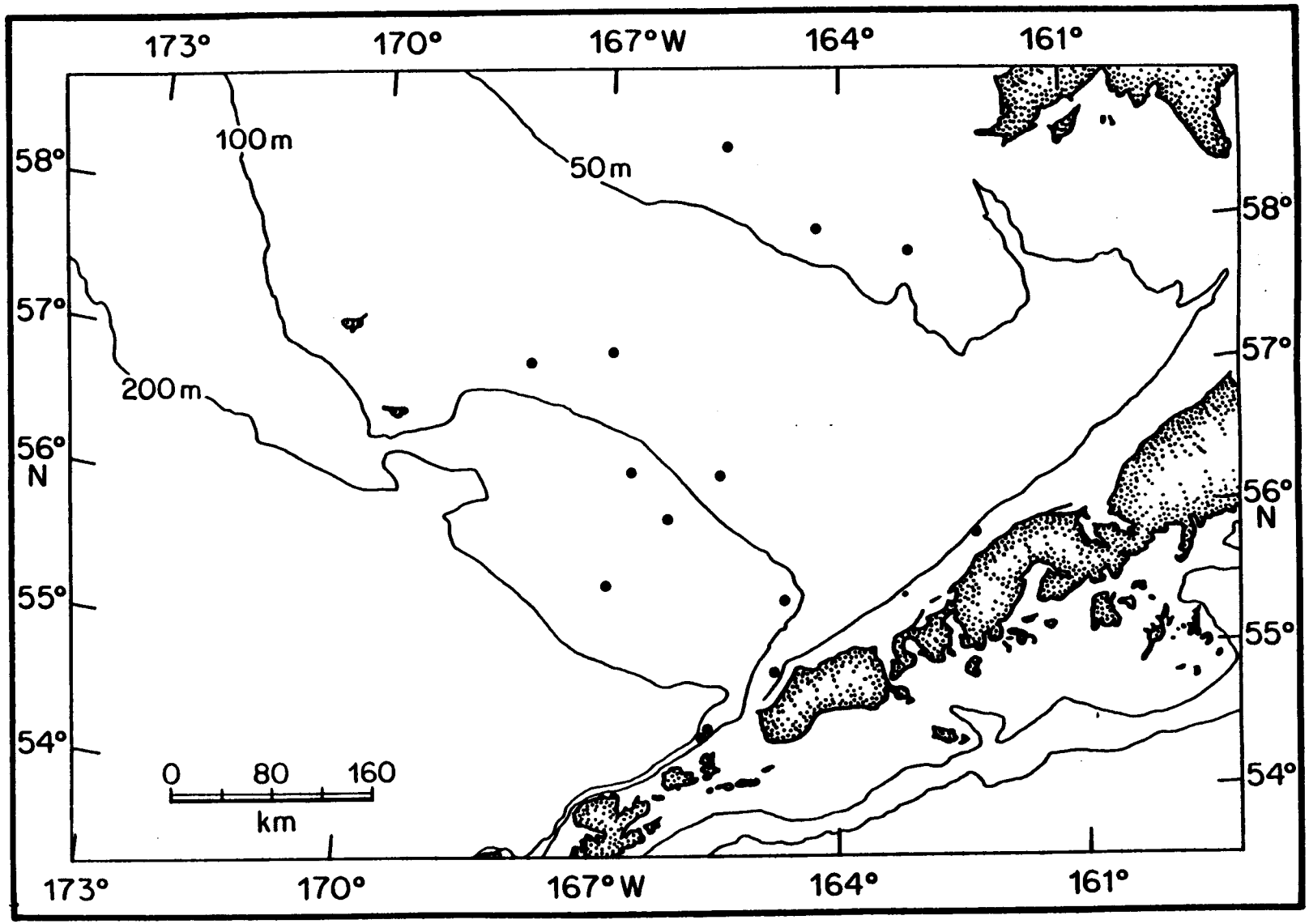


Figure 6.5 Distribution of Pandalus goniurus larvae (black dot), all years 1976-1981, and all months April - July combined. Refer to station maps of Section 2.0 for extent of coverage.

Pandalopsis dispar was taken only once during the following cruises; PROBES 1981, NOAA 1981 (R/V Alaska), PROBES 1980 and 1978, thus making it the least frequently caught pandalid species. Stages I, II, IV,and V were taken during the months of June and July. The northernmost range for this shrimp is given as the Pribilof Islands where the NOAA 1981 (R/V Alaska) cruise caught a single animal.

Distribution and Abundance of Pandalus borealis: Larvae of this species were found in the greatest abundance between the 100 and 200 m isobaths over the St. George Basin (Figs. 6.6 to 6.9). Highest P. borealis larval densities were found during the NOAA 1977 cruise in April and May (Figure 6.6) with concentrations ranging from 1200-6200 larvae/100 m^2. Comparably high larval densities, ranging from 1100-7200 larvae/100 m^2, were also found in June 1979 (NOAA cruise, not pictured). PROBES 1980 larval densities for P. borealis followed this same general distribution pattern but with higher abundances near the 100 m isobath.

In marked contrast, very low P. borealis densities were found during the 1981 PROBES and NOAA cruises compared to 1977 (Fig. 6.7 vs. 6.6). Although larvae seemed to be more widely dispersed up into the middle shelf domain during 1981, their abundance over the outer shelf domain was rarely greater than 500 larvae/100 m^2.

Monthly variation in P. borealis distribution and abundance between April and May/June 1978 is shown in Figures 6.8 and 6.9. The relatively clustered pattern of high density (1000-5000 larvae/100 m^2) in April 1978 (Fig. 6.8) over the central outer shelf, spread throughout the St.

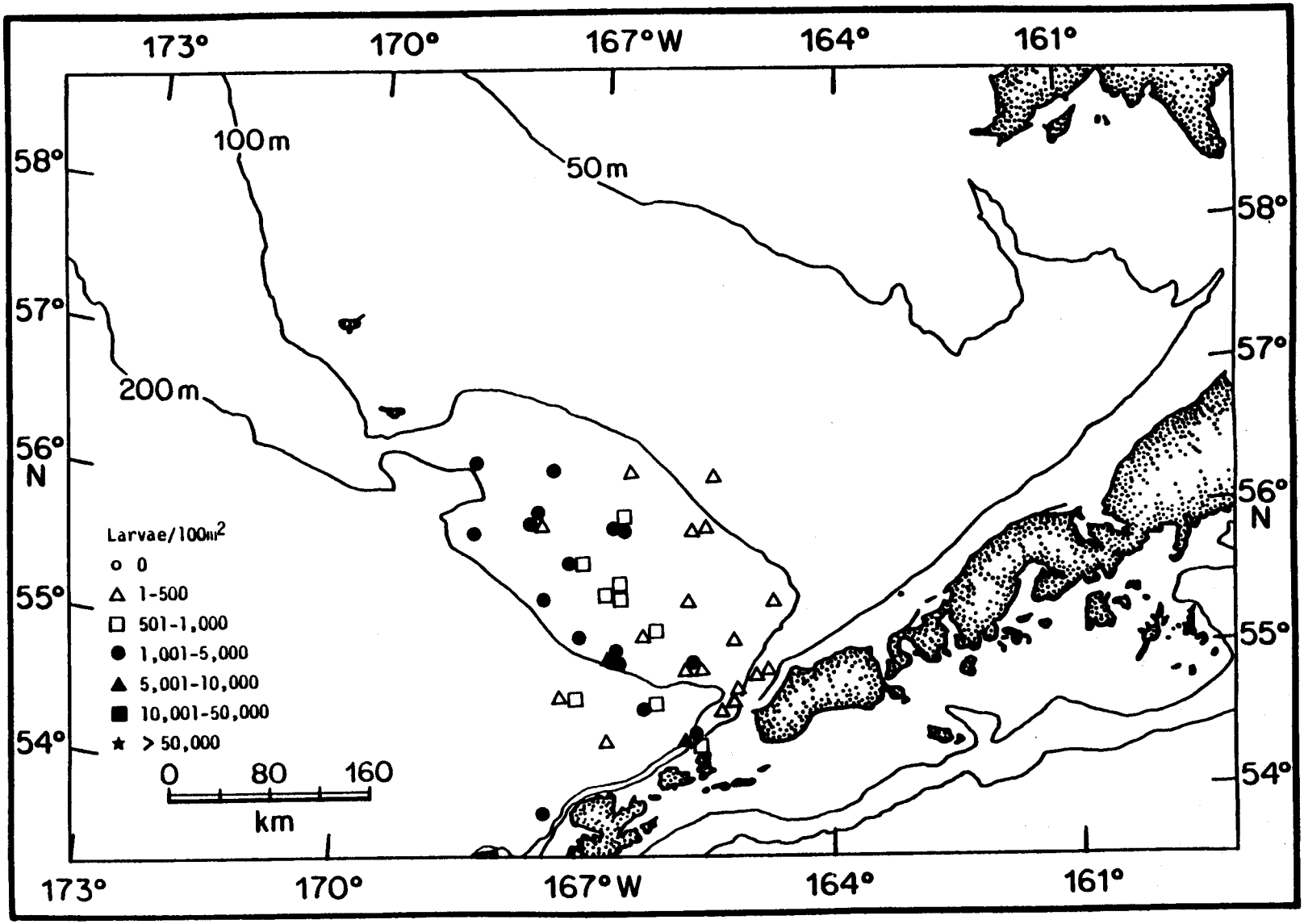


Figure 6.6 Distribution and abundance of Pandalus borealis larvae from NOAA 1977, April and May combined. Only positive stations are shown; see Section 2.0 for cruise tracks and all station locations.

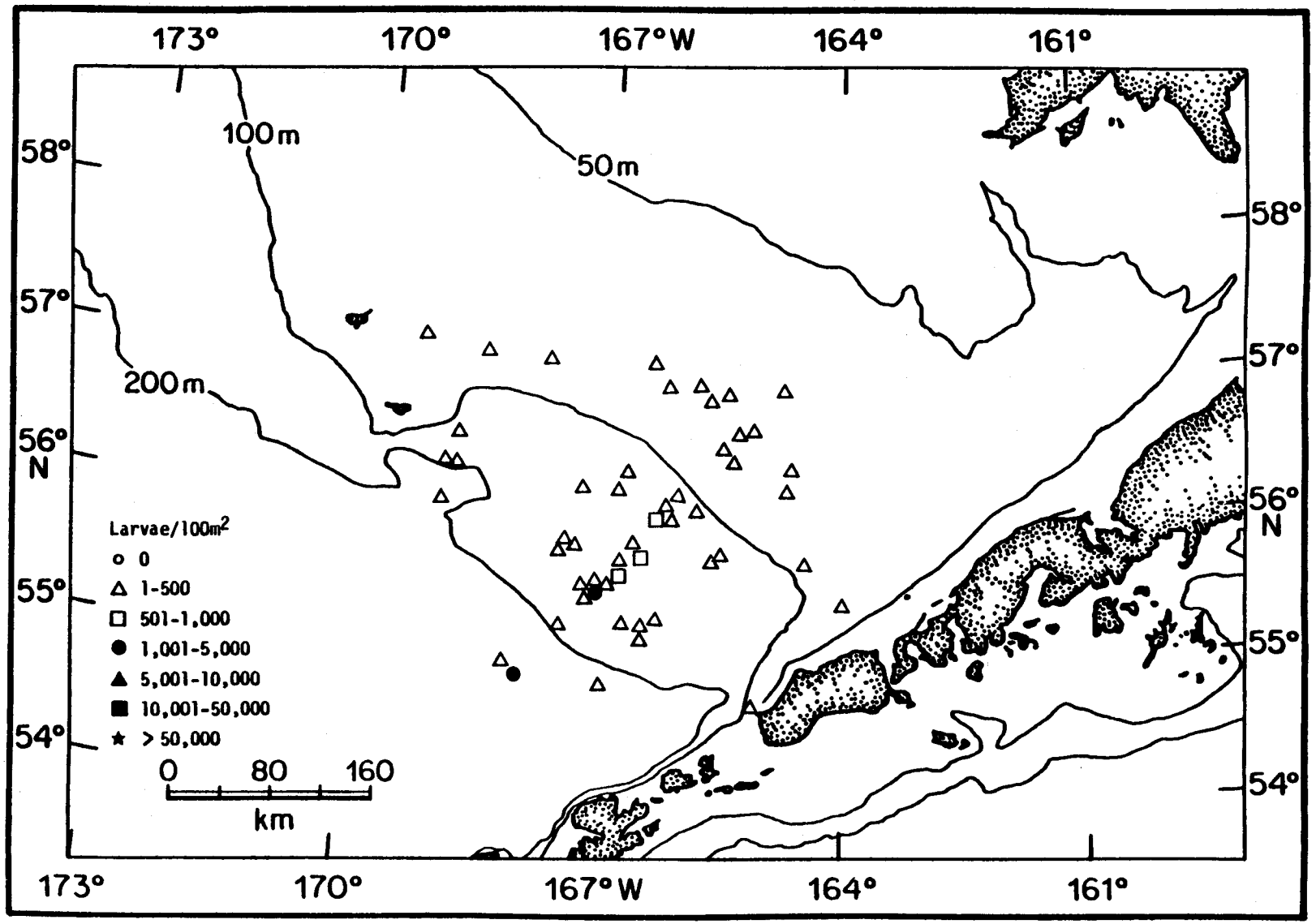


Figure 6.7 Distribution and abundance of P. borealis larvae from PROBES 1981 and NOAA 1981, April-July combined. Only positive stations are shown; see Section 2.0 for cruise tracks and all stations.

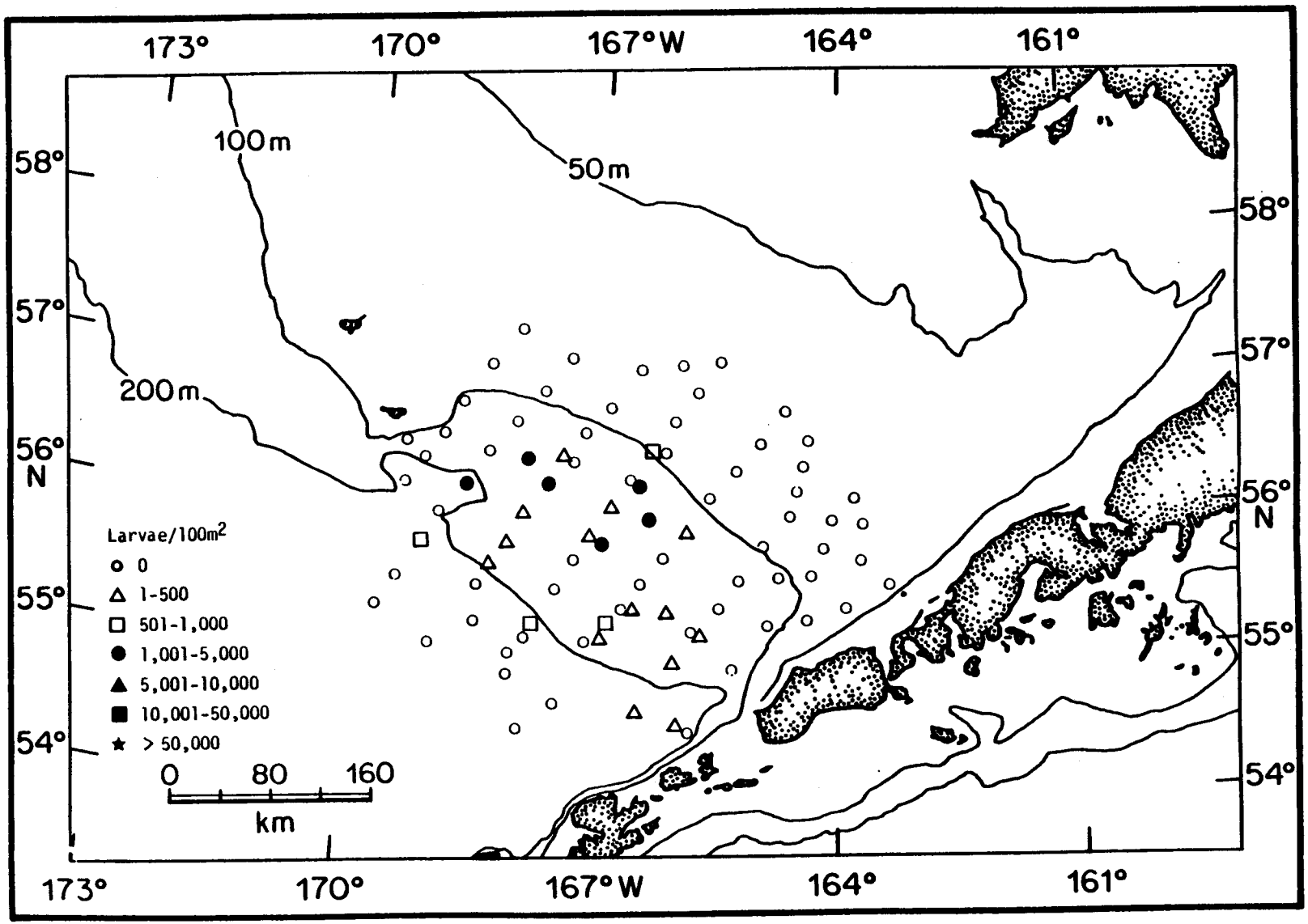


Figure 6.8 Distribution and abundance of P. borealis larvae from PROBES 1978, April only. Zero stations where no larvae were caught are included.

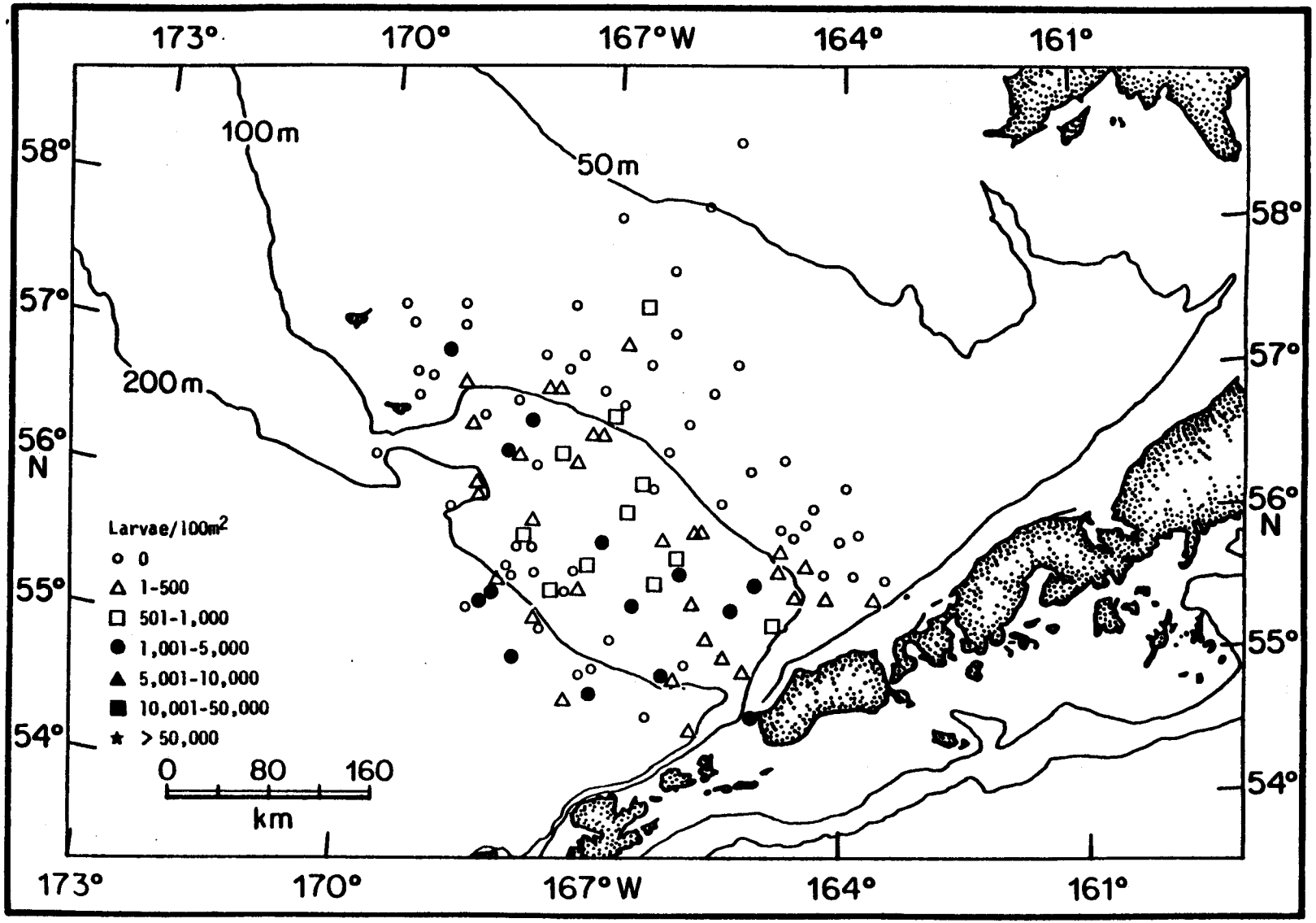


Figure 6.9 Distribution and abundance of P. borealis larvae from PROBES 1978, May and June combined. Zero stations are included where no larvae were caught.

George Basin and extended over the shelf break beyond the 200 m isobath by May and June 1978 (Fig. 6.9).

The outer shelf domain, where P. borealis larvae were primarily found, was assigned to strata 2, 5, and 8 (see Fig. 2.21) for computer assisted data analysis (see Section 2.0). Figure 6.10 gives a monthly comparison of the mean densities of P. borealis larvae in stratum 2 for four years. Generally, densities increase over time from April to June from less than 500/100 m^2 to over 1000/100 m^2. The very high values of 1172 larvae/100 m^2 given for April 1977 may indicate that P. borealis hatched out somewhat earlier that year. Generally, stratum 2 mean densities ranged from 250 larvae/100 m^2 in April to 720 larvae/100 m^2 in May to 1340 larvae/100 m^2 in June. The PROBES 1981 cruise, as shown earlier in Figure 6.7, had consistently lower mean densities; 102 larvae/100 m^2 in April, 373 in May, 197 in June, and 227 in July. These lower densities may reflect a real decrease in abundance or a geographical sampling bias imposed by adhering mainly to the PROBES A line (see Fig. 2.13, middle transect).

A cross-shelf comparison of P. borealis mean densities appears in Table 6.5 for PROBES 1978 data; no other cruise sampled these 9 strata as extensively during May and June. Comparing strata 8, 2, and 5, the outer shelf domain, gives a picture of relatively homogeneous distribution of P. borealis larvae over the St. George Basin between the 100-200 m isobaths. A comparison of the middle domain, strata 9, 1, and 6 with the outer shelf domain shows a decrease in both mean densities (Table 6.5) and percentage of positive stations. A similar comparison of the

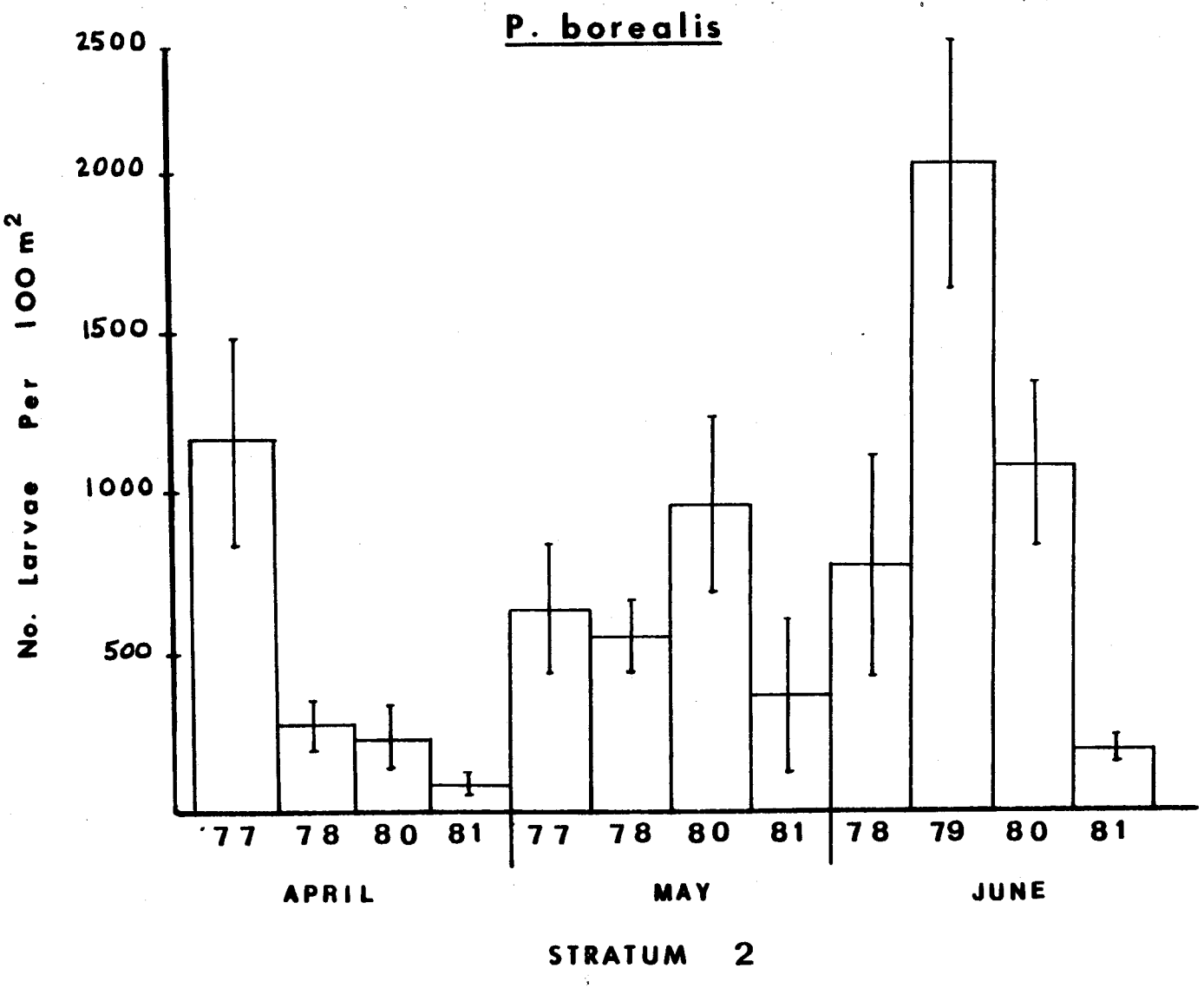
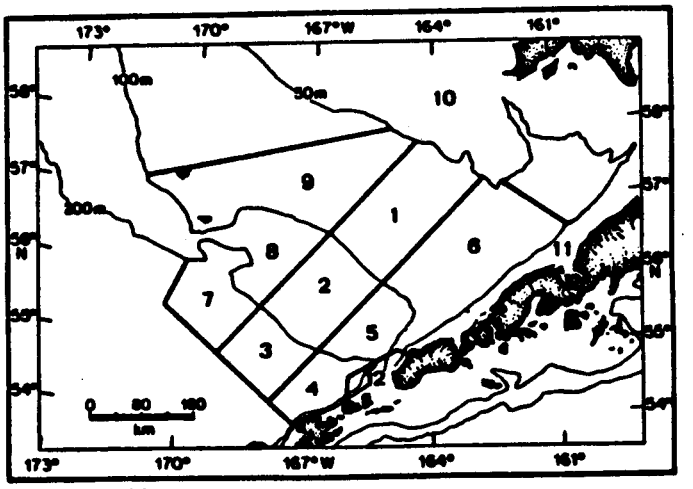


Figure 6.10 P. borealis larval abundance in stratum 2 during April, May and June from 1977-1981. Values are the mean density ±1 standard error. Zero stations are included in calculations.

Table 6.5. Cross-shelf comparison of mean densities of P. borealis larvae during May and June from PROBES 1978. Zero stations omitted from calculations. Total number of stations (N) sampled within each stratum shown. See Figure below for strata locations.

Stratum	Mean Density ± S.D. (# larvae/100 m^2)	% positive stations	N
	Oceanic/Shelf Break Domain		
7	714 ± 729	71%	7
3	1003 ± 680	57%	7
4	*	*	-
	Outer Shelf Domain		
8	675 ± 615	59%	17
2	878 ± 702	68%	19
5	626 ± 494	92%	12
	Middle Shelf Domain		
9	377 ± 318	35%	26
1	0	0%	7
6	175 ± 81	27%	15

*Insufficient data.



outer shelf with the oceanic area beyond the shelf break shows high values for mean larval density and percentage of positive stations (note that fewer stations were sampled beyond the shelf break). Unfortunately, stratum 4 was not sampled sufficiently to complete the matrix.

Vertical Distribution of P. borealis: PROBES 1980 and 1981 MOCNESS data were used for analyses of vertical depth distribution. Both unweighted and weighted average abundance values were calculated for each depth interval. Even though there were few stations with extremely high larval densities at any one depth interval, unweighted (zero stations included) values were determined to give a clearer picture of larval depth distribution. Figure 6.11 illustrates the proportion of the total population of P. borealis larvae at each depth interval for 1980 and 1981 PROBES cruises. The total cumulative percentages of larvae in each of the depth intervals for 1980 and 1981 were 17-32% in the upper 20 m, 49-61% in the upper 40 m, 65-75% in the upper 60 m, and 90-95% in the upper 80 m. From the values it is evident that P. borealis larvae are relatively homogeneously distributed throughout the water column down to 80 m, with about 50+% of the larvae in the upper 40 m and 40+% in the lower 40 m.

Distribution and Abundance of Pandalus tridens: The earliest record of P. tridens larvae was from samples collected near Unimak Pass in mid-April 1977 (no larvae were found in the February-March collections). By late April in 1978 they were found southwest of St. George Island, whereas in 1980 and 1981, they were first found along the PROBES A line at stations at depths from about 150 m to more than 200 m.

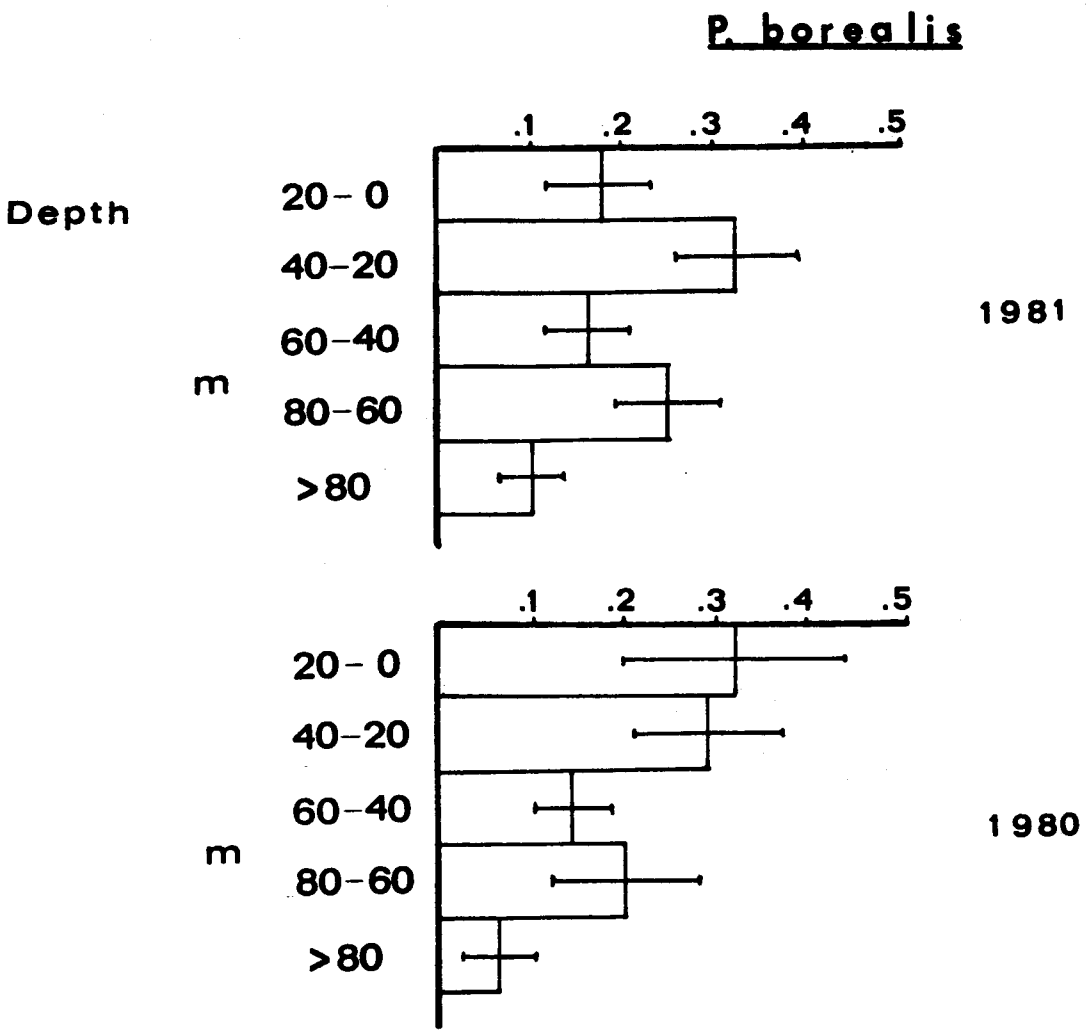


Figure 6.11 Vertical Depth Distribution of P. borealis larvae (all zoeal stages) from PROBES 1980 and 1981. Values expressed as an average proportion ±1 standard error.

Since P. tridens occurred less frequently than P. borealis, Figure 6.12 shows abundance and distribution for April-July for all year combined except PROBES 1978. Highest larval densities were clustered southwest of the 200 m isobath over the shelf break (1000-4000 larvae/100 m^2) and from Unimak Pass to Unalaska Island (5000-6000 larvae/100 m^2). The highest mean larval density by stratum was 1461 larvae/100 m^2 for stratum 12 in the Unimak Pass area during the NOAA 1977 cruise. In general, P. tridens larvae were found only rarely shoreward of the 100 m isobath over the middle shelf domain.

Figures 6.13 and 6.14 compare P. tridens larval distribution in April with May and June distribution from PROBES 1978. April hatch out occurred south of St. George at the Pribilof Islands late in April (Fig. 6.13). By May and June larvae were most abundant southwest of the shelf break (1000-4000 larvae/100 m^2 in strata 3 and 4) and over the southern part of the St. George Basin (1000-2000 larvae/100 m^2 in stratum 5). By May and June, P. tridens overlapped P. borealis larval distribution over the St. George Basin and west of the shelf break (compare Figs. 6.9 and 6.13).

Figure 6.15 contrasts May and June mean larval densities in stratum 2 with stratum 3 for the years 1978, 1980, and 1981. (Since this species was less common than P. borealis, and since the extent and degree of sampling varied within strata interannually, zero stations - no larvae found - were omitted from calculations of mean density.) There was a three- to five-fold increase in larval density of P. tridens in stratum 3 beyond the shelf break as compared to stratum 2 of the

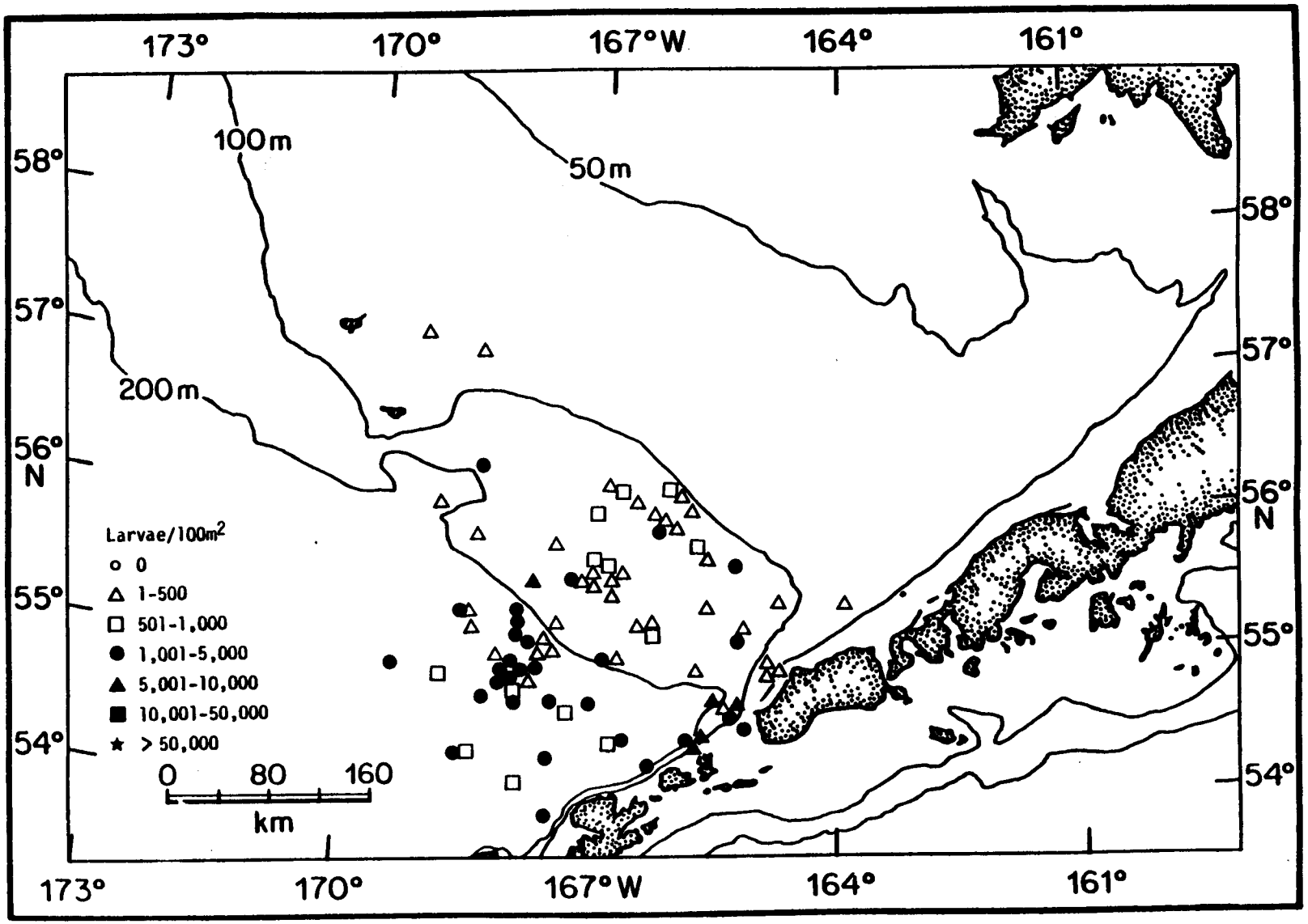


Figure 6.12 Distribution and abundance of Pandalus tridens larvae from all months April - July, all years except PROBES 1978 combined. Zero stations omitted; see Section 2.0 for cruise maps and stations.

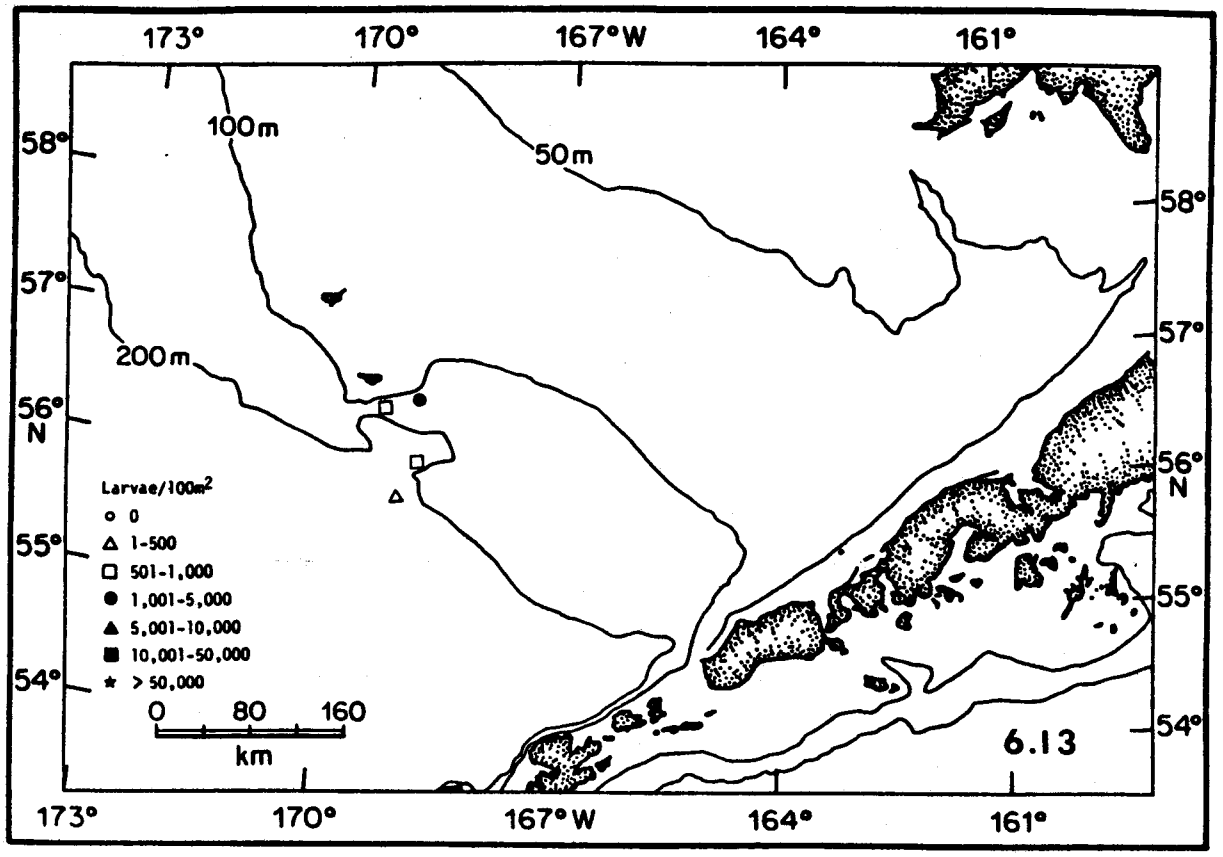


Figure 6.13 Distribution and abundance of P. tridens larvae from PROBES 1978, April only. Zero stations omitted; see Section 2.0 for cruise maps and stations.

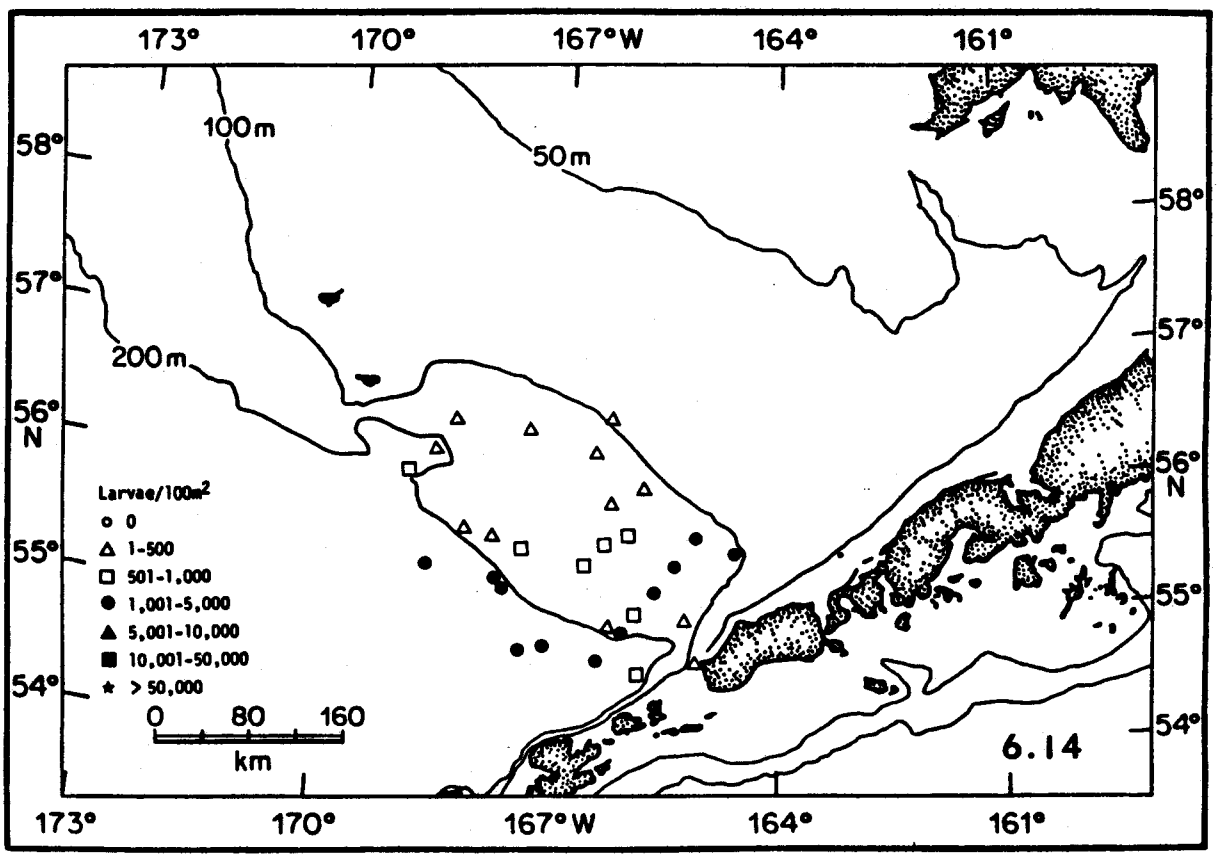


Figure 6.14 Distribution and abundance of P. tridens larvae from PROBES 1978, May and June. Zero stations omitted. See Section 2.0 for location of all stations sampled during this cruise.

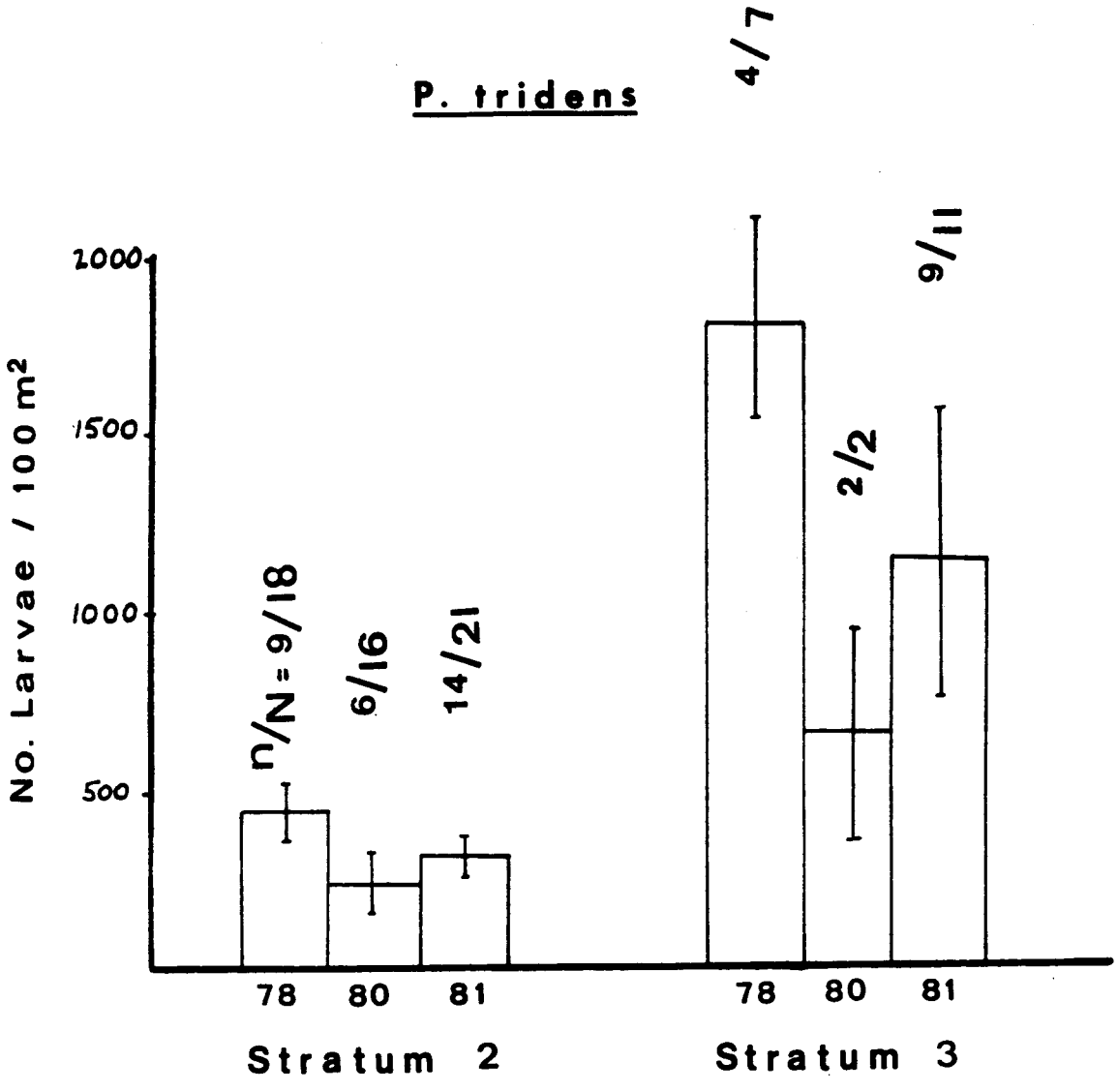


Figure 6.15 P. tridens larval abundance in strata 2 and 3 during May and June from PROBES 1978, 1980 and 1981. Values expressed as mean density ±1 standard error. Zero stations are not included in these calculations. The number of positive stations (n) and the total number of stations sampled (N) for each stratum-year combination is shown above the bars.

outer shelf during those years. Samples in June 1979 (NOAA) confirmed this trend when the highest monthly mean density of 1798±926 P. tridens larvae/100 m^2 occurred in June 1979 in stratum 3.

A cross-shelf comparison of P. tridens larvae incorporating 1978 PROBES data appears in Table 6.6. Unlike the homogeneous distribution of P. borealis larvae throughout the St. George Basin between the 100-200 m isobaths (Table 6.5; strata 8, 2, and 5), P. tridens larval distribution was much more concentrated near the Aleutian Peninsula (stratum 5) in the outer shelf domain just north of Unimak Pass. Generally higher larval densities seaward of the shelf break showed that to be the area of greatest abundance with the maximum density appearing closest to the coastal area in stratum 4 (although this last density was calculated from only 2 stations). P. tridens larvae were less abundant in the outer shelf domain and virtually absent (except for 1 of 36 stations) from the middle shelf domain.

P. tridens larvae were not caught in sufficient abundance to analyze the vertical depth distribution in 1980, but MOCNESS data from PROBES 1981 (Fig. 6.16) revealed a homogeneous depth distribtion of P. tridens larvae in the top 60 m, similar to P. borealis larval vertical distribution (Fig. 6.11). The total cumulative percentages of larvae in each of the depth intervals were 31% in the uper 20 m, 54% in the upper 40m, 83% in the upper 60 m and 97% in the upper 80 m. A breakdown of the data gave similar results for both 100-200 m stations and 200-1800 m stations.

Table 6.6. Cross-shelf comparison of mean densities of *P. tridens* larvae during May and June from PROBES 1978. Zero stations omitted from calculations. Total number of stations (N) sampled within strata shown. See Figure 2.21 for strata locations.

Stratum	Mean Density ± S.D. (# larvae/100 m^2)	% positive stations	N
	Oceanic/Shelf Break Domain		
7	873 ± 719	43%	7
3	1816 ± 733	57%	7
4	2740 ± 3033	100%	2
	Outer Shelf Domain		
8	190 ± 132	18%	17
2	436 ± 301	50%	18
5	1127 ± 610	75%	12
	Middle Shelf Domain		
9	0	0%	15
1	187*	14%	7
6	0	0%	14

*Based on 1 positive station.

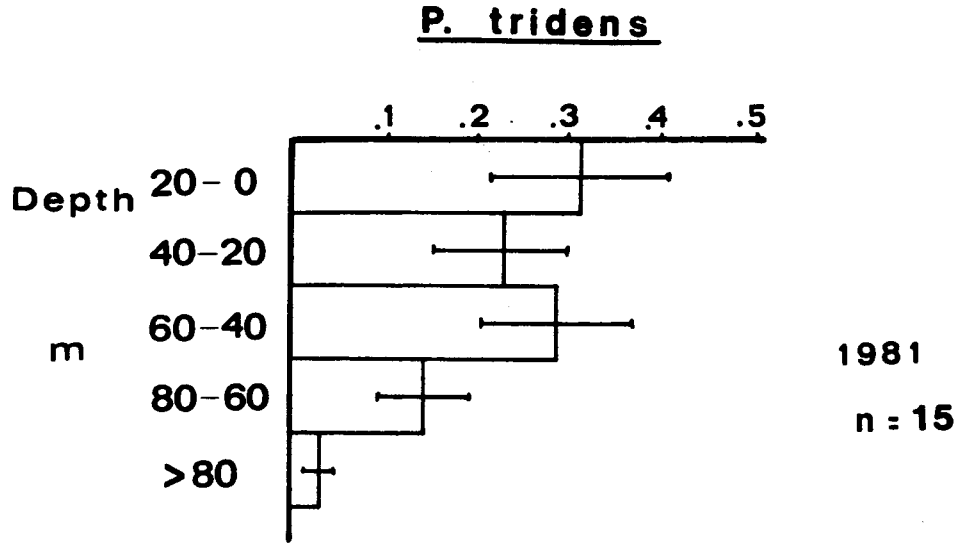


Figure 6.16 Vertical depth distribution of P. tridens larvae from PROBES 1981. Values expressed as the mean proportion ±1 standard error. A total of 15 MOCNESS stations at which P. tridens occurred were used for analyses.

Distribution and Abundance of Pandalus stenolepis: Larvae of P. stenolepis were infrequently caught on all cruises from 1976 to 1981. Figure 6.17 shows abundance and distribution of P. stenolepis larvae from all cruises, all months combined. Their distribution overlaps both P. borealis and P. tridens larvae with highest densities located near Unimak Pass. Mean densities in 1981 ranged from 290-480 larvae/100 m^2 in strata 2 and 3 during summer months. Larvae were completely absent from the northwestern section of the St. George Basin in accord with northern limits of adult ranges at Unalaska Island (Butler 1980). Occurrence of larvae in the lower St. George Basin may indicate the extent of larval drift in currents coming north through Unimak Pass, although it would not account for the isolated locations near the Pribilof Islands or on the middle shelf domain where P. stenolepis larvae were taken. The presence of these larvae may indicate that the range of P. stenolepis extends further north than previously thought.

The greatest density of P. stenolepis larvae for all years and all strata, 1284±1129 larvae/100 m^2, was found during NOAA 1977 in stratum 12 at Unimak Pass. P. stenolepis larvae were not caught with enough regularity to do either a comparison of density by stratum, a cross-shelf comparison, or a vertical depth distribution analysis. No P. stenolepis larvae were taken during the NOAA '76 cruise. Their percent frequency of occurrence among all stations sampled ranged from a low of 2% in 1980 to a high of 17% in 1977.

Summary of Pandalus spp. Distribution and Abundance:

1) Larvae of the pandalids apparently hatch in early April.

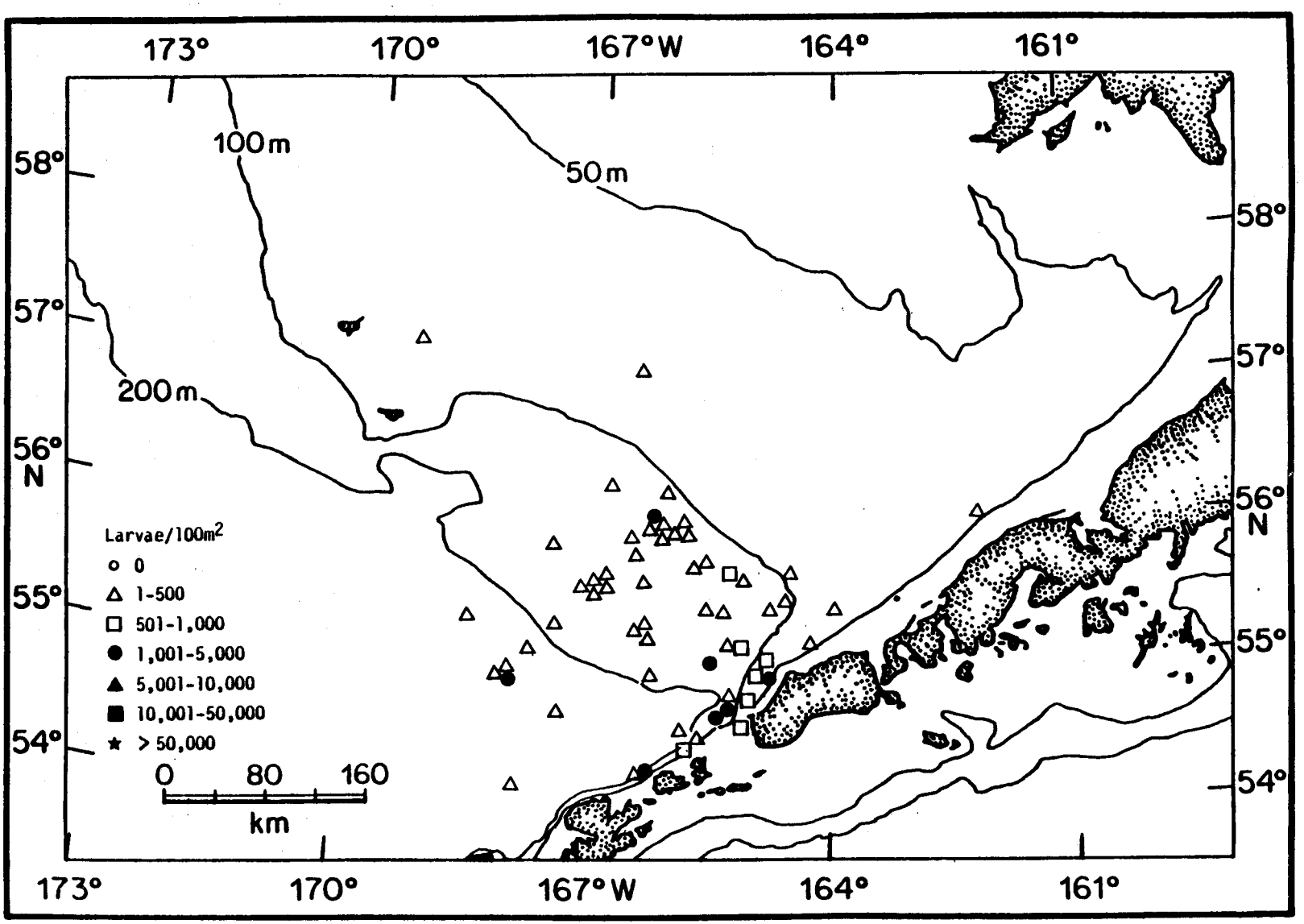


Figure 6.17 Distribution and abundance of P. stenolepis larvae from all years 1976-1981, all months April-July combined. Zero stations omitted. See section 2.0 for all station locations.

2) While hatchout of P. borealis larvae does not occur over a protracted period of time (no greater than a 3-week period), the hatchout time for P. tridens and P. stenolepis may be somewhat longer.

3) P. borealis larvae are generally most abundant in the outer shelf domain over the St. George Basin. P. tridens larvae are most abundant beyond the shelf break over deep water, but also range throughout the outer shelf domain. P. stenolepis occur over much of the St. George Basin between the 100 and 200 m isobaths but with much lower frequency than P. borealis or P. tridens larvae.

4) Mean densities of P. borealis larvae over the St. George Basin were about 600-900 larvae/100 m^2 in May and June. Mean densities of P. tridens larvae beyond the shelf break were about 600-1000 larvae/100 m^2 in May and June. Mean densities for other species (P. stenolepis, P. goniurus and Pandalopsis dispar) were significantly less.

5) Larvae were distributed homogeneously throughout the water column from 0-80 m; more than 80% of larvae were found in the upper 60 m.

6) Larvae molt about every 2-3 weeks so P. borealis would progress through six larval stages, metamorphose to a megalops, and settle to the benthos about mid-August. P. tridens and P. stenolepis may take until late August or early September because they have more larval stages.

6.6.2 Hippolytidae

Larval Duration: Hippolytid larvae were the only shrimp zoeae collected in the early spring (mid-February to mid-March, NOAA cruise 1978), when

SI zoeae were first taken in March 1978 near Akutan Island. While the adults most commonly taken in this area include Eualus gamardi belcheri, E. suckleyi, and E. stoneyi (Paul Anderson, NMFS, Kodiak, Alaska, personal communication, October 1981), approximately five types of larval hippolytids and their larval stages were delineated from 1976-1981 samples. The sheer number of possible species (about 20, see Table 6.2) and lack of definitive larval descriptions for all species made further identification impossible at this point. Assigning definite zoeal stages is difficult because genera in this family have from 2 to 9 stages. The five different types of larval hippolytids were staged, but analysis of stage frequency and molt frequenty was not conducted. As with the pandalids, sampling did not continue late enough in the summer to document the timing of metamorphosis to the benthos.

Distribution and Abundance: Ivanov (1969) states that adult hippolytids generally dominate over shelf depths of 40 to 80 m. This may very well be true, but the larvae apppeared to be a ubiquitous group, as prevalent as the pandalids over the outer shelf domain at stations between the 100-200 m isobaths of the St. George Basin (Figs. 6.18, 6.19). In addition to their wide distribution, abundance was commonly greater than 1000 larvae/100 m^2 over much of the St. George Basin and 1000-8000 larvae/100 m^2 beyond the shelf break and on either side of Unimak Pass. Data of 1981 support this pattern of low density but wide distribution over the middle shelf, higher densities over the central St. George Basin of the outer shelf domain, and greatest aggregations beyond the shelf break (Fig. 6.18). The highest density (5600 larvae/100 m^2) for 1981 was taken at the southwest tip of Unimak Island. Variation between

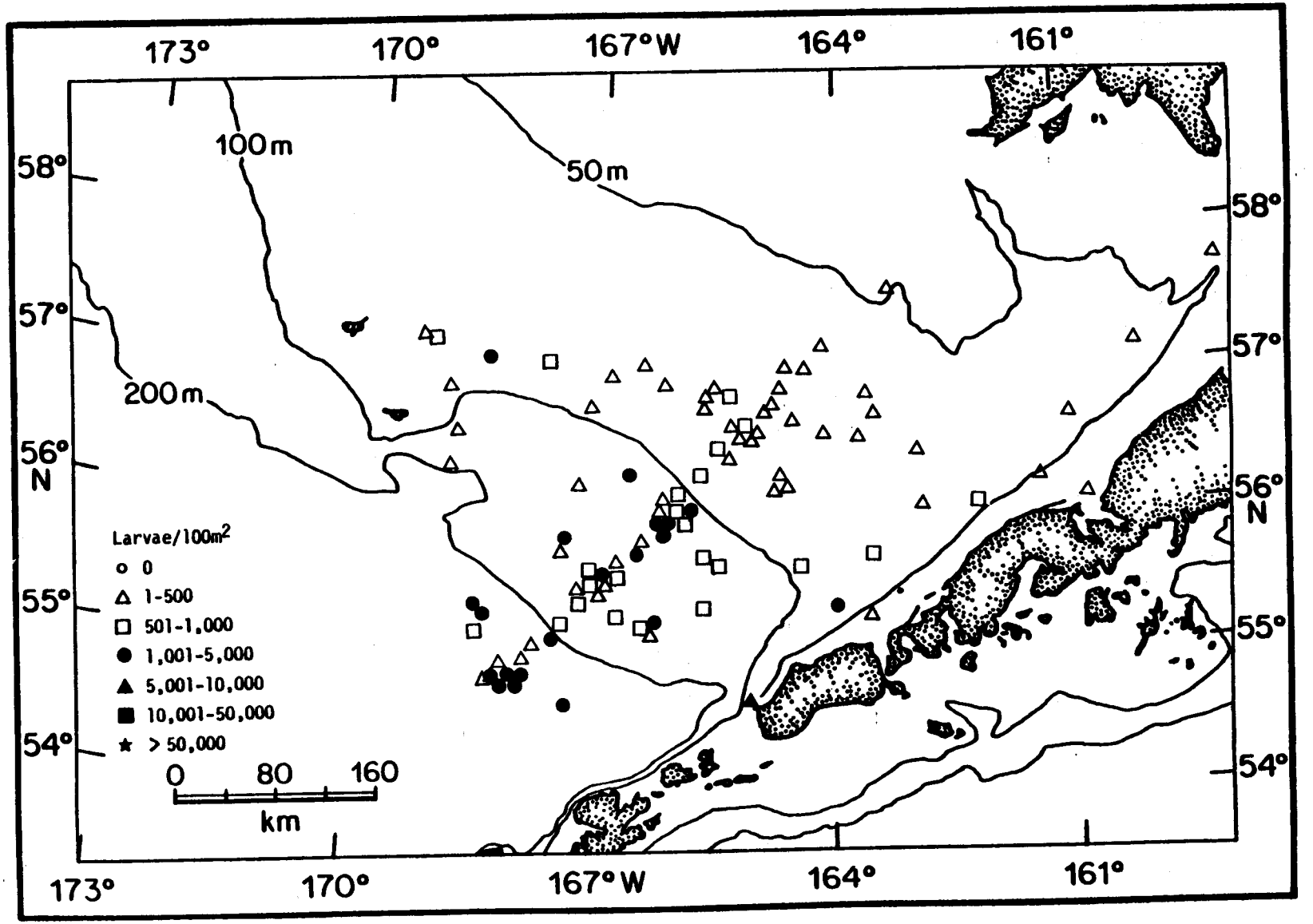


Figure 6.18 Distribution and abundance of Hippolytidae shrimp larvae from PROBES 1981 and NOAA 1981, April-July combined. Zero stations omitted.

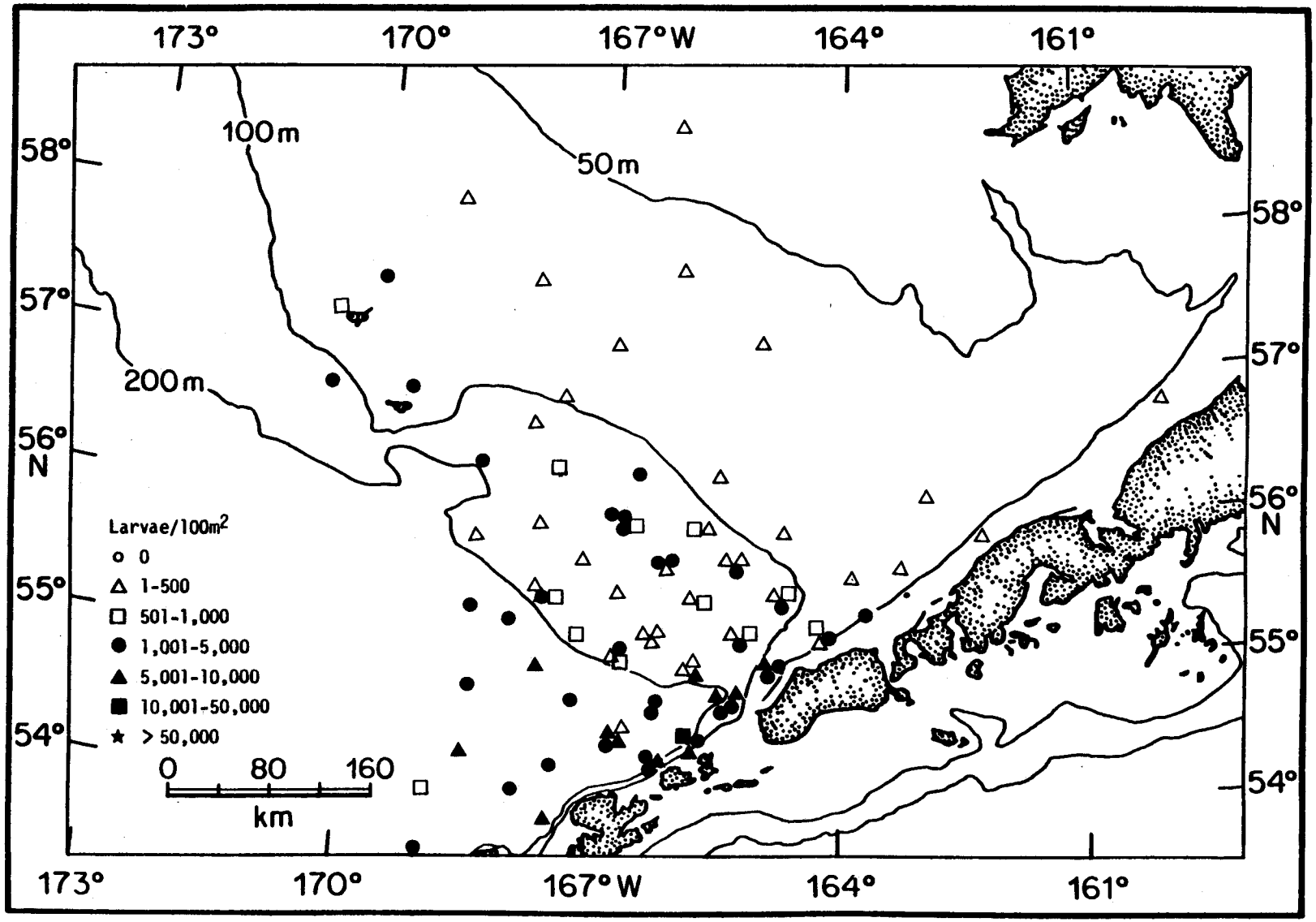


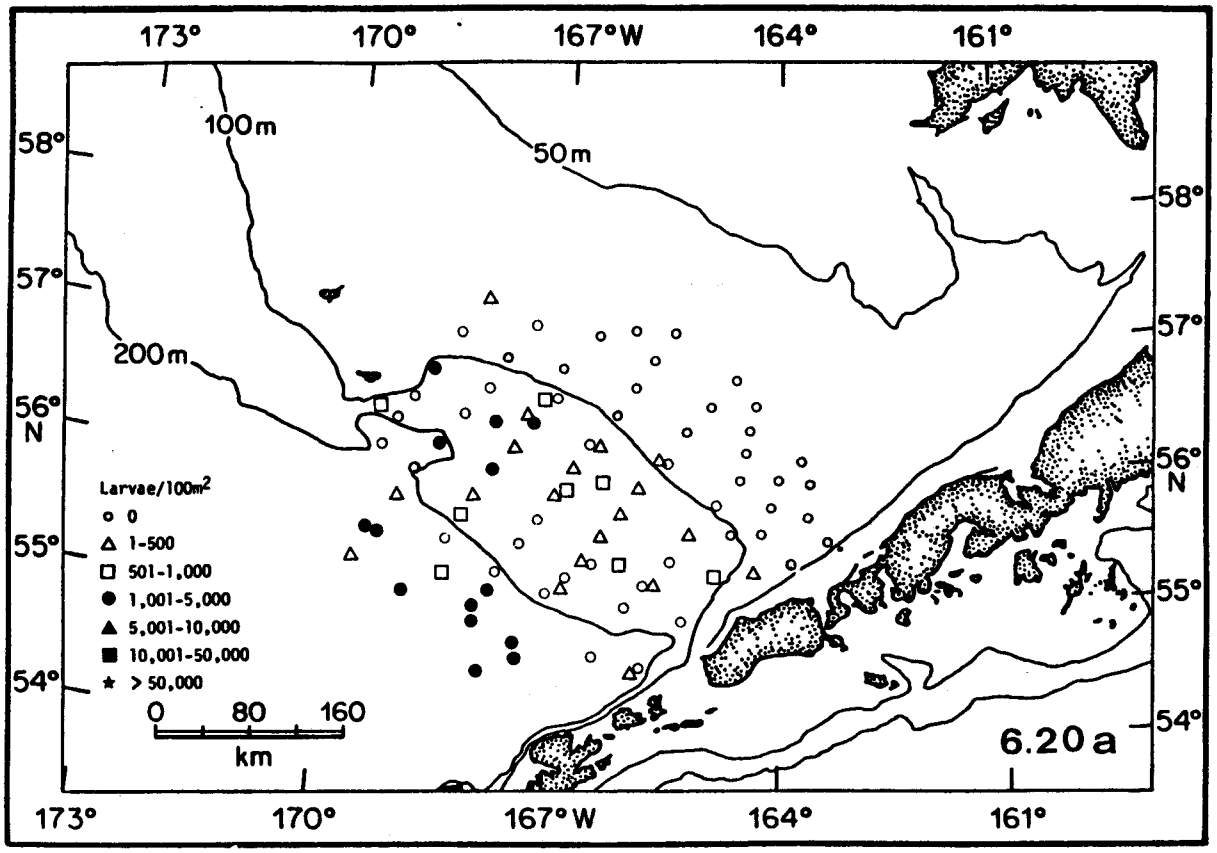
Figure 6.19 Distribution and abundance of Hippolytidae shrimp larvae from NOAA 1976 and 1977, April and May combined. All zero stations omitted.

months within a single year can be seen by comparing larval abundance for April, May and June during PROBES 1978 (Fig. 6.20 a and b). Distribution in April was widely spread over the outer shelf domain and greatest concentrations were found beyond the shelf break (Fig. 6.20a). Distribution in May and June 1978 seemed to be concentrated mainly into 2 bands; one just west of the 100 m isobath and one just beyond the shelf break at the 200 m isobath. By this time of year some larvae were found up in the middle shelf domain. The highest concentration of larvae (12,000 larvae/100 m^2) was found at the western tip of Unimak Island. Further work to identify the species within the hippolytid group would help to delineate distribution patterns of individual species.

Figure 6.21 illustrates mean larval hippolytid densities by month and by years in stratum 3 just west of the 200 m isobath. consistently high mean larval densities (1000-2400 larvae/100 m^2) were found in the months of April, May, and June in stratum 3 during the years 1977-1981. By comparison, slightly lower mean larval densities (600-1650 larvae/100 m^2) were found during May and June in stratum 2 during those years.

A more complete picture of mean larval densities for hippolytids is given in Table 6.7 for PROBES May and June 1978 data. Strata beyond the shelf break again had the highest mean densities which were three-fold greater toward the Aleutian Islands (stratum 4) than toward St. George Island (stratum 7).

Hippolytid larvae were found from 0-80 meters in the water column. Figure 6.22 illustrates the larval depth distribution of hippolytids



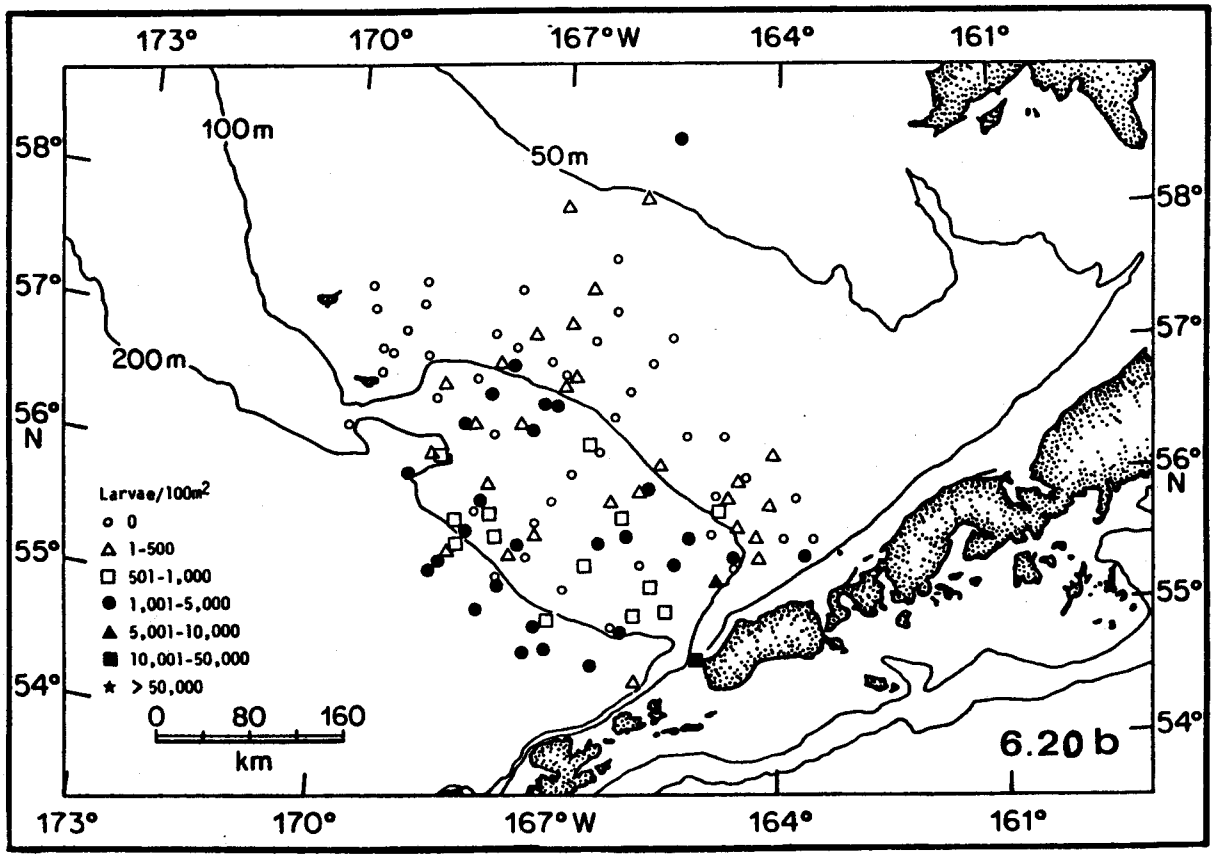
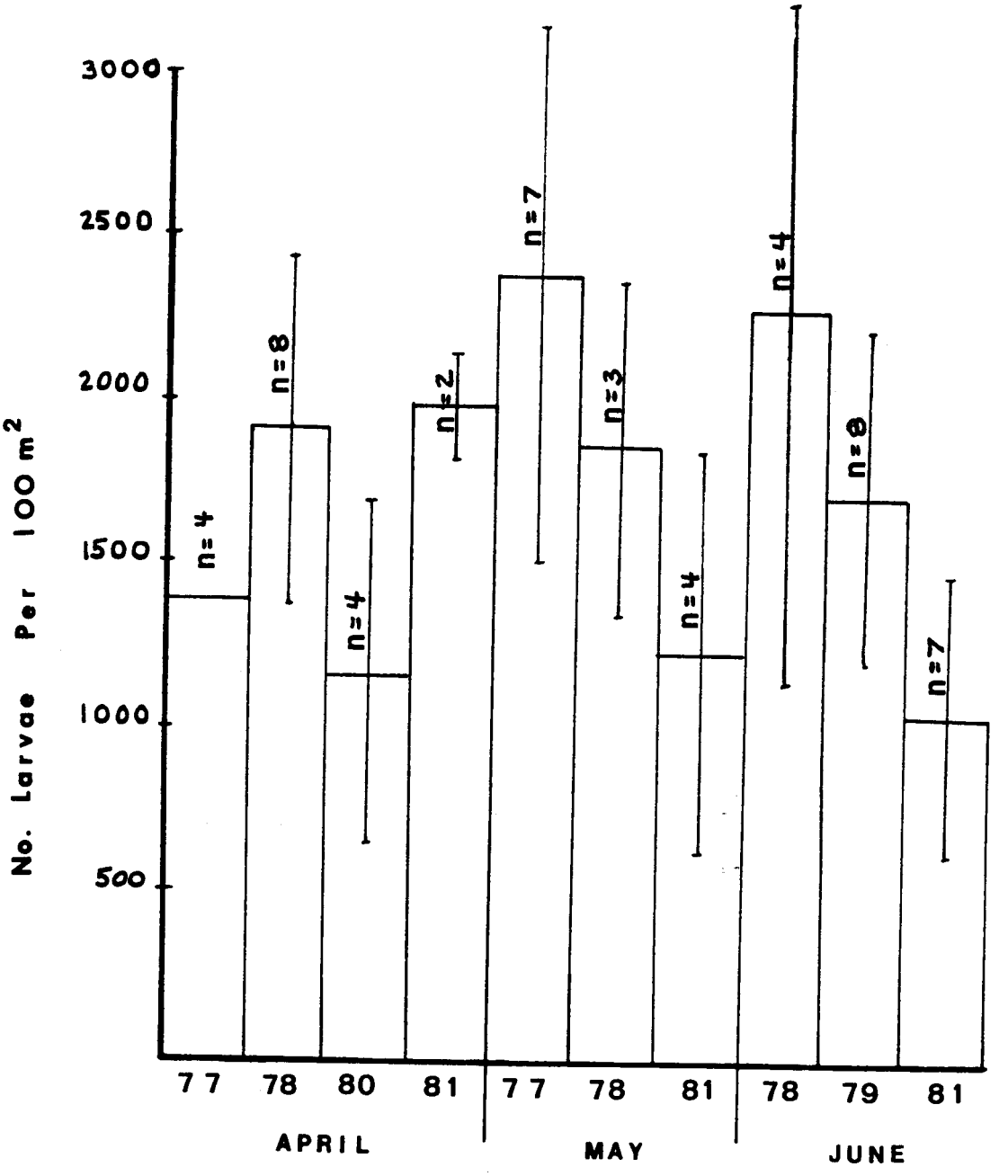


Figure 6.20 Distribution and abundance of Hippolytidae shrimp larvae from PROBES 1978; (a) April only, (b) May and June. Zero stations included.



Stratum 3

HIPPOLYTID LARVAE

Figure 6.21 Hippolytidae shrimp larval abundance in stratum 3 from 1977-1981 by months April, May and June. Values expressed as mean density ±1 standard error. Zero stations are included in these values.

Table 6.7. Cross-shelf comparison of mean densities of Hippolytidae shrimp larvae during May and June from PROBES 1978. Zero stations omitted from calculations. See Figure 2.21 for strata locations. Total stations sampled = N.

Stratum	Mean Density ± 1 S.D. larvae/100 m^2	% positive stations	N
	Oceanic/Shelf Break Domain		
7	836 ± 597	100%	7
3	2445 ± 1575	86%	6
4	2655 ± 3153	100%	2
	Outer Shelf Domain		
8	956 ± 674	76%	17
2	1032 ± 1150	67%	18
5	2033 ± 1736	75%	12
	Middle Shelf Domain		
9	253 ± 317	53%	17
1	143*	14%	7
6	567 ± 800	64%	14

*Based on 1 positive station.

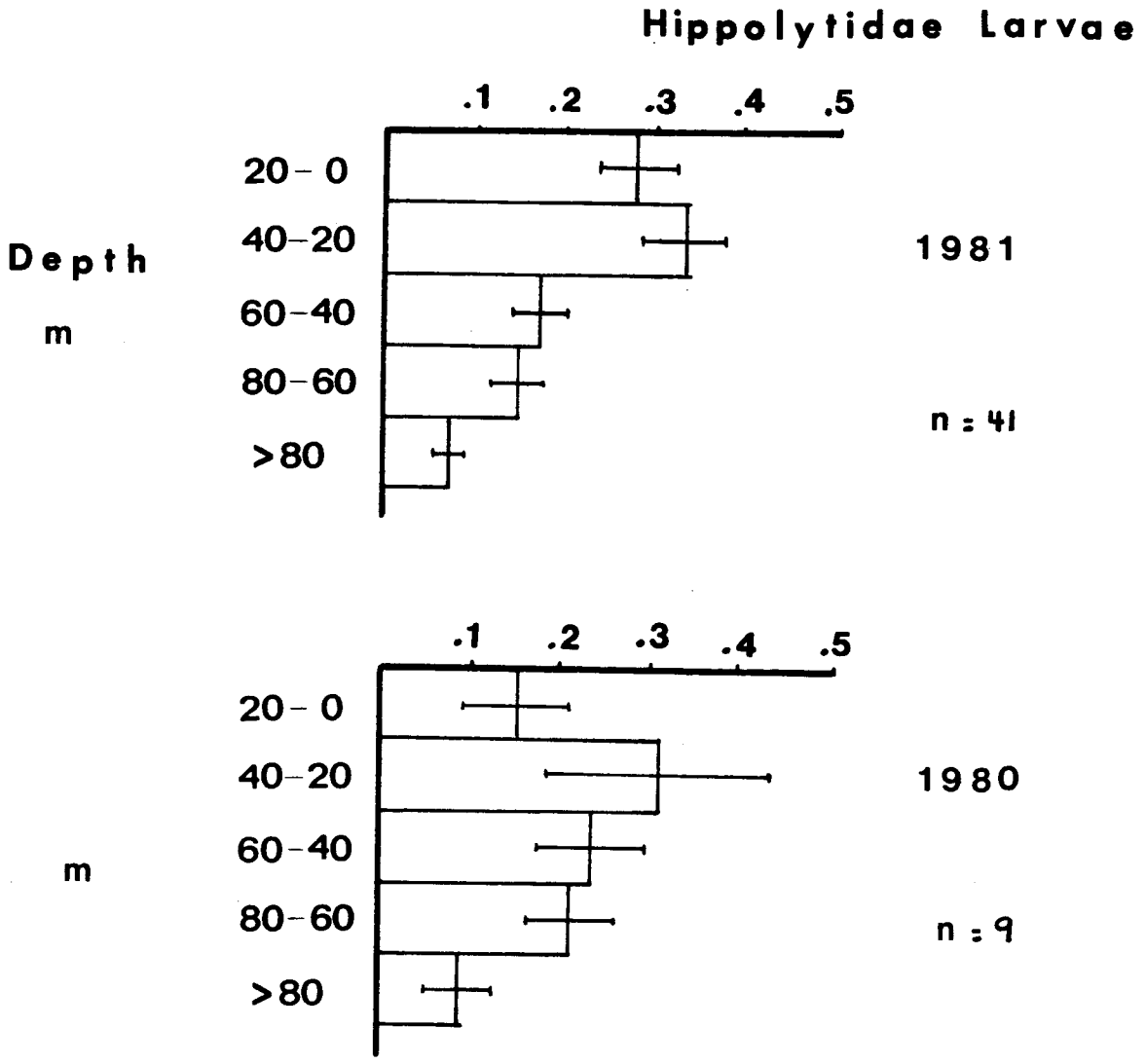


Figure 6.22 Vertical depth distribution of Hippolytidae shrimp larvae from PROBES 1980 and 1981. Values expressed as an average proportion ±1 standard error.

during PROBES 1980 and 1981 sampling from April to July. The total cumulative percentages of larvae in each depth interval were: 15-28% in the upper 20 m; 46-62% in the upper 40 m; 70-79% in the upper 60 m; and 94% in the upper 80 m. This homogeneous distribution from 0-80 m is similar to the pattern for P. borealis. MOCNESS data for PROBES 1981 were analyzed by month (Fig. 6.23). Larvae were concentrated in the 40-80 m depths during April, in the 0-40 m interval during May and June, and homogeneously throughout 0-80 m by late June and July. Examining the pattern of larval depth distribution within each depth interval (Fig. 6.23) clearly shows the highest percentage of larvae (about 40%) in the 20-0 and 40-20 m intervals during May and June, and a high percentage of larvae (about 30%) in the 80-60 m interval both in April and then again in late June and July. This changing pattern of hippolytid larval depth distribution might be correlated to food availability or temperature, light and other factors. Correlations are difficult to perform since the hippolytids are a multi-species group.

Summary:

1) Larvae of some hippolytids hatch out as early as March, while other species not until April or May.

2) Hippolytids are distributed widely over the St. George Basin, into the mid-shelf domain and beyond the shelf break.

3) Greatest densities occurred beyond the shelf break and along the Aleutian Islands, especially near Unimak Pass. Mean densities beyond the shelf break ranged from 1000-2000 larvae/100 m^2 in May and June during years from 1977-1981.

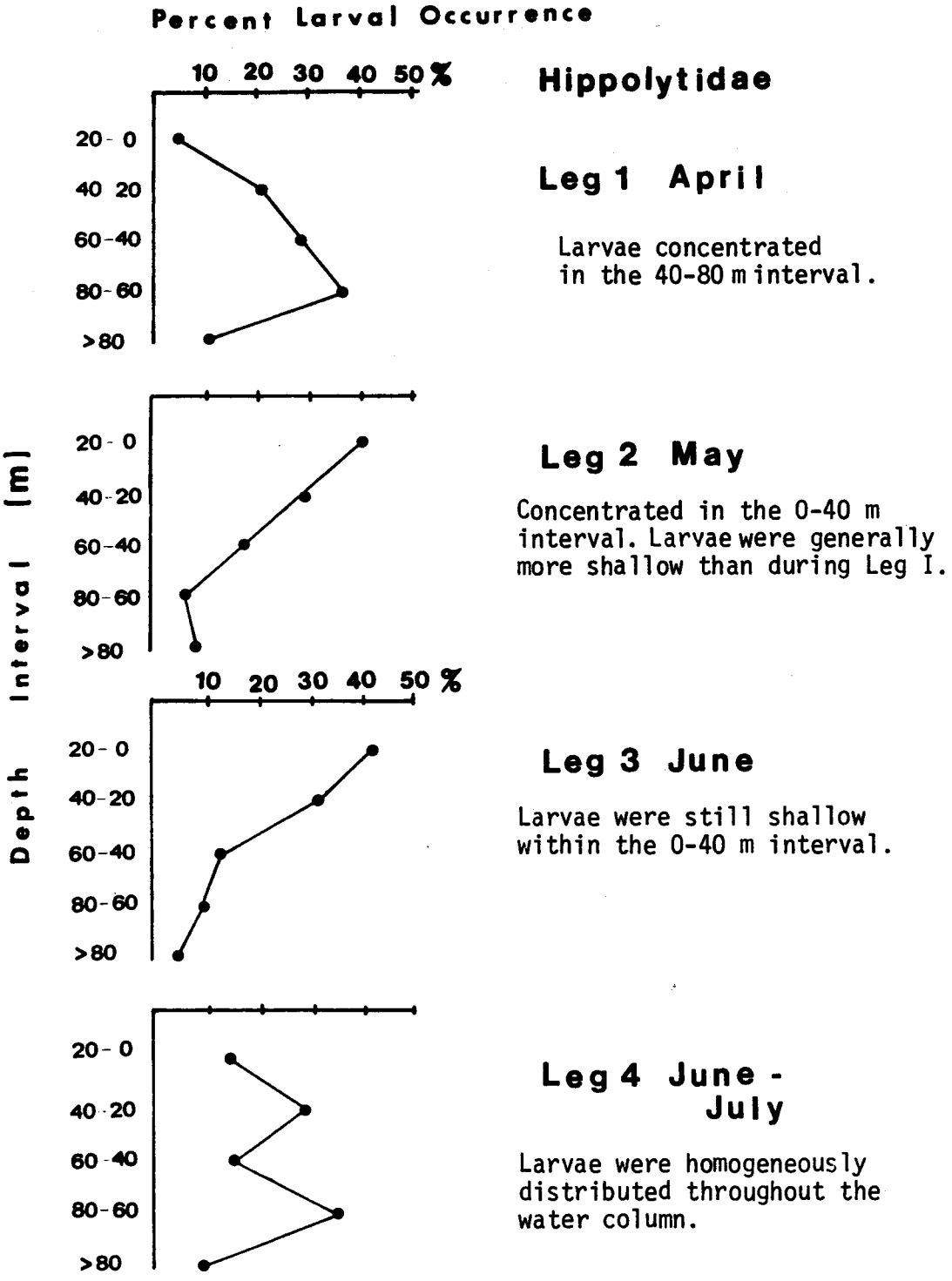


Figure 6.23 Vertical depth distribution of Hippolytidae shrimp larvae by month from PROBES 1981. Values expressed as percent occurrence of larvae versus depth.

4) Larvae were distributed nomogeneously throughout the water column from 0-80 m although the depth of preponderance sometimes shifted month to month.

5) Larvae probably metamorphose and settle out of the water column by late August to early September.

6.6.3 Crangonidae

Larval Duration: Stage I Crangon spp. larvae were first collected over the St. George Basin in early April to mid-April (1977, 1978, 1980 and 1981 cruises). They were still present in the water column by the end of June in 1978, indicating an extended period of hatchout in that year, whereas in 1981 SI were not taken after mid-May. The duration of larval stages in 1981 is shown in Figure 6.24. Since SI and II were taken from the start of sampling, hatchout must have begun in late March 1981. An intermolt period of 12-16 days between SII-III and III-IV is similar to the 2-3 week intermolt period found for Pandalus borealis. Since the larvae of Crangon spp. have up to 7 zoeal stages (Kurata 1964), they may be in the water column until mid- to late August. The long durations for each stage, 45-60 days, shown in Figure 6.24, are probably exaggerated since there are more than one species of crangonid larvae included in this group.

Crangonids have one of the fastest rates of development (i.e., about a 2 week intermolt period) of all natantian shrimp of the St. George Basin, as shown by the molt frequency histogram (Fig. 6.25) for data from PROBES 1981. The protracted hatchout time (April - June) is

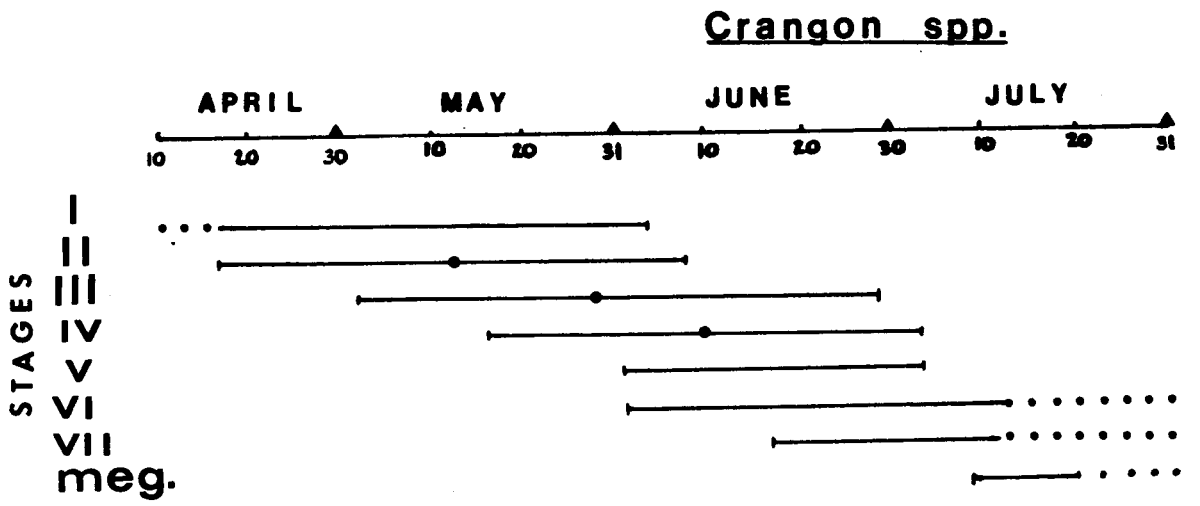


Figure 6.24 Crangon spp. larval stage durations from PROBES 1981. Dots represent hypothetical time duration for certain stages not sampled early or late enough to note complete development.

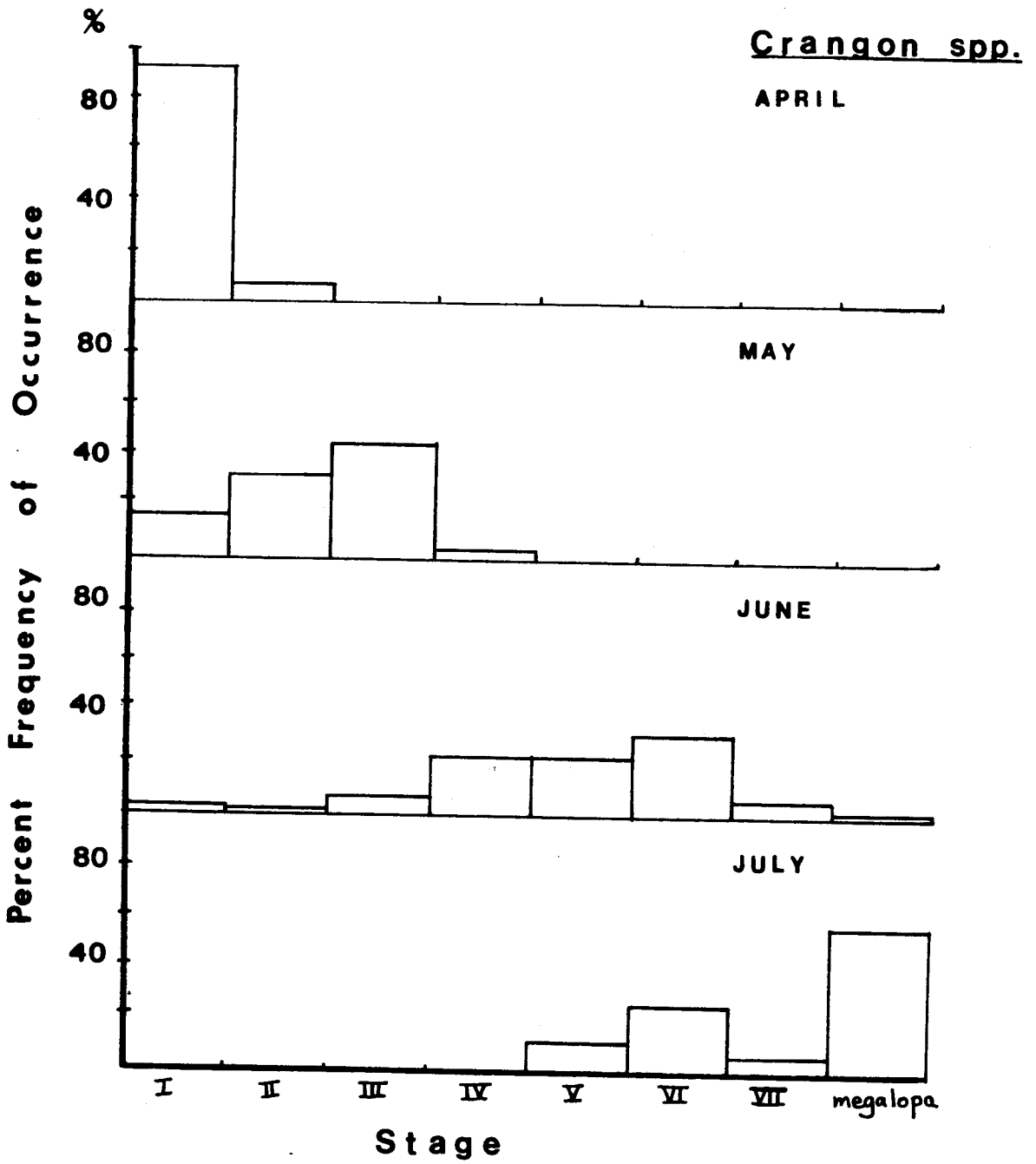


Figure 6.25 Crangon spp. stage frequency of occurrence by month from PROBES 1981.

most probably due to the mix of species in our samples. Even though they have 5-7 larval stages before the megalops is reached, the majority of larvae (given a 2 week intermolt period) would have metamorphosed and settled out of the water column by early August in 1981. In April of that year, 93% of the larvae were SI in April, while 58% were megalopae by July.

Argis spp. (A. lar, A. dentata and A. ovifer) were present at 2% or 13 of the 626 station locations sampled from 1976-1981 (Fig. 6.26). Except for one station (A_5 on the PROBES A line), they favored the mid-shelf domain and stations < 100 m sonic depths. All stages, I, II and megalopae, were taken during April to July. Megalopae in particular were taken as early as May 23rd (NOAA, R/V Alaska) and as late as July 4th (PROBES) in 1981.

Distribution and Abundance: Four species of adult crangonids, Crangon communis, C. dalli, Argis dentata, and A. lar, are routinely taken during trawl surveys of the St. George Basin (Paul Anderson, NMFS, Kodiak, Alaska, personal communication). According to Ivanov (1969), crangonid adults dominate the 0-50 m depth zone of the inner shelf domain. This region was only sporadically sampled during the 1976-1981 cruises and thus substantiation of this fact was difficult. However, nearshore distribution of crangonids was confirmed during the 1982 OCSEAP cruises along the North Aleutian Shelf. From Unimak Island to Port Moller, the dominant shallow water shrimp taxa were Crangonidae (D. Armstrong, pers. observation, June 1982, R/V Miller Freeman), primarily C. communis, C. alaskensis and A. dentata.

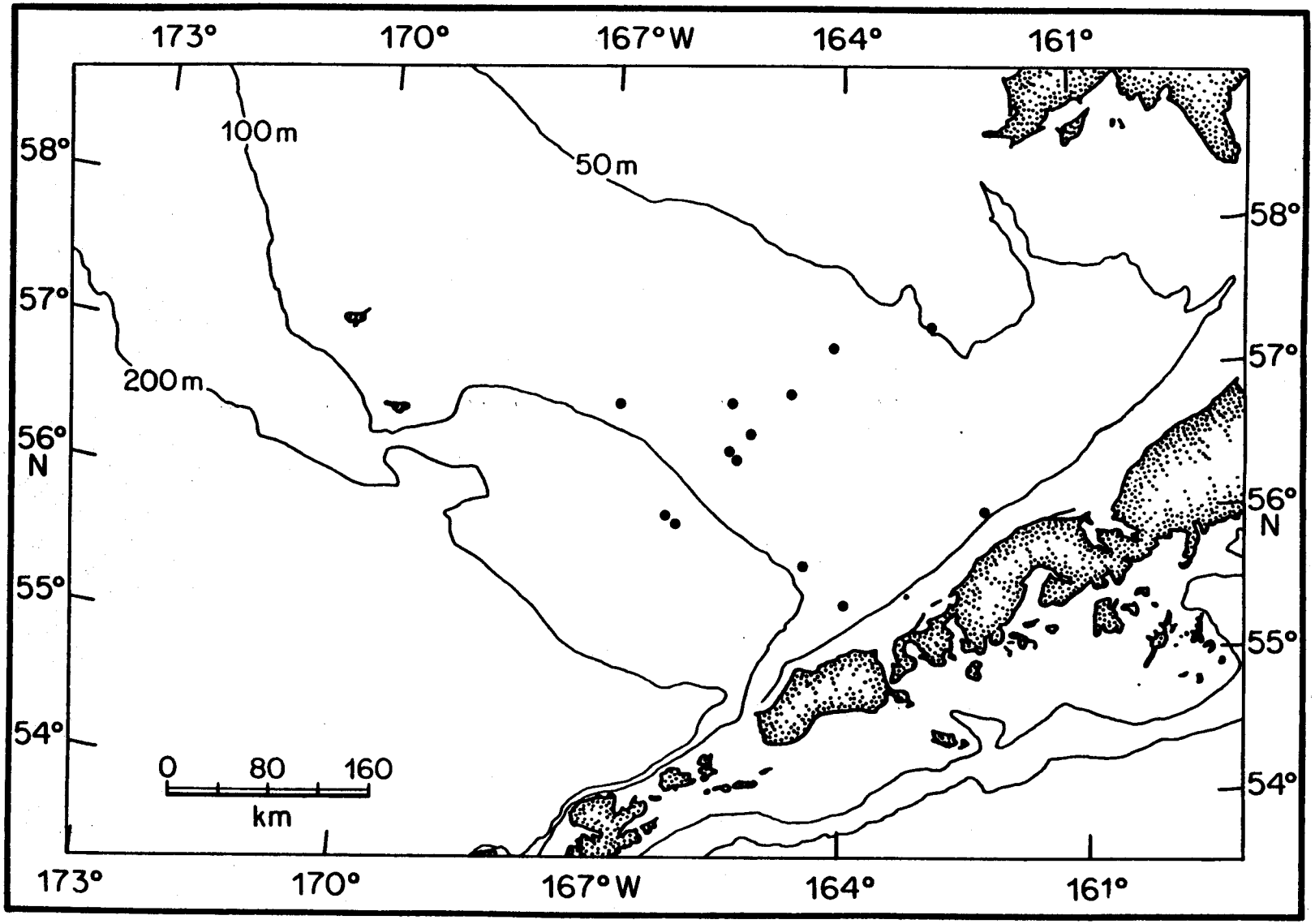


Figure 6.26 Argis spp. distribution from all years 1976-1981, all months April-July combined. Positive station locations indicated by a small black dot. See Section 2.0 for station locations and cruises.

Larval crangonids, Crangon spp., were consistently found in greater abundance over the St. George Basin of the outer shelf domain in a band west of the 100 m isobath. Figures 6.27-6.30 depict the larval distribution and abundance of Crangon spp. from PROBES and NOAA cruises from 1976 to 1981. While the crangonids were almost as wide ranging as the hippolytids, they were generally absent beyond the shelf break and most prevalent over the inner shelf domain (less than 50 m). The two high density (> 1000 larvae/100 m^2) stations in the inner shelf domain (Fig. 6.27) were due to a different species than found at the high density stations over the St. George Basin. Figure 6.28 gives the distribution of Crangon spp. larvae during April and May of 1976 and 1977 (NOAA). Greatest larval densities were found in the outer shelf domain of the St. George Basin midway between the 100 and 200 m isobaths and also off Akutan and Unalaska Islands.

Monthly variation in density is illustrated by comparing Figs. 6.29 for April and 6.30 for May and June PROBES 1978. By April in 1978, Crangon spp. were distributed at fairly low densities throughout the St. George Basin and infrequently over the southern half of the mid-shelf domain. By May and June, larvae were concentrated in a band along the 100 m isobath at slightly higher densities than found in April (Fig. 6.30). This is somewhat different from the pattern seen in 1981 when sampling effort concentrated on the PROBES A line and distribution by May and June was extensive over the middle shelf domain (Fig. 6.27). Monthly variation is also illustrated by Figure 6.31 that depicts Crangon spp. larval mean densities in stratum 2 by month and by year. Mean

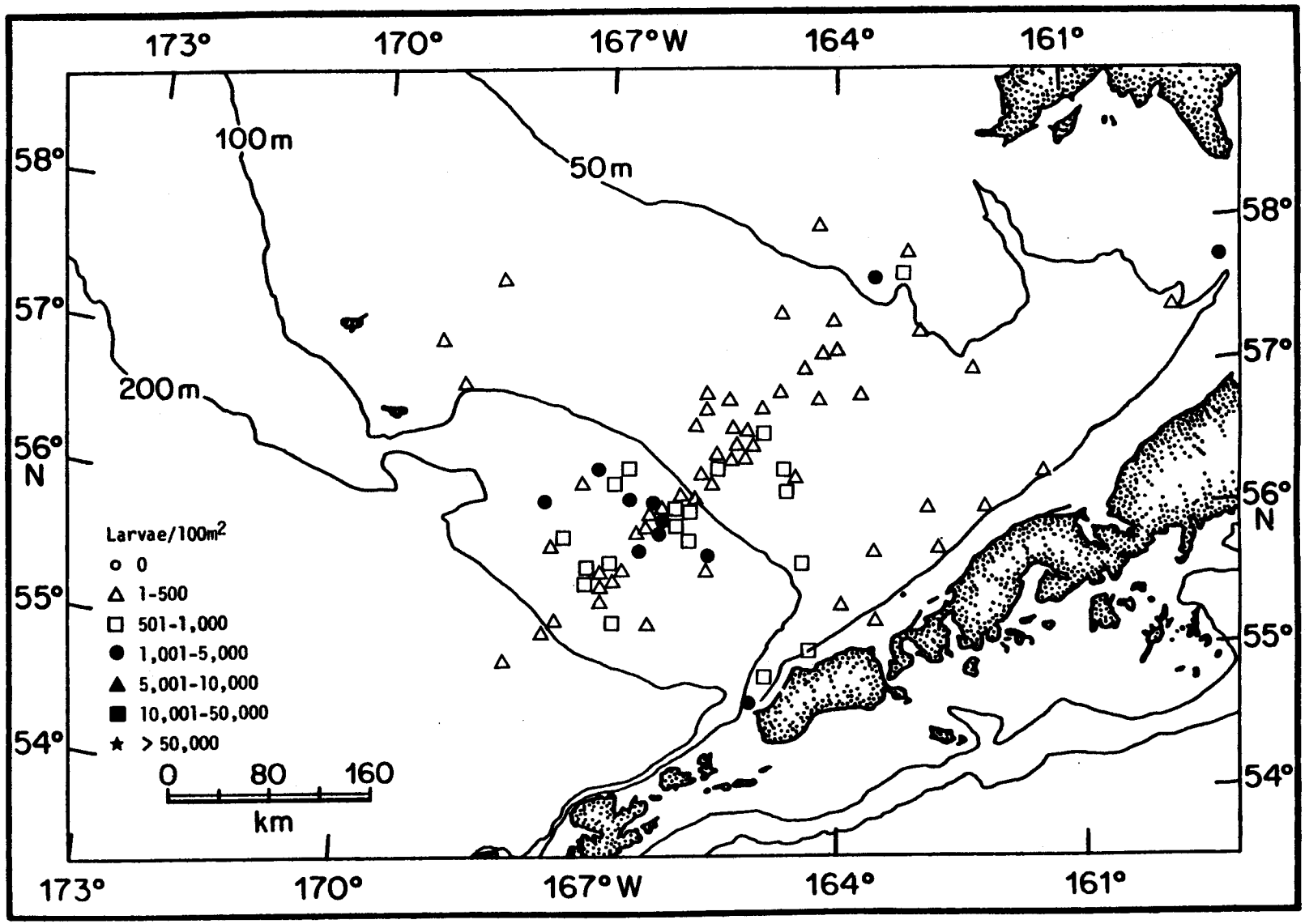


Figure 6.27 Distribution and abundance of Crangon spp. larvae. NOAA 1979 and 1981, PROBES 1980 and 1981, all months April-July combined.

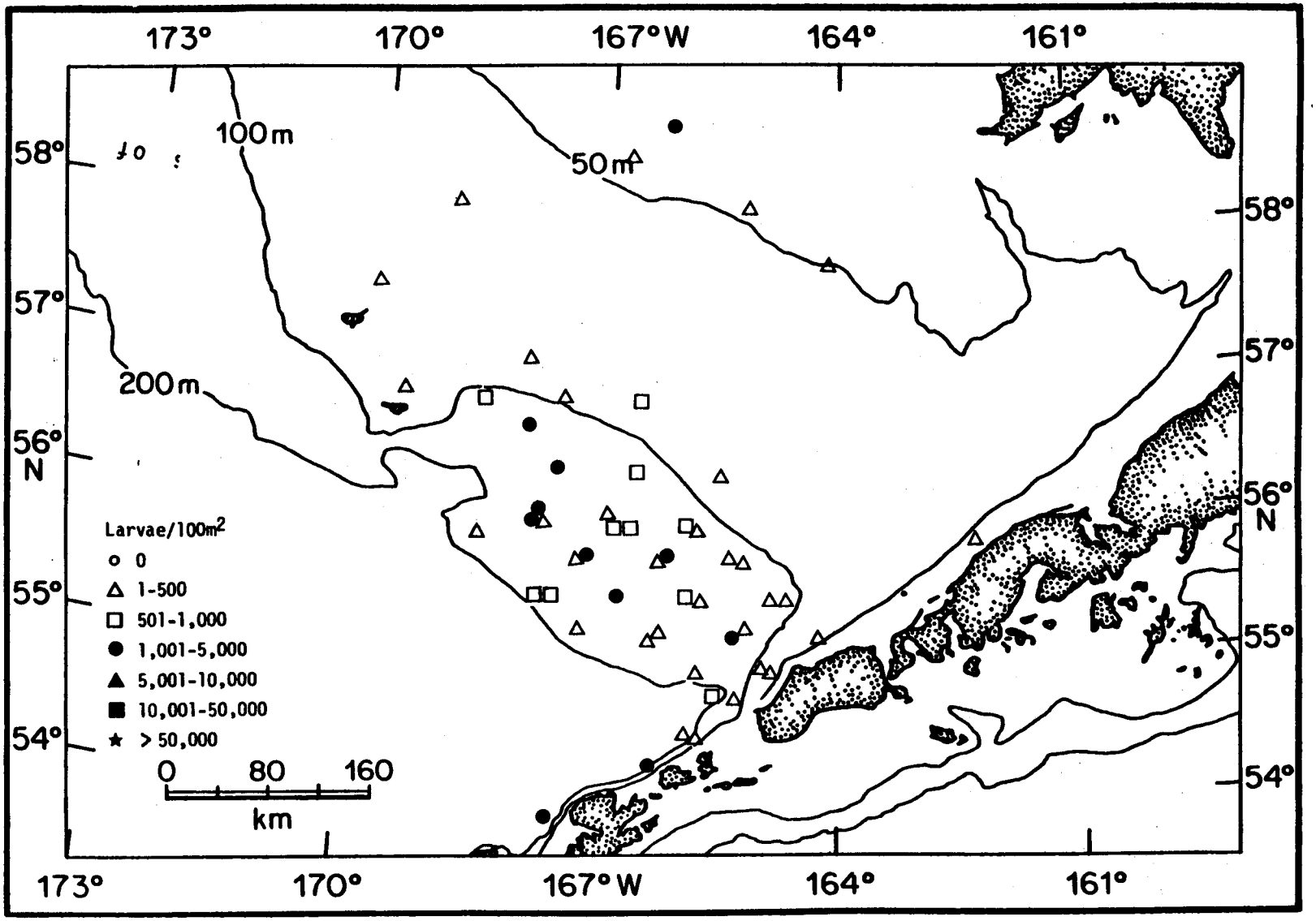


Figure 6.28 Distribution and abundance of Crangon spp. larvae from NOAA 1976 and 1977, April and May combined. Zero stations omitted. See Section 2.0 for all station locations for these cruises.

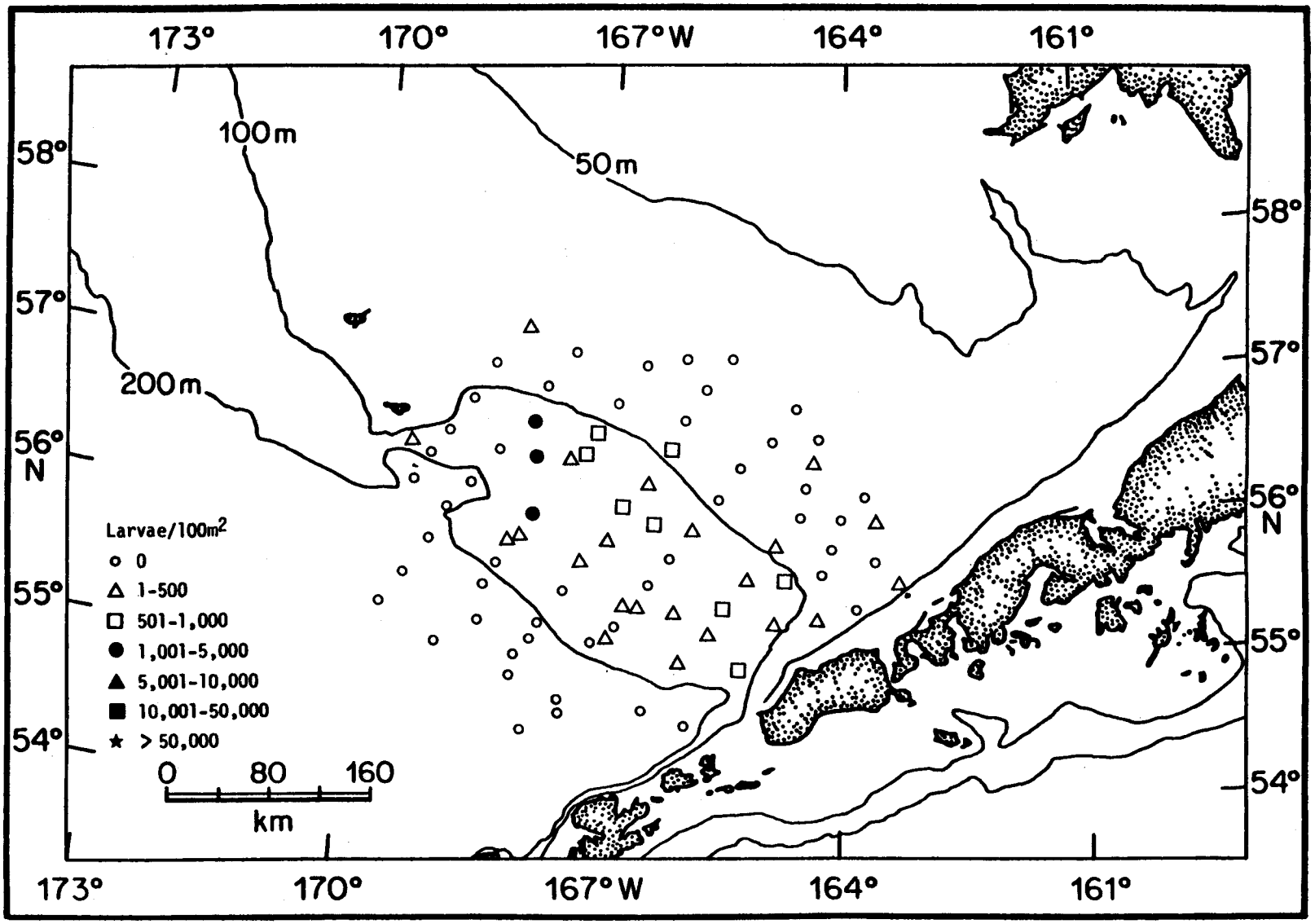


Figure 6.29 Distribution and abundance of Crangon spp. larvae from PROBES 1978, April. Zero stations included.

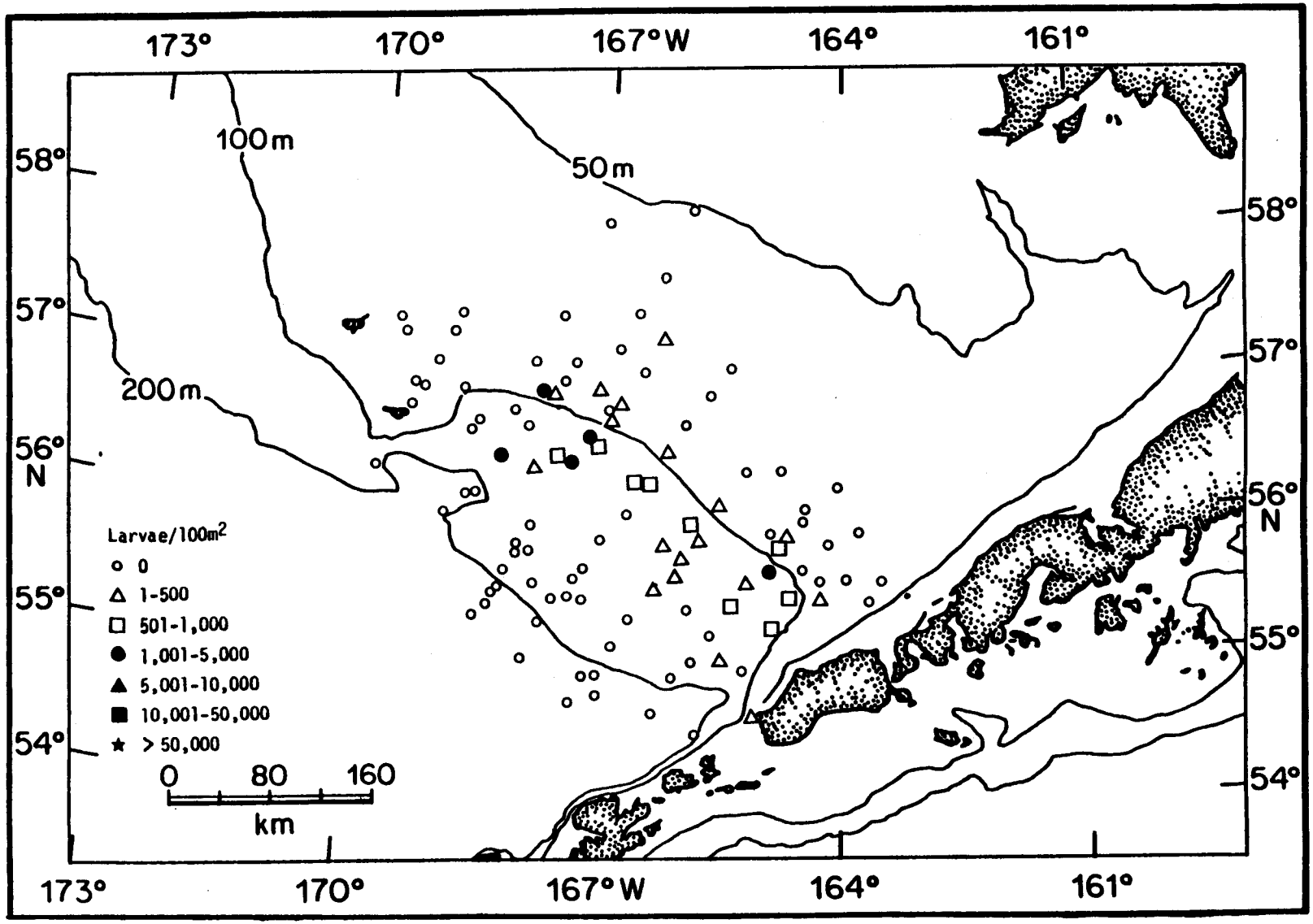


Figure 6.30 Distribution and abundance of Crangon spp. larvae from PROBES 1978, May and June. Zero stations included.

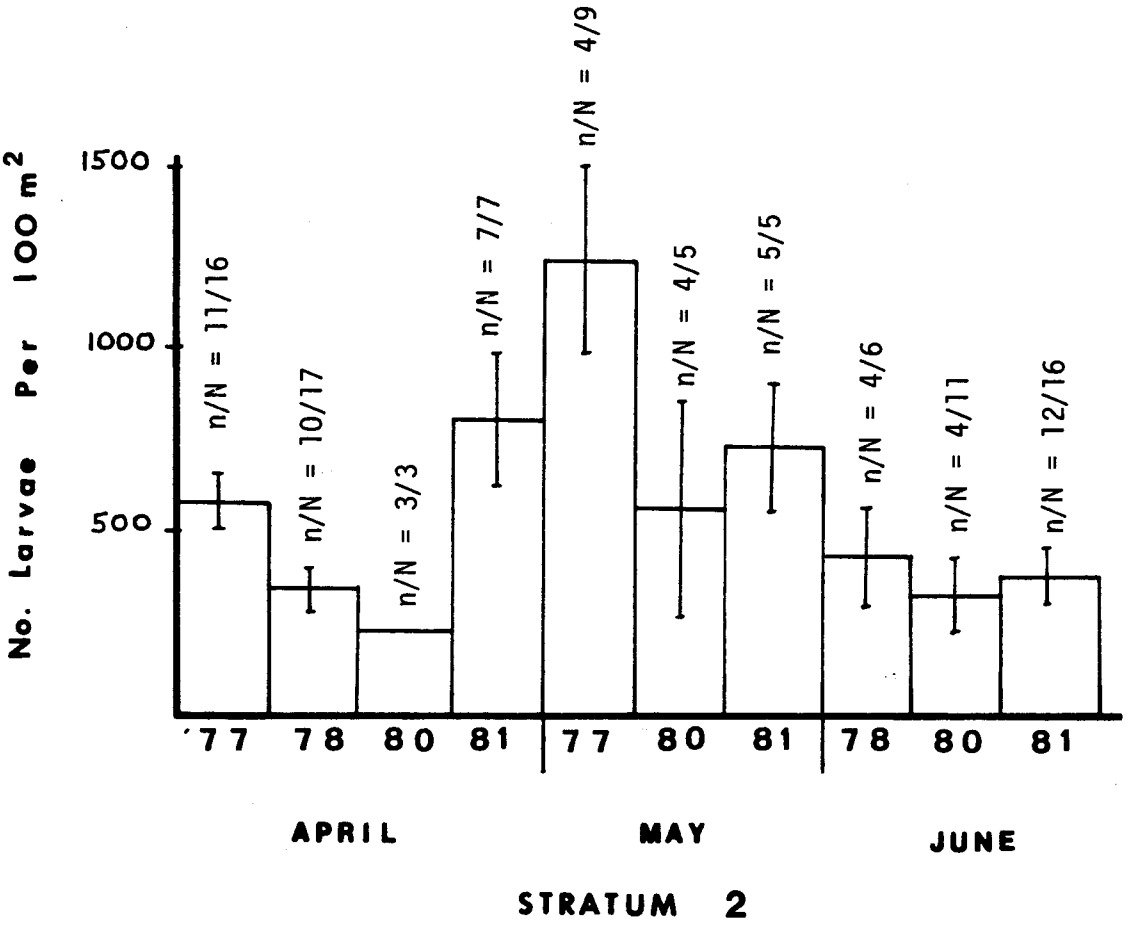


Figure 6.31 Crangon spp. larval abundance in stratum 2 from 1977-1981 during April, May and June. Values expressed as mean density ±1 standard error. Zero stations were excluded from these calculations. The number of positive stations (n) and the total number of stations sampled (N) for each year is shown above the bars.

larval densities were generally low (< 500/100 m^2), but greatest abundance always occurred in May (1000 larvae/100 m^2) over stratum 2. The frequency of occurrence of larval crangonids in the 1981 samples was high (present in 75-100% of the samples), whereas in other years crangonids were taken less frequently (in 33-80% of the samples). The lowest mean densities were consistently taken in 1980. Table 6.8, the cross-shelf comparison of mean densities of Crangon spp. larvae during May and June PROBES 1978, demonstrates three trends. First, the absence of any Crangon spp. larvae beyond the shelf break; second, in the outer shelf domain, highest densities were found in the north and south of the St. George Basin; third, crangonids were less abundant over the middle shelf with mean density between 260-375 larvae/100 m^2. Crangonids were consistently less abundant than either the pandalids or hippolytids.

MOCNESS data from PROBES 1980 and 1981 cruises were analyzed but there were insufficent stations during 1980 for a complete workup of vertical depth distribution. Only 5 stations out of a possible 26 had more than 6 larvae per station and a sample size of 5 stations was regarded as unacceptable. For the 1981 data, a homogeneous distribution of Crangon spp. larvae throughout the water column is shown in Fig. 6.32. Crangon spp. larvae were distributed between 0-80 m with 16% in the upper 20 m, 47% in the upper 40 m, 76% in the upper 60 m, and 93% in the upper 80 m.

Summary:

1) Hatchout of Crangon spp. begins in late March and the larvae remain in the water column until early August.

Table 6.8. Cross-shelf comparison of mean densities of *Crangon* spp. larvae during May and June from PROBES 1978. Zero stations in each stratum omitted in these calculations. See Figure 2.21 for strata locations. Total number of stations sampled = N.

Stratum	Mean Density ± S.D. (larvae/100 m^2)	% positive stations	N
	Oceanic/Shelf Break Domain		
7	0	0%	7
3	0	0%	7
4	0	0%	2
	Outer Shelf Domain		
8	1119 ± 694	35%	17
2	310 ± 260	44%	18
5	818 ± 547	50%	12
	Middle Shelf Domain		
9	375 ± 481	35%	17
1	330 ± 202	29%	7
6	264 ± 278	21%	14

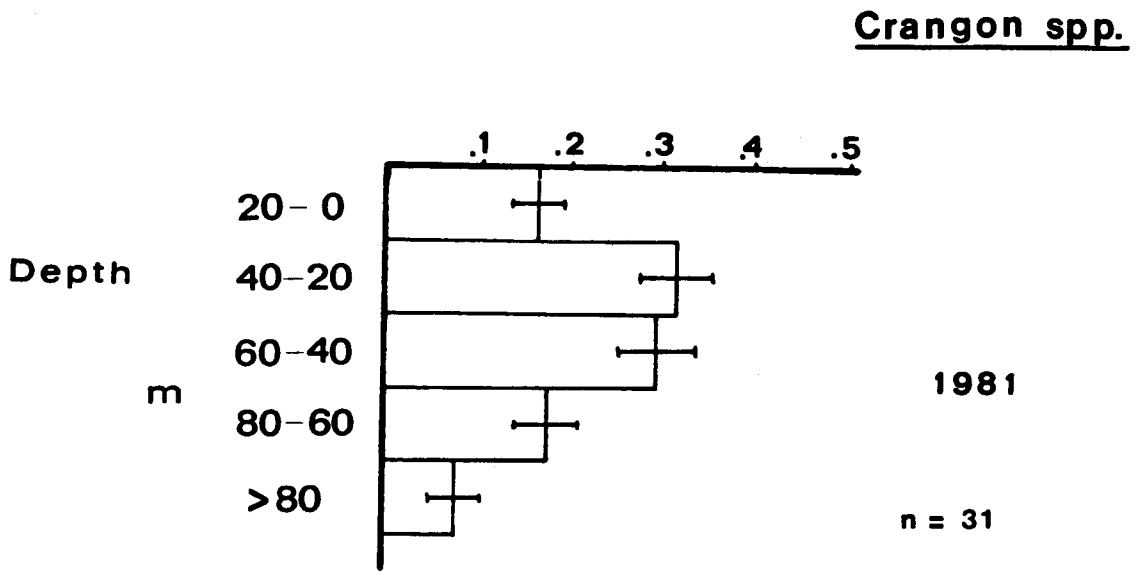


Figure 6.32 Vertical depth distribution of Crangon spp. larvae from PROBES 1981. Values expressed as an average proportion ±1 standard error. Total number of MOCNESS stations used in these calculations is given by n.

2) The intermolt period of about 2 weeks seems to be the shortest of all the shrimp taxa.

3) Crangonids are widely distributed over the St. George Basin and extend into the middle and inner shelf domains.

4) Crangonids were caught less frequently than either the pandalids or hippolytids.

5) Greatest densities occurred over the outer shelf domain where average mean densities were 300-1000 larvae/100 m^2. Middle shelf domain densities were generally about 300 larvae/100 m^2. Outer shelf domain densities tended to be greater near the Pribilofs and the Aleutian Island chain rather than over the central St. George Basin.

6) Larvae were distributed homogeneously throughout the water column from 0-80 m.

6.6.4 Penaeidae

The spiny larval form of disputed origin(s), currently assigned to the family Penaeidae, is assumed to come from deep dwelling parental stocks since larvae were most abundant at stations of depths $\geq$ 200 m.

Larval Duration: Stage I spiny larvae were first taken in mid-April in 1977, 1978, 1980 and 1981. Larval stage duration is shown in Figure 6.33 for PROBES 1981 data. Note the very long durations for SII and III; 75 days for SII, and 56 days for SIII. Although not shown by

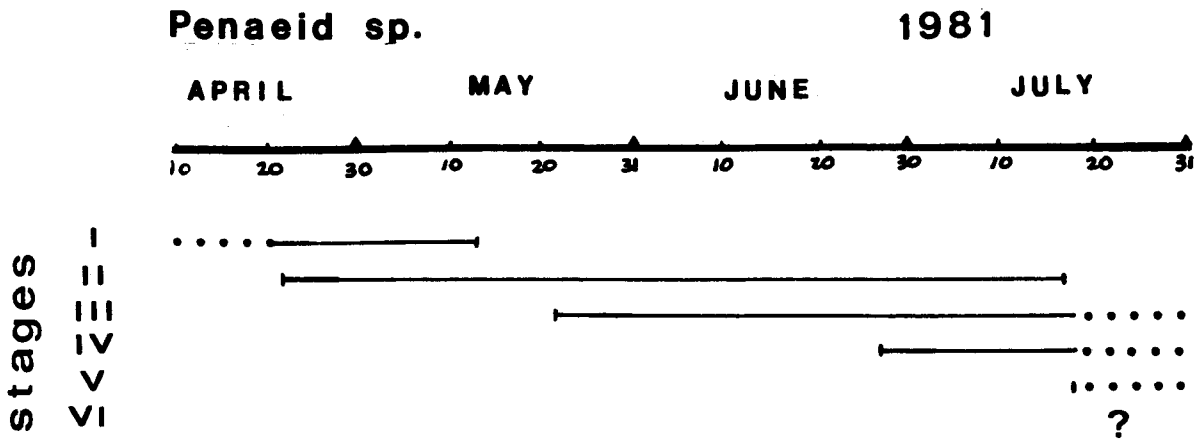


Figure 6.33 Penaeid sp. larval stage durations from PROBES 1981. Dots represent hypothetical portions of stage duration for which no samples were available.

Figure 6.33, these deepwater shrimp must have a protracted hatchout period. [Late summer sampling,as taken in August 1982, will be examined for later stages (IV-VI) of this species.] Kurata (1964) described SVI and VII of a similar spiny larva, which he assigned to Glyphocrangon spp. One sample collected in October 1980 by the R/V Alpha Helix from east of the 200 m isobath contained one of these later SVI larvae. Additional late summer examples of this spiny larva may have been collected among the 1982 samples. Neither the total number of larval stages nor the total duration of planktonic larval life is known for this species.

A molt frequency histogram, based on the PROBES 1981 cruises, is given in Figure 6.34 for these spiny larvae. The intermolt period seems to be about 20 days and thus (given at least 7 larval stages) these zoeae would be in the water column until the end of September or early October (as supported by the Alpha Helix collection in October 1980).

Distribution and Abundance: Positive station values for all years, 1976-1981, were combined for Figure 6.35. The deep water origin (> 200 m) of these spiny penaeid larvae is evident, and maximum densities of 1000-9000 larvae/100 m^2 occurred in strata 7, 3, and 4 beyond the shelf break. Abundance of these larvae over the outer shelf domain of the St. George Basin was generally very low, with densities ranging from 20-200 larvae/100 m^2 in strata 8, 2 and 5 except during May 1977 (NOAA) when higher densities of 200-3000 larvae/100 m^2 were taken in strata 8 and 5. Spiny larvae were rarely caught during the 1976, 1979, and 1980 cruises and were caught in very low numbers (< 500 larvae/100 m^2) in stratum 3

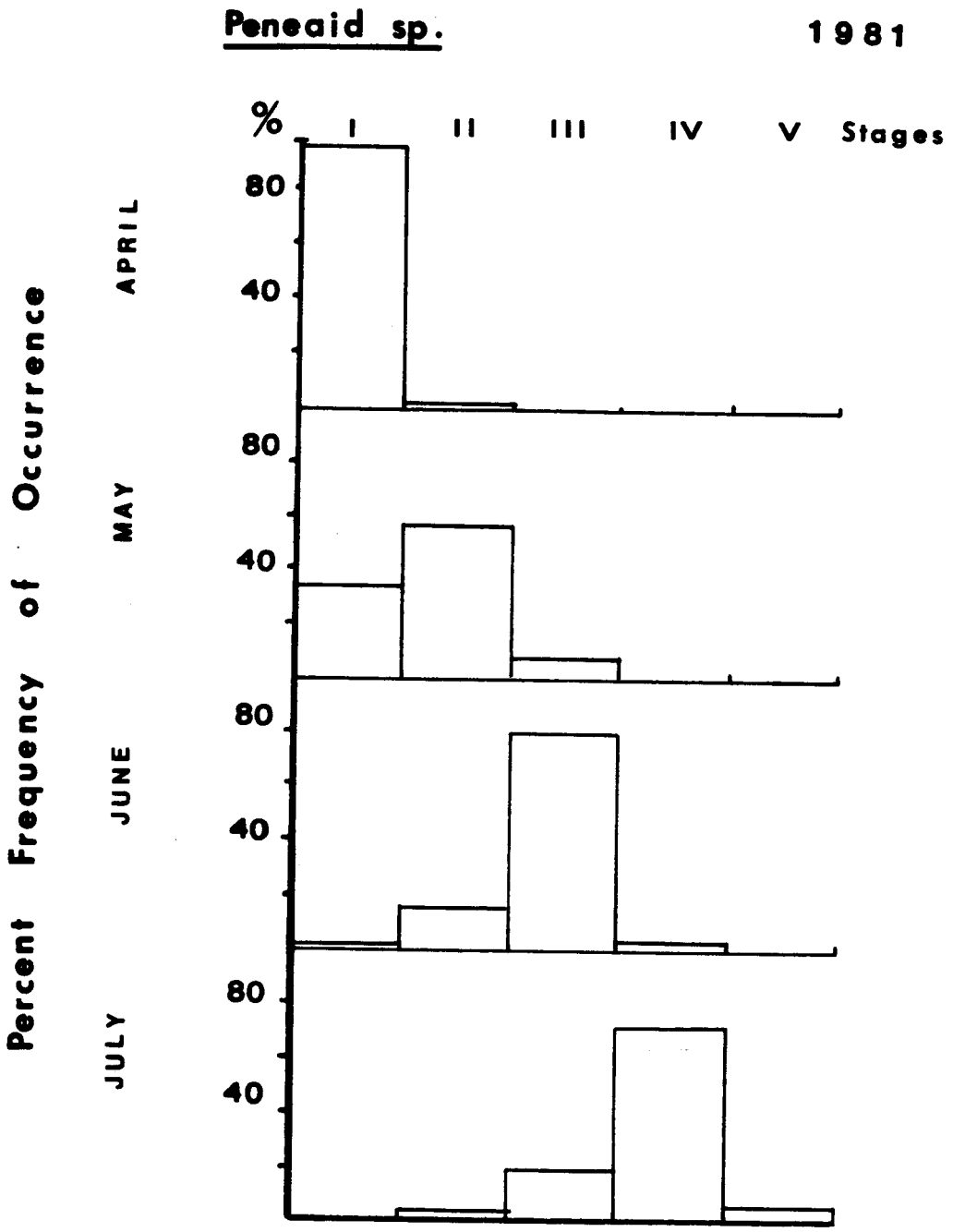


Figure 6.34 Penaeid sp. stage frequency by month from PROBES 1981.

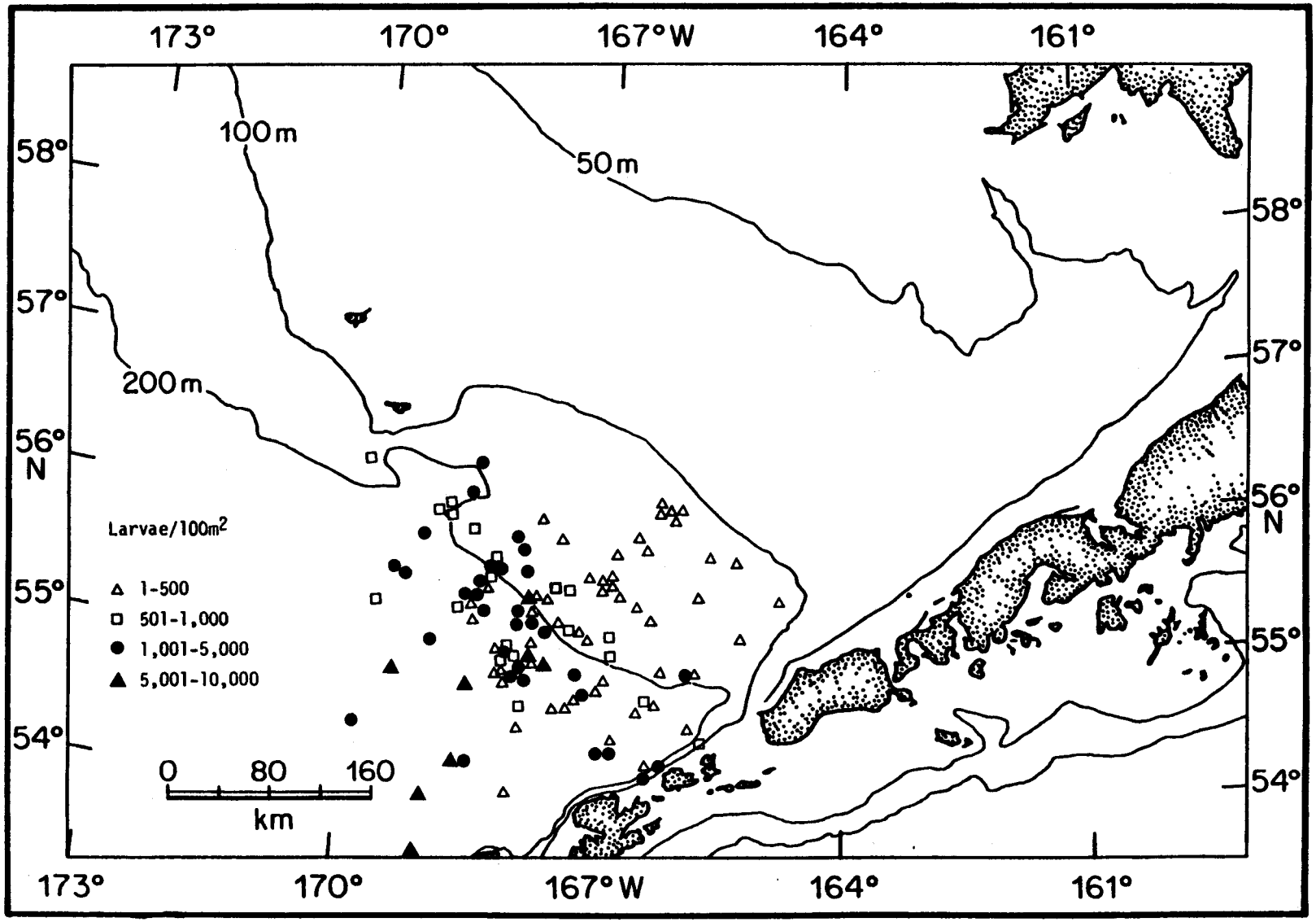


Figure 6.35 Distribution and abundance of penaeid species larvae all years 1976-1981 and all months April-July combined. Zero stations omitted.

in 1981 due to the sampling patterns employed during those years. No spiny larvae were ever found in the middle shelf domain (strata 9, 1, and 6) during any of the cruises.

Table 6.9 compares mean larval densities during April and May from NOAA 1977 with densities during May and June from PROBES 1978. Generally higher mean penaeid densities occurred during 1977 for all strata except stratum 8. In addition, the pattern of increasing abundance with increasing station depth is clearly apparent; none was found over the middle shelf, but an average of 4390/100 m^2 was found in stratum 3 over the shelf break.

Vertical Distrubtion: Of all the shrimp, these spiny larvae were the most homogeneously distributed in the water column from 0-80 m (see Fig. 6.36). Based on PROBES 19801 MOCNESS data, a cumulative total of 20% of penaeid spp. larvae appeared in the upper 20 m, 45% in the upper 40 m, 75% in the upper 60 m, and 98 % in the upper 80 m. Low abundance of these spiny larvae in PROBES 1980 samples precluded any depth distribution analysis for that year.

Summary:

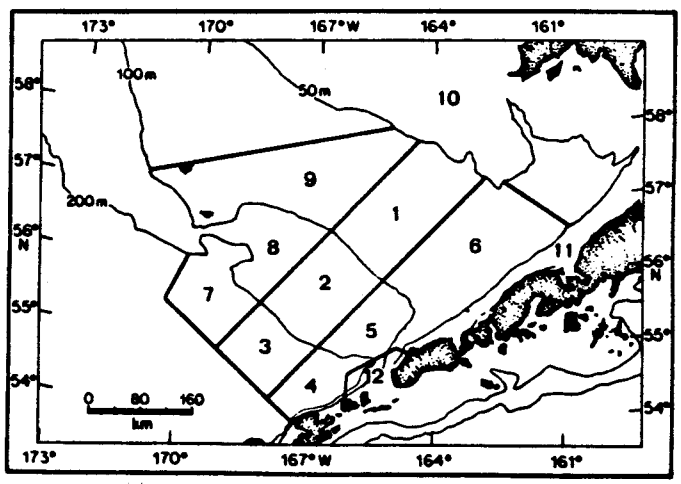
1) A type of spiny larva, tentatively assigned to the family Penaeidae, was taken less frequently than the other families of shrimp.

2) It was found predominantly beyond the shelf break in deep water (> 200 m).

Table 6.9. Cross-shelf comparison of mean densities of Penaeid sp. larvae during April and May from NOAA 1977 with May and June from PROBES 1978. See Figure below for strata locations. Total number of stations sampled = N.

	NOAA 1977 (April/May)			PROBES 1978 (May/June)		
Stratum	$\bar{X} \pm 1$ S.D.	N	% positive stations	$\bar{X} \pm 1$ S.D.	N	% positive stations
			Oceanic/Shelf Break Domain			
7	1590	1	*	777 ± 508	7	86%
3	4390 ± 3748	11	82%	1196 ± 1116	7	71%
4	778 ± 912	13	69%	315 ± 84	2	100%
			Outer Shelf Domain			
8	400 ± 919	8	38%	583 ± 1106	17	24%
2	336 ± 1271	25	36%	142 ± 334	24	17%
5	116 ± 287	18	33%	17 ± 59	12	8%
			Middle Shelf Domain			
9	0	2	0%	0	17	0%
1	0	1	0%	0	0	0%
6	0	10	0%	0	15	0%

*Only 1 positive station sampled.



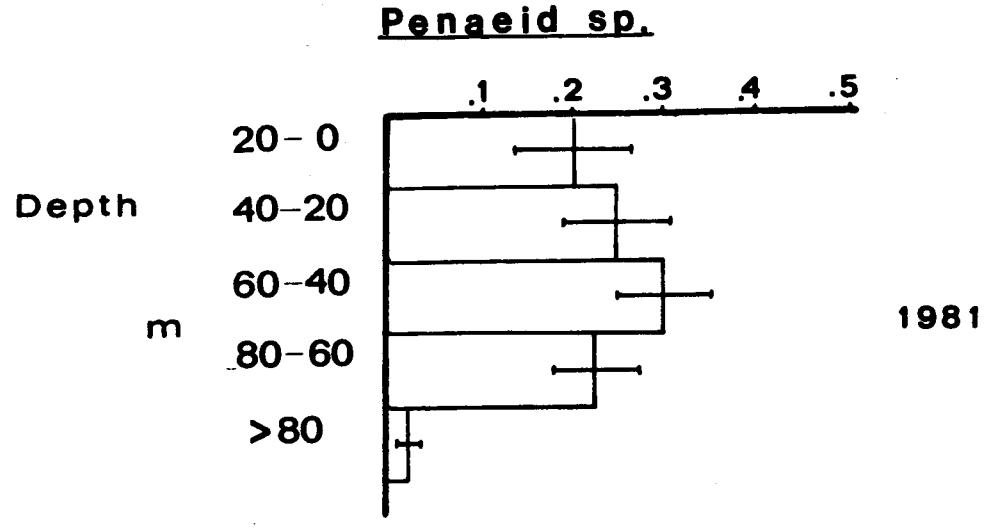


Figure 6.36 Vertical depth distribution of penaeid sp. larvae from PROBES 1981. Values expressed as an average proportion ±1 standard error.

3) Larvae were in the water column from hatchout in mid-April until metamorphosis - at least until late September or early October.

4) These larvae apparently have a protracted hatchout period and an intermolt duration of approximately three weeks.

5) These larvae are homogeneously distributed throughout the water column from 0-80 m.

6.7 General Shrimp Summary

1. Peak hatch of shrimp larvae in the southeastern Bering Sea occurs in early April for species in the families Pandalidae, Crangonidae, Penaeidae, and Hippolytidae; some larvae of the latter family hatch in early March.

2. Zoeal stages molt about every 2-3.5 weeks and are predicted to metamorphose to benthic juveniles about mid-August to September.

3. Larvae of *Pandalus borealis* and most pandalids are most densely distributed over the St. George Basin between the 100 m and 200 m isobath (Outer Shelf Domain); *P. tridens* larval densities are greatest beyond the shelf-break in deep water.

4. Hippolytid larvae are distributed throughout the St. George Basin south to Unimak Pass and in deep water southwest of the 200 m isobath to Unalaska Island.

5. Crangonid larvae are the least abundant of the three principal families and also are centered over the outer and middle shelf domains of the St. George Basin.

6. Relatively few shrimp larvae are found in the Middle Shelf Domain northeast of the 100 m isobath. Unimak Pass is a region of high larval shrimp densities.

7. Data on the magnitude of benthic shrimp populations is scarce because routine sampling gear is thought to inefficiently catch these relatively small crustaceans.

8. Although shrimp have no present commercial importance in the southeastern Bering Sea, their role in the benthic food webs of this area should not be overlooked. Shrimp are a major part of the diets of marine mammals and commercially important species of fish and crab. Environmental perturbations caused by pollution that affect major fluctuations in shrimp stocks could have ramifications throughout the benthic community.

7.0 DISTRIBUTION AND ABUNDANCE OF HERMIT CRABS (PAGURIDAE) IN THE S. E. BERING SEA

Jan Armstrong and Brett Dumbauld

7.1 Introduction

At least 21 species of hermit crab from the family Paguridae are reported to occur in the Bering Sea (Appendix 3). Some of these species are found strictly in intertidal areas (e.g. Pagurus middendorffii) while others are found in sublittoral areas, primarily on rocky substrata (e.g. Pagurus beringanus, P. kennerlyi, P. hirsutiusculus, Elassochirus gilli). Only seven of these species are regularly found in benthic trawls from the study area in the southeastern Bering Sea (Table 7.1).

7.1.1 Life History

The life history of hermit crabs in the genera Pagurus, Elassochirus, and Labidochirus includes four planktonic zoeal stages and one megalops stage (termed glaucothoe in the older literature); the latter undergoes metamorphosis and settles as a benthic juvenile (Thompson 1903; Hart 1937; Miller and Coffin 1961; Nyblade 1974; Nyblade and McLaughlin 1975). Four of the species which are commonly found in southeastern Bering Sea trawl samples have been raised from egg to adult in the laboratory (Table 7.2; Nyblade 1974; Nyblade and McLaughlin 1975). Laboratory culture has also been completed for six of the remaining species reported to occur in the Bering Sea (Nyblade 1974) and some studies have been conducted on larvae of Pagurus middendorffii, P. trigonocheirus, Dermaturas mandtii, and other species from plankton samples (Kurata 1964a, b; Makarov 1966).

Table 7.1. Frequency of adult and juvenile pagurid crabs in 1975 and 1976, southeastern Bering Sea, benthic trawl samples and preferred habitats (Adapted from Nyblade, 1974; McLaughlin, 1974; Feder and Jewett, 1980).

Species	Depth	% of tows in which species occurred 1975(<80m)	1976(80-200m)
Pagurus aleuticus	15 - 435 m soft bottom	-	34.6
P. capillatus	4 - 431 m mud	46.4	26.9
P. confragosus	68 - 435 m	-	44.2
P. ochotensis	Subtidal - 249 m sand	38.7	-
P. trigonocheirus	Subtidal - 183 m	45.9	36.5
Elassochirus cavimanus	37 - 252 m	-	31.7
Labidochirus splendescens	Subtidal - 411 m soft bottom	32.9	-

Table 7.2. Reproductive data for four species of Paguridae collected in the San Juan Islands, Washington. Species are also common in the Southeastern Bering Sea (Adapted from Nyblade 1974).

Species	Number of broods per year	Time of egg extrusion	Time of larval hatch	Egg dry wt. (µg)	Annual egg production per 100 mg female	Larval duration (days)	
						Zoea	Megalops
Pagurus aleuticus	1	No data	Spring only March-May	2.32	No data	61.2	20.2
P. capillatus	1	Jan.	Spring only March-May	3.09	1.88×10^3	53.9	17.1
P. ochotensis	2-3	Autumn (For spring hatch)	Spring through summer March-Sept.	3.09	1.13×10^3	59.0	21.0
Labidochirus splendescens	1	July-August	Spring only March-April	3.83	7.08×10^2	76.1	21.0

7.1.2 Reproduction

Reproductive season among hermit crabs differs by species and locality (Nyblade 1974). Copulation and egg extrusion usually occur from autumn through spring. Some species have a single brood and release larvae only in the spring, while multiple brooders may release larvae throughout the summer months (Table 7.2). Egg development time from extrusion to hatching has been recorded only for the second brood in multiple brooding species, and varies from 1.5 to 2.0 months in the laboratory (Nyblade 1974). Egg size and number per female also vary with species. Like the larvae of other invertebrates, those of hermit crabs appear in the water column later in more northern waters (Stephenson 1935; Pike and Willliamson 1959). Therefore, with some allowance for latitude, the laboratory and field data of Nyblade (1974) for hermit crabs collected in the San Juan Archipelago (Table 7.2), may be applied tentatively to the same species found in the southeastern Bering Sea. Zoeal duration for most species falls in the range of 50-60 days. Laboratory studies have demonstrated that they are primary carnivores during this period and may feed on copepod nauplii, copepodites, barnacle nauplii, polychaete trochophores, and other small planktonic larvae (Roberts 1974). Duration of the megalops stage is approximately 21 days with little variation among species.

7.1.3 Benthic Distribution

Individual species of adult and juvenile hermit crabs were found in as many as 46% of benthic trawls taken in the southeastern Bering Sea in 1975 (primarily north of the Pribilof Islands and shallower than 80 m)

and 1976 (between the Pribilof Islands and Unimak Island between the 80 and 200 m isobaths; Table 7.1). The greatest number of decapod crustacean species were recorded for the genus Pagurus (Feder and Jewett 1980), but due to their small size they did not constitute a significant portion of the wet weight sample biomass of epifauna (e.g., 12,302 individuals of Pagurus trigonocheirus contributed to only 1.3% of the total wet weight of the 1975 trawl samples). Biomass estimates for pagurids averaged only .043 g/m^2 compared to .665 g/m^2 for Chionoecetes opilio and .361 for Chionoecetes bairdi, the dominant crab species collected.

7.1.4 Food and Predators

Adult hermit crabs have been shown to be predominately omnivorous detritus feeders and use their chelipids and third maxillipeds to scrape and sort food from bottom deposits. Scavenging and predation have been shown to be accessory and opportunistic behavior patterns (Orton 1927; Roberts 1968; Greenwood 1972). In turn, hermit crabs are preyed upon by king crab (Paralithodes camtschatica), Tanner crab (Chionoecetes spp.), Alaska plaice (Pleuronectes quadrituberculatus), Pacific cod (Gadus macrocephalus), and seastars (Asterias amurensis) (Feder and Jewett 1980, 1981).

7.2 Results and Discussion

Pagurid crab larvae were found in 65% of all the samples examined from 1976-1980 (April-June), 61% of all PROBES 1981, and 100% of all NOAA 1981 (April-July) samples.

7.2.1 Larval Duration

Although several stage I pagurid larvae were found in early March (NOAA 1978) indicating a hatchout period of late February to early March for at least 1 pagurid species, high densities of pagurid larvae were not found until April (Fig. 7.2) indicating a mid to late March hatchout period for the majority of pagurid species. During 1981, some stage I pagurid larvae were still present as late as July (Table 7.2 and Fig. 7.1) illustrating the asynchronous hatchout periods and possibly multiple brood strategies of species in the pagurid group.

Pagurid larvae were not identified to species but were separated into individual zoeal (I-IV) and megalops stages. Densities were calculated for each individual larval stage. Average densities for each month (1981) were used to examine the relative frequency of occurrence of various larval stages. However, molt frequency is somewhat difficult to gauge from present data since numerous pagurid species are grouped together.

A larval stage frequency histogram for PROBES 1981 (Fig. 7.1) shows the basic developmental trend among the pagurids from April to July. In April and May a majority of the pagurids are SI, by June SIII, and by July SIV with a small percentage of pagurids reaching the megalops stage. The intermolt period for pagurids must be 3-4 weeks between stages and thus total duration of planktonic life would approach 3.5-4.0 months from April-August for most species.

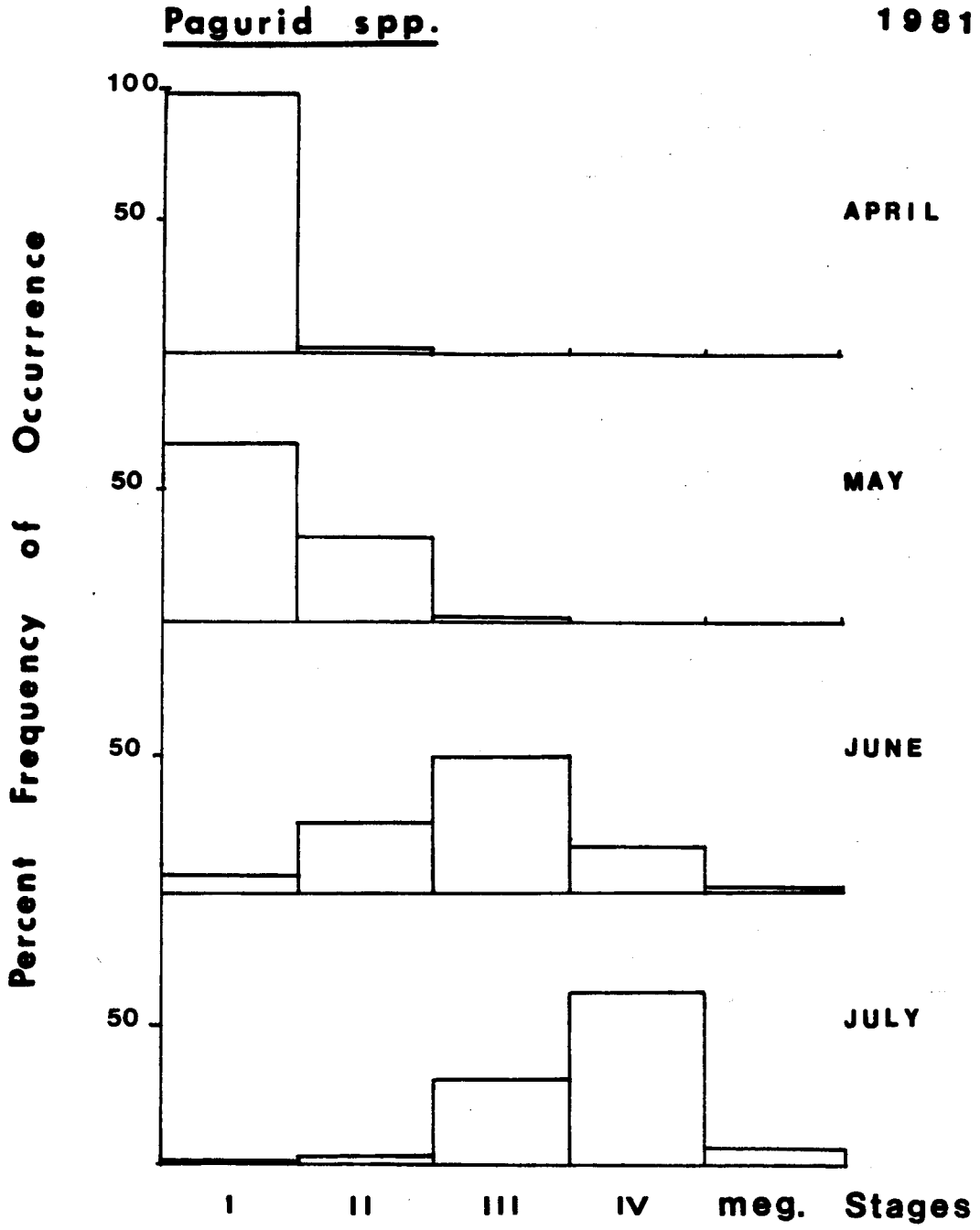


Figure 7.1 Paguridae stage frequency histogram by month from PROBES 1981 (April-July).

7.2.2 Distribution and Abundance

Since the family Paguridae encompasses several species in the southeastern Bering Sea, this group's ubiquitous distribution is not surprising. Figure 7.2 illustrates larval densities in April from PROBES 1978 and NOAA 1978 and NOAA 1977. Greatest larval densities appear in a continuous band just west of the 100 m isobath from north to south of the middle shelf domain, and along the Aleutian Islands from Amak Island to Akutan Island. Densities were typically an order of magnitude greater east of the 100 m isobath than over the outer shelf domain of the St. George Basin. Comparing April to May/June distribution (Fig. 7.3), high densities and greatest abundance were found overlapping the middle and outer shelf domains along the 100 m isobath. The same general patterns were again found from data of PROBES 1980 (Fig. 7.4) and PROBES 1981 (Fig. 7.5). While pagurid densities were generally lower in 1980, all the densities >1000 larvae/100 m^2 were taken in May and June. Lower densities in 1980 compared to 1981 appear along the 70 m isobath from Port Moller to the Pribilof Islands. During 1981, pagurid abundance was highest and most extensive over the middle shelf (strata 2, 5, 8) east of the 100 m isobath and along the 50 m isobath parallel to the North Aleutian Shelf from Unimak Island to Port Moller (Fig. 7.5); a continuation of the coastal band of high densities seen in Figure 7.3 from May/June 1976-79. The highest density was collected in April (57,000 larvae/100 m^2) just northeast of the 100 m isobath indicated by the star in Figure 7.2. A cross-shelf comparison of mean densities of Paguridae larvae during May and June PROBES 1978 (Table 7.3) highlights the preponderance of animals over the middle shelf domain and the high density overlap

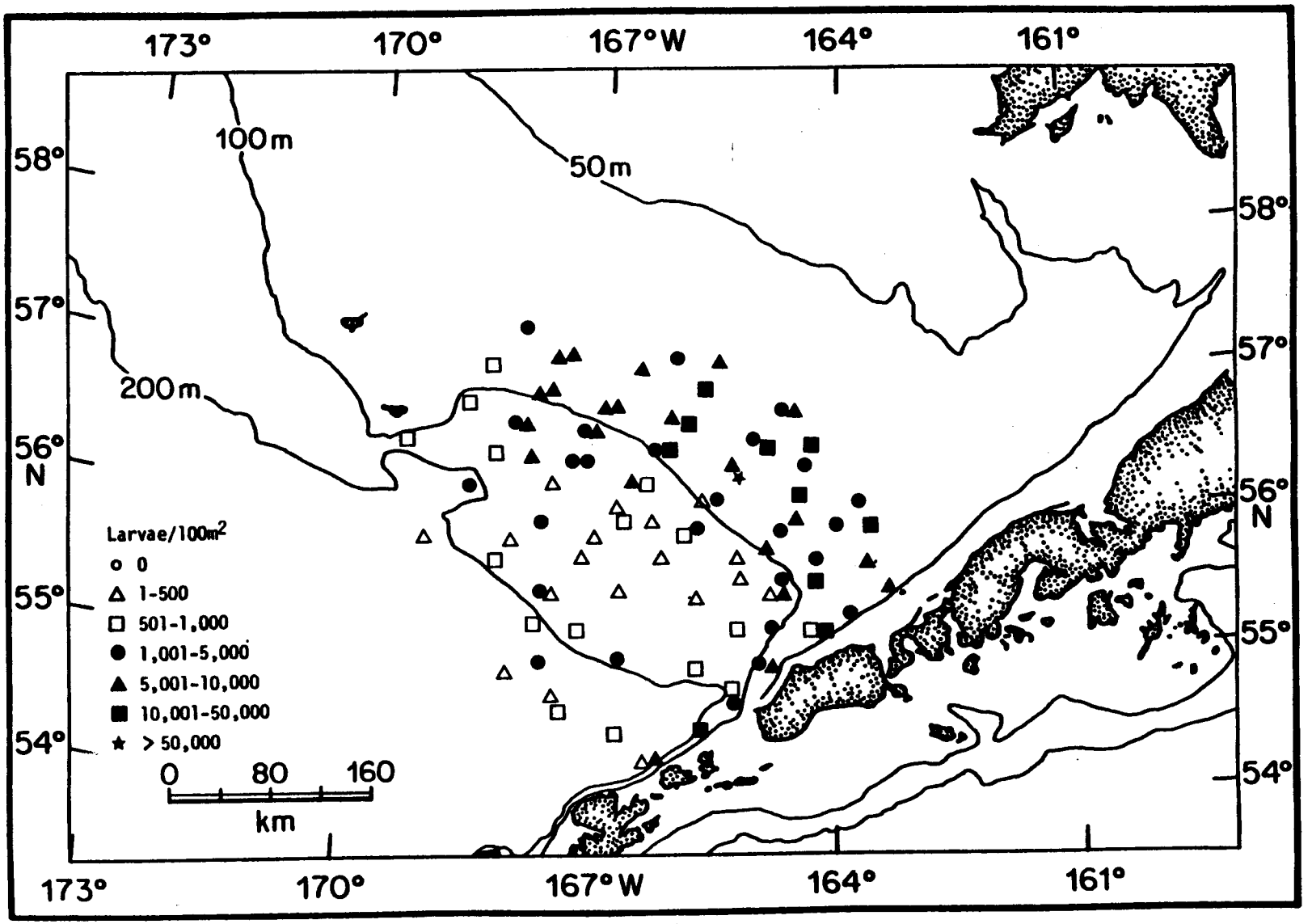


Figure 7.2 Distribution and abundance of Paguridae larvae during April from NOAA 1977 and PROBES 1978. Only positive stations were included. See Section 2.0 for all station locations.

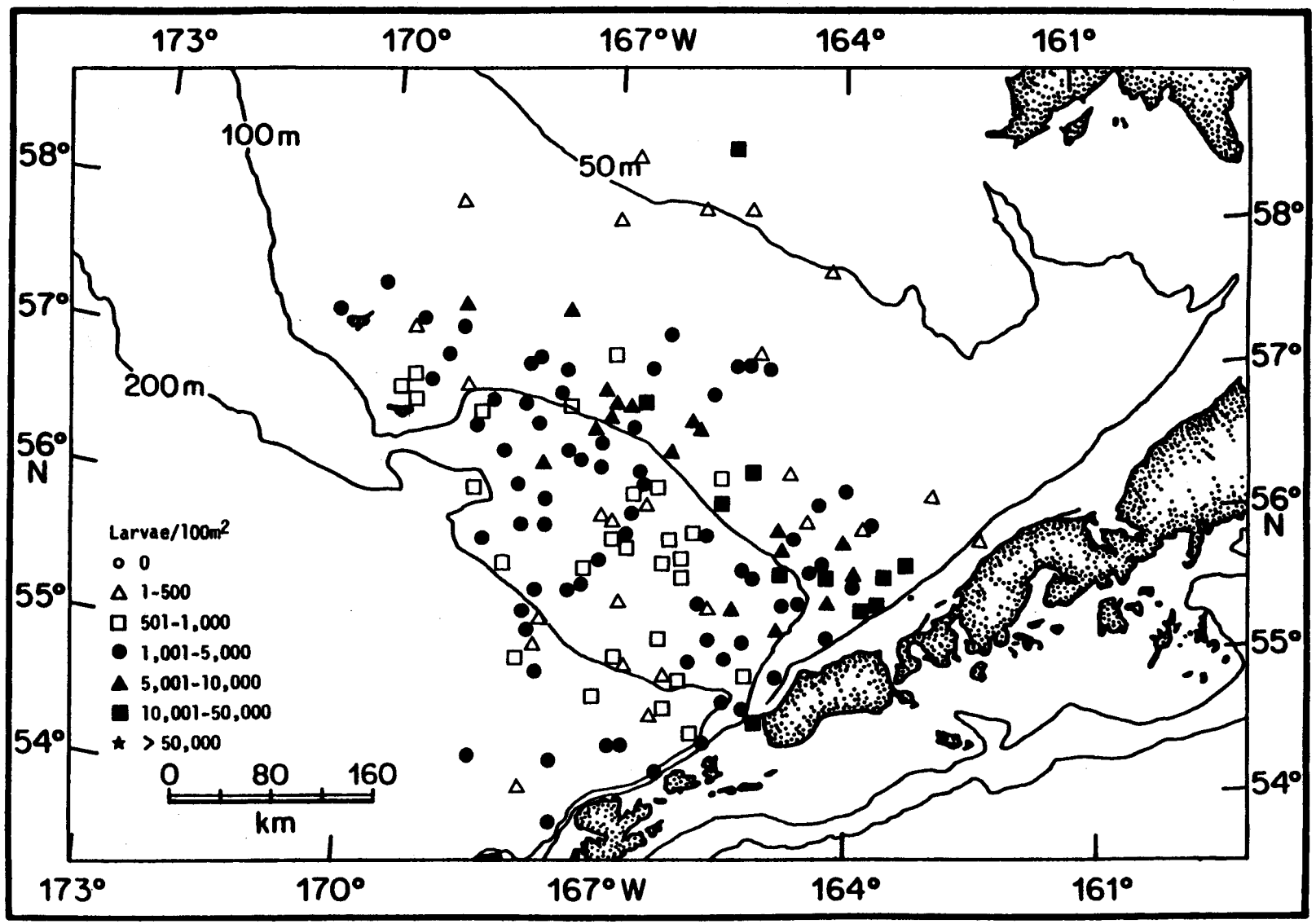


Figure 7.3 Distribution and abundance of Paguridae larvae during May and June from NOAA 1976, 1977, 1979 and PROBES 1978. Only positive stations were included.

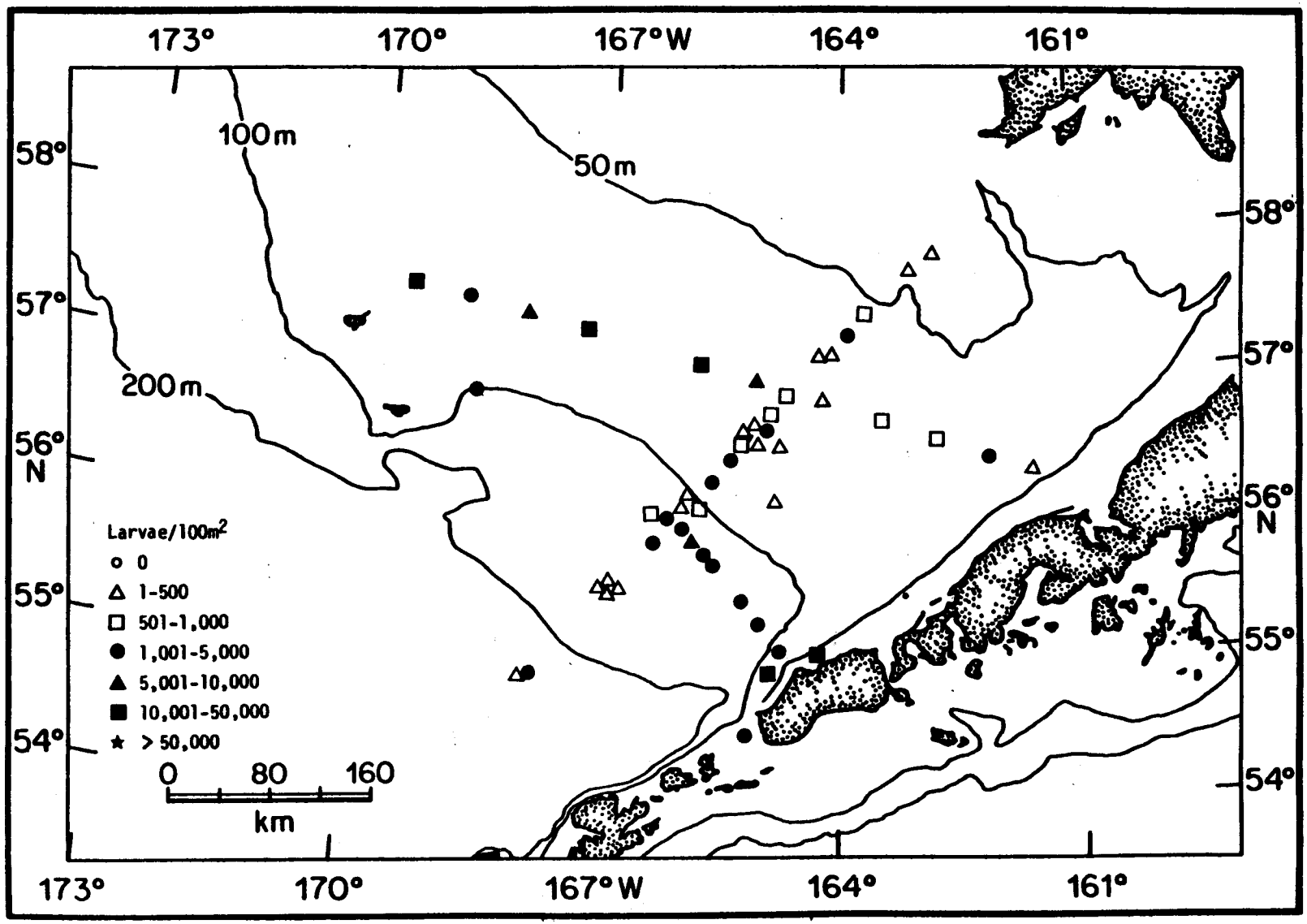


Figure 7.4 Distribution and abundance of Paguridae larvae during April-June from PROBES 1980. Only positive stations were included.

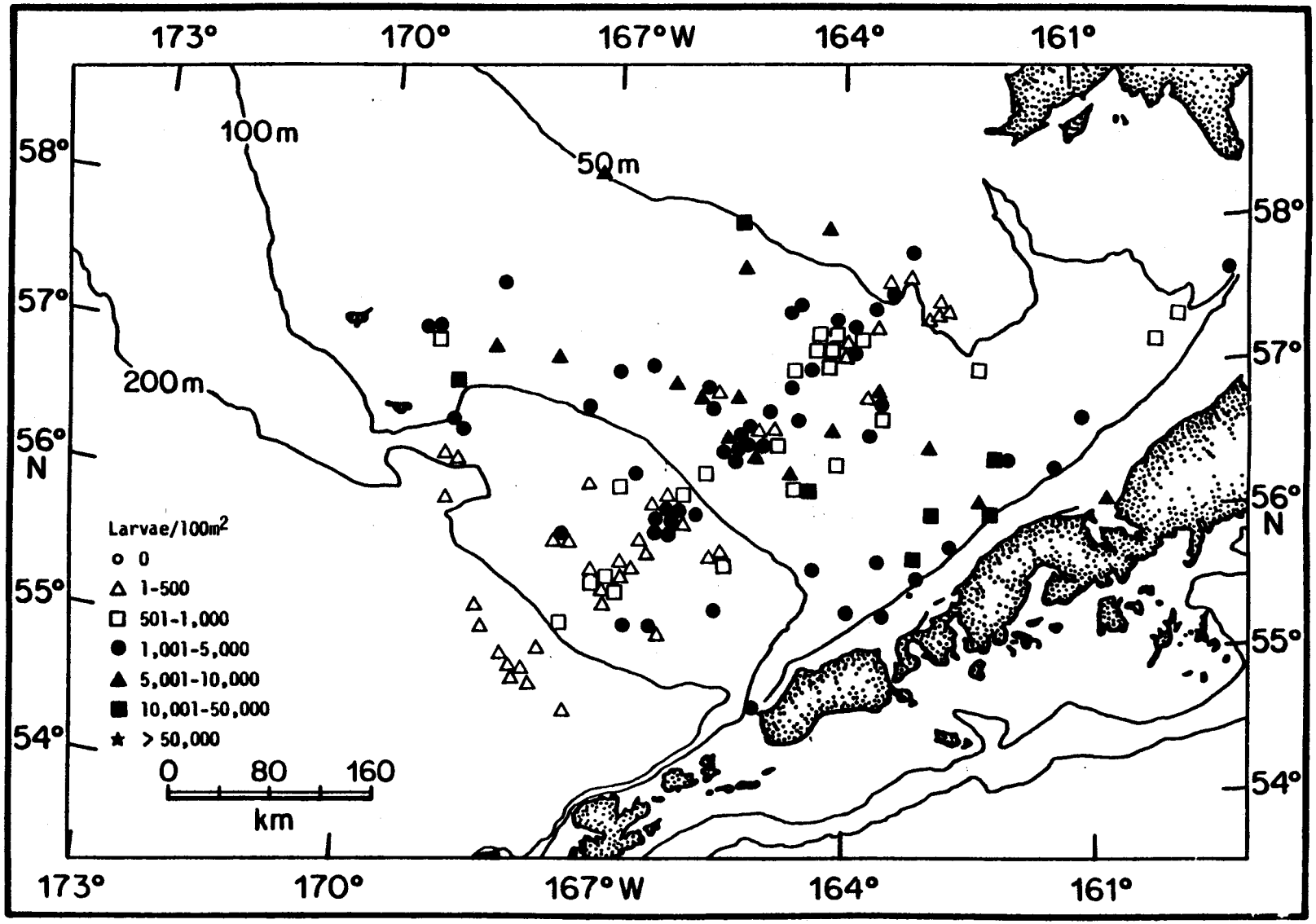
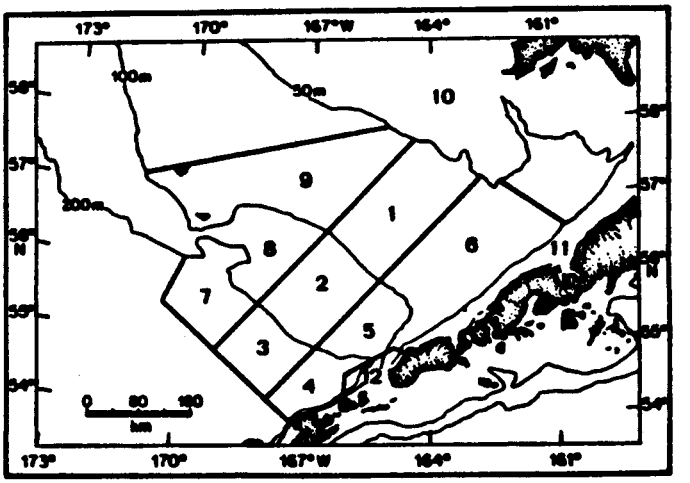


Figure 7.5 Distribution and abundance of Paguridae larvae during April-July from PROBES and NOAA 1981. Only positive stations were included.

Table 7.3. Cross-shelf comparison of mean densities of Paguridae larvae during May and June from PROBES 1978. Zero stations omitted in calculating these means. Total number of stations surveyed within each stratum = N. See Figure below for strata locations.

Stratum	$\bar{X} \pm 1$ SD (larvae/100 m2)	% positive stations	N
	Oceanic/Shelf Break Domain		
7	663*	14%	7
3	580 ± 259	43%	7
4	485 ± 156	100%	2
	Outer Shelf Domain		
8	3804 ± 3260	65%	17
2	1406 ± 1133	56%	18
5	4910 ± 6348	100%	12
	Middle Shelf Domain		
9	5272 ± 4350	82%	17
1	7566 ± 6911	100%	7
6	8241 ± 8741	100%	14

*Value based on only one positive station.



into strata of the outer shelf domain (strata 5 and 8) during May and June. The cross-shelf increase of ten-fold in density is shown in Figure 7.6 for the years 1976-1981; only data of 1980 deviated from the trend of high middle shelf density (stratum 1) to low outer shelf and shelf break densities (strata 2 and 3). Stratum 1 mean densities ranged from 1148 to 7566 larvae/100 m^2 (1980 low and 1978 high), compared to stratum 2 densities of 649 to 1364 (1979 low and 1980 high). General scarcity in stratum 3 is illustrated by mean densities of 147 to 858 larvae/100 m^2 (1981 low and 1980 high).

7.2.3 Vertical Distribution

Vertical depth distribution of Paguridae larvae was studied by analysis of MOCNESS samples from PROBES 1980 and 1981 (Fig. 7.7). Pagurid larvae were occasionally found down to 120-300 m but were primarily concentrated within 0-80 m. Unlike the homogeneous distribution found among the shrimp taxa, pagurids preferred the upper depth intervals with 44-47% in the upper 20 m, 71-76% in the upper 40 m, 84-89% in the upper 60 m, 95-96% in the upper 80 m, and 4-5% below 80 m. A diel comparison of vertical depth distributions is given in Figure 7.8 for light (local mean time (LMT) = 07:00 - 19:59) versus dark (LMT = 20:00 - 06:59) at stations <100 m sonic depth (middle shelf domain) and stations between 100-200 m sonic depth (outer shelf domain) from PROBES 1981. Percent occurrence of pagurid larvae during daylight hours was consistent between middle shelf and outer shelf stations; 30-33% for the 20-0 m interval, 40-45% for the 40-20 m interval, 12-23% for the 60-40 m interval, 2-7% for the 80-60 m interval, and 0-6% below 80 m. Samples taken during

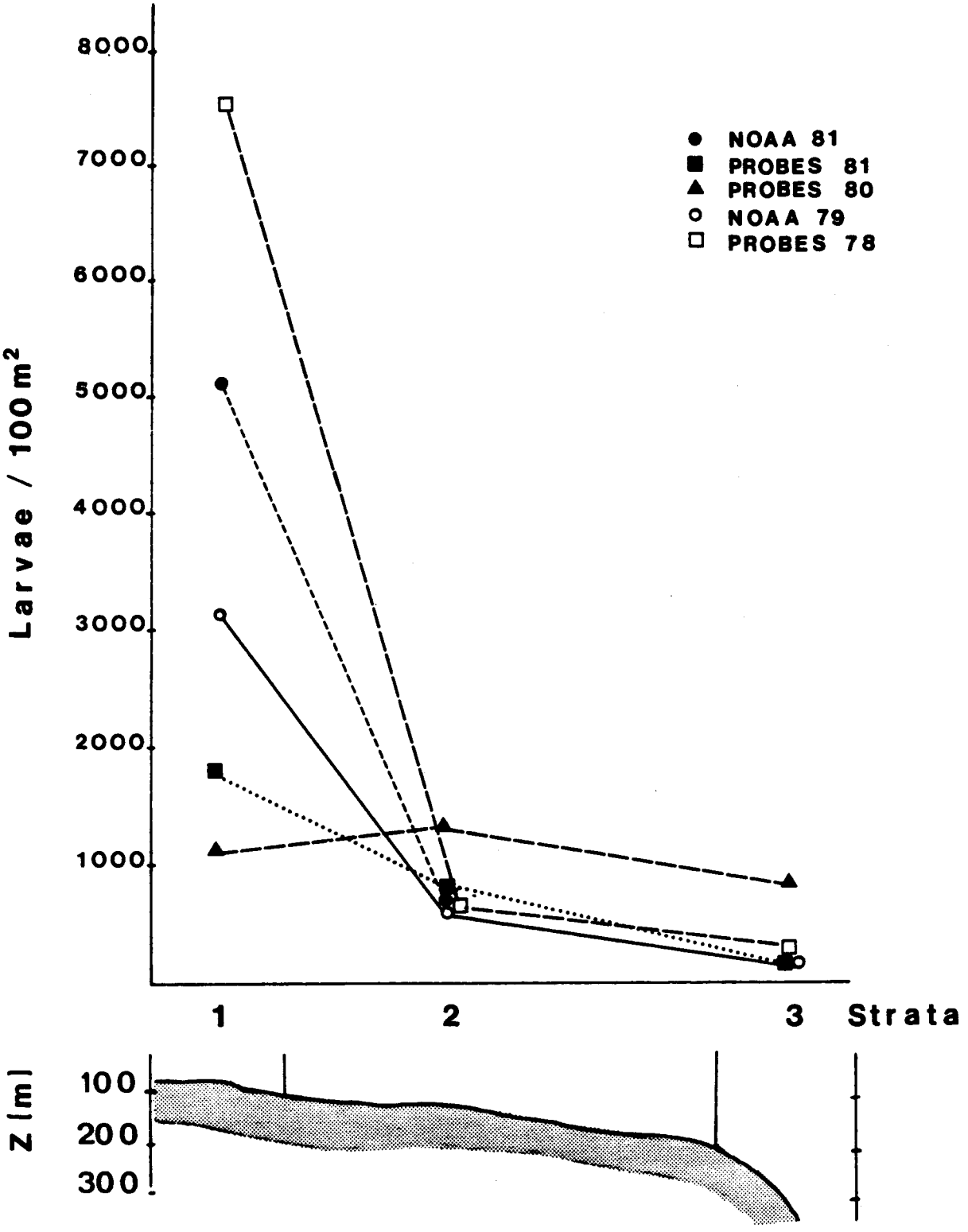


Figure 7.6 Mean larval densities of Paguridae by stratum for cruises 1978-1981.

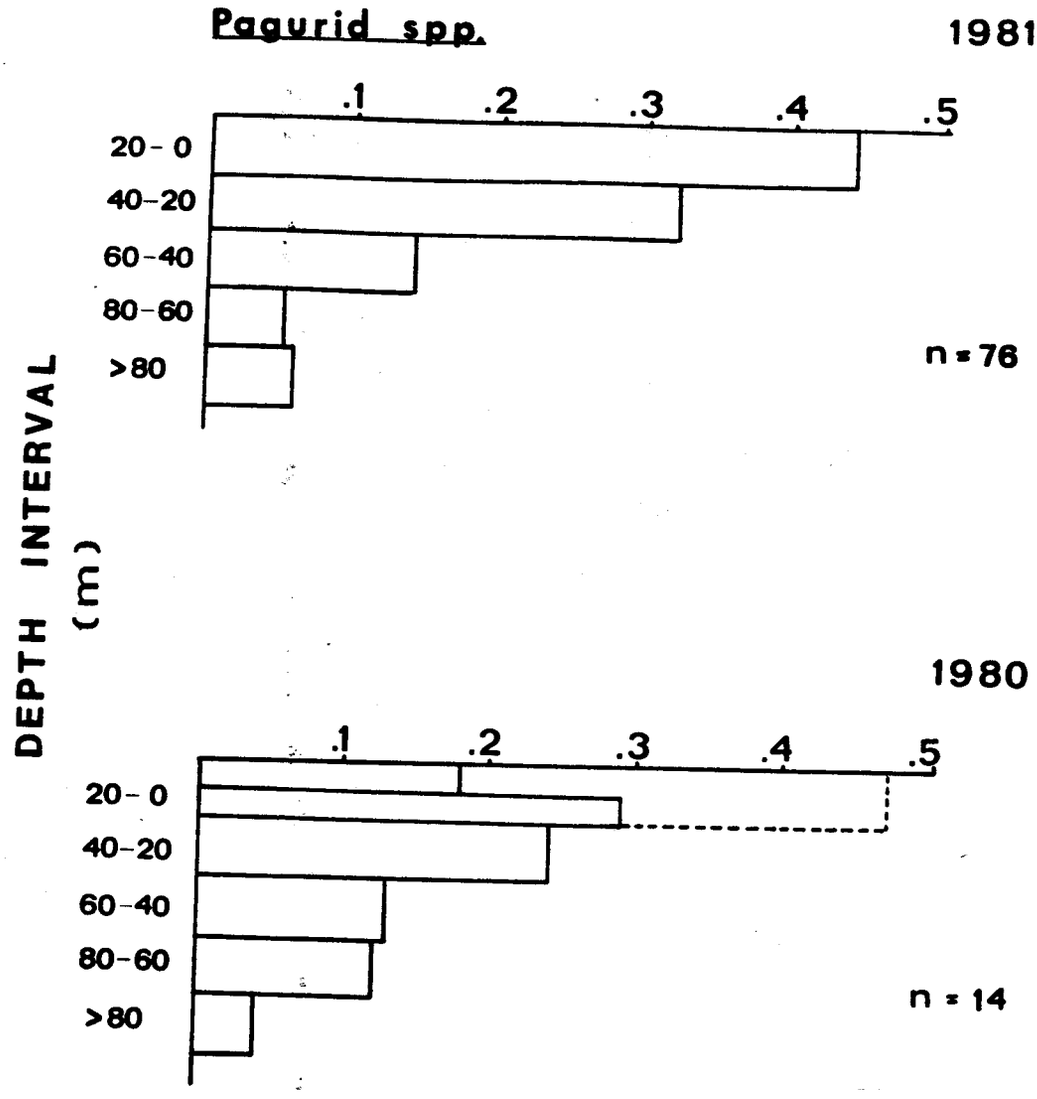


Figure 7.7 Vertical depth distribution of Paguridae larvae from MOCNESS samples PROBES 1980 and 1981. Number of stations sampled for this analysis is given by n.

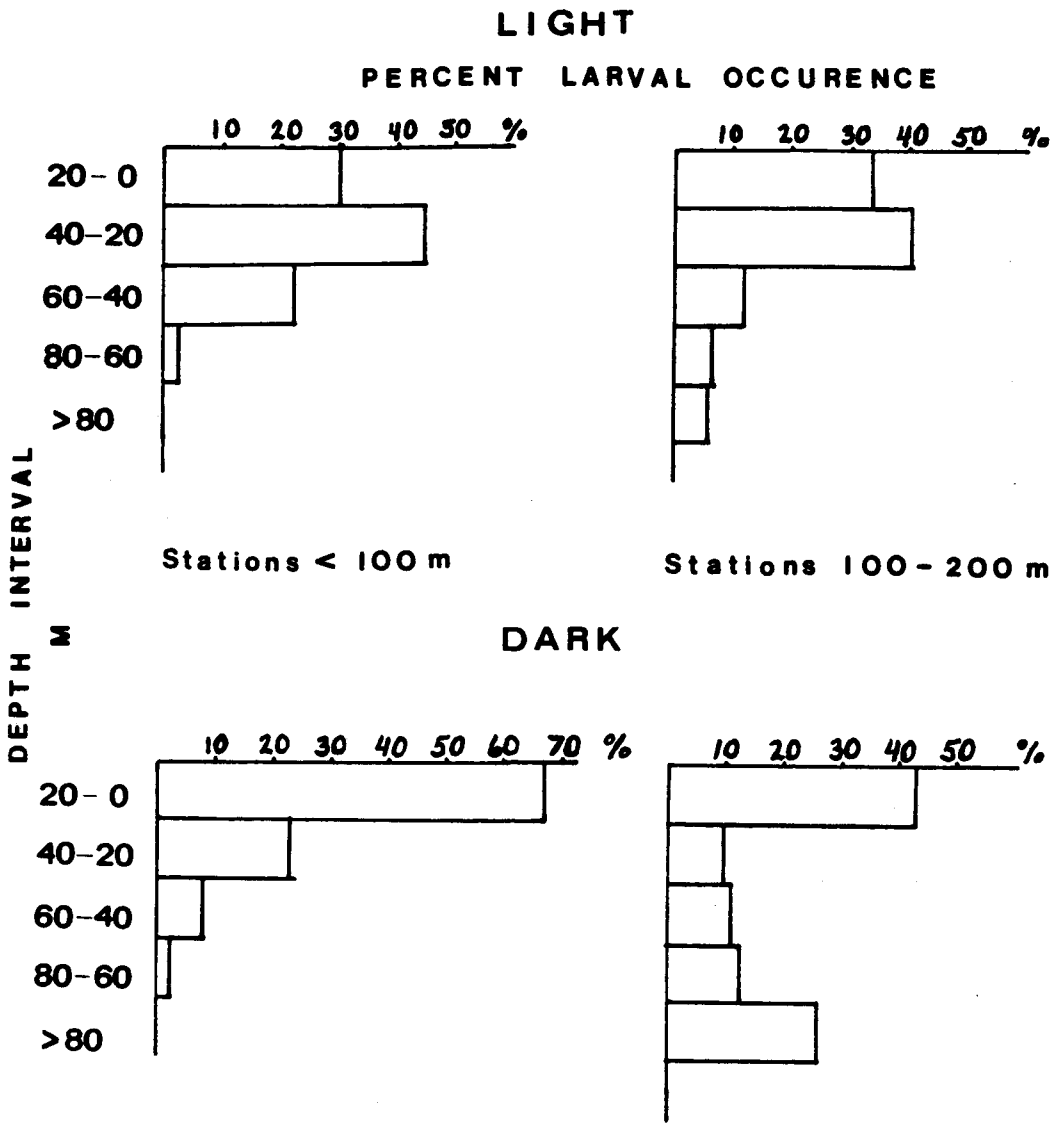


Figure 7.8 Vertical depth distribution of Paguridae larvae, diel comparison: light vs. dark, samples at stations < 100 m sonic depth and stations 100-200 m sonic depth from PROBES 1981.

dark hours showed very different distribution patterns depending on the station depth. Stations <100 m sonic depth had a majority of larvae in the upper 20 m while stations 100-200 m had many larvae in the upper 20 m but also a significant percentage in the >80 m interval. These data suggest vertical migratory behavior that could be a significant factor in exposure to surface oil.

Distribution of pelagic pagurid larvae cannot be compared with that of adults since good information is lacking on benthic distribution of adult hermit crabs in the southeastern Bering Sea. This group is routinely undersampled by conventional survey gear and yet their biomass may be substantial and their trophic position important to the benthic community that includes several commercially valuable predators of hermit crabs. Large populations of adult pagurids are expected to concentrate northeast of the 100 m isobath (as do the larvae) and along the 50-100 m isobaths along the Aleutian Island chain. A point of interest would be whether different species dominate either side of the 100 m isobath as seems to occur for Chionoecetes bairdi and C. opilio over the outer and middle shelf domains, respectively (see Section 4.0).

7.3 Summary

1) Pagurid distribution was ubiquitous throughout the southeastern Bering Sea.

2) Pagurid crab larvae were found from early March until mid July with greatest densities during April over the middle shelf.

3) Larval duration in the plankton is expected to last 3.5-4.0 months for most species which have 4 zoeal plus a megalops stage and an intermolt period of approximately 3 weeks.

4) Greatest larval densities appeared in a continuous band along and east of the 100 m isobath and and along the Aleutian Islands from Amak Island to Akutan Island between the 50-100 m isobaths; there was a substantial decline in density over the St. George Basin. Larval densities across the middle shelf domain were 10-fold higher than densities beyond the shelf break and 3-5 times higher than outer shelf densities during May and June (7566/100 m^2 vs. 249/100 m^2 vs 658/100 m^2 in 1978).

5) Pagurid larvae were generally concentrated in the upper 40 meters at both middle and outer shelf stations, and there was an indication of diel vertical migration toward the surface during dark hours.

8.0 POSSIBLE OIL IMPACTS ON DECAPOD LARVAE IN THE SOUTHEASTERN BERING SEA WITH EMPHASIS ON THE ST. GEORGE BASIN

This two-year study of population dynamics of decapod larvae has drawn on six years' worth of zooplankton samples to determine spatial and temporal variation in distribution and abundance, in order to predict the possible impacts of oil development on this most sensitive life-history stage. Other factors of general biology have been elucidated; for example, the time and synchrony of hatch and its interannual variability, rate of larval development and time in the water column, molt frequency, and, in the case of commercial species targeted in surveys, the relationship between distribution of benthic female stocks and centers of larval abundance.

In many respects however, the data are incomplete, a shortcoming that has prompted over the past 1.5 years recommendations and proposals for additional research. Some of the proposed research is now ongoing (spring/summer 1983) as studies at the Pribilof Islands on blue king and Erimacrus crab biology and on red king crab along the North Aleutian Shelf. These investigations should add substantial information on critical habitat requirements of the species and allow an assessment of the relative sensitivity of such habitat to oil impact.

This last chapter is used to discuss scenarios of oil mishaps in the southeastern Bering Sea and consequences to pelagic larvae of several taxa. This will be done by first reviewing several models of water

and oil transport developed for the region, discussing oil toxicity to crustacean larvae, highlighting biological misconceptions of past models and suggesting modifications based on the present study, and finally predicting oil impact on larvae over the St. George Basin and nearshore along the North Aleutian Shelf.

8.1 A Review of Water and Oil Transport Models

Attempts to predict oil impacts in the southeastern Bering Sea should be based on best possible information available regarding physical and biological processes of the system, and specific life-history and ecological information for the principal species of interest. It is often necessary to establish rather tenuous links between species biology and assumptions regarding processes that influence populations because data are sketchy or non-existent for the system in question, and must therefore come from oil studies on different species or in different oceans.

Two models of physical transport processes, water movements, and biological interactions and responses to oil in the Bering Sea have been constructed by Leendertse and Liu (1981) and Sonntag et al. (1980), and several models of water transport and circulation based on net current directions and velocity have been developed by Hebard (1959) and Kinder and Schumacher (1981), and on methane profiles by Cline et al. (1981).

Water movement and resultant larval transport are important considerations in predictions of oil impact because larvae or oil may be moved toward or away from each other depending on area and timing of a spill, or both may be entrained together for days to weeks in a water mass

circulating over the shelf. Current and transport processes in the area of major larval king and Tanner crab populations are the most important to consider, and in this regard the North Aleutian Shelf along the 50 m isobath and the St. George Basin in the vicinity of the 100 m isobath are most important. Hebard (1959) described currents moving to the northwest through Unimak Pass, with a component then moving northeast along the North Aleutian Shelf. Although the direction of the current is highly variable and changes with tide, there is a net movement of 2.0- 5.5 cm/sec eastward and northward into Bristol Bay. Hebard was the first to suggest that larvae of red king crab could be transported long distances before metamorphosis, and thus recruitment of juveniles in one area like Port Moller might be dependent on up-current populations near Amak Island. Kinder and Schumacher (1981b) summarized data for current patterns in the southeastern Bering Sea and showed weak currents of 2-5 cm/sec along the NAS and 1-5 cm/sec moving northwest over the St. Geoge Basin (Fig. 8.1). They stress that instantaneous flow can be substantially greater than these averages (up to 20X greater than the long-term vector) and direction quite variable. Cline et al. (1981) used methane profiles to calculate current speeds of 7 cm/sec northeast along the NAS and 5 cm/sec northwest over the St. George Basin, both values in close agreement with current meter readings.

The importance of such information is to gauge the movement of crab larvae in currents relative to origins and surface speeds of oil movement. Such exercises have been done by Leendertse and Liu (1981) and

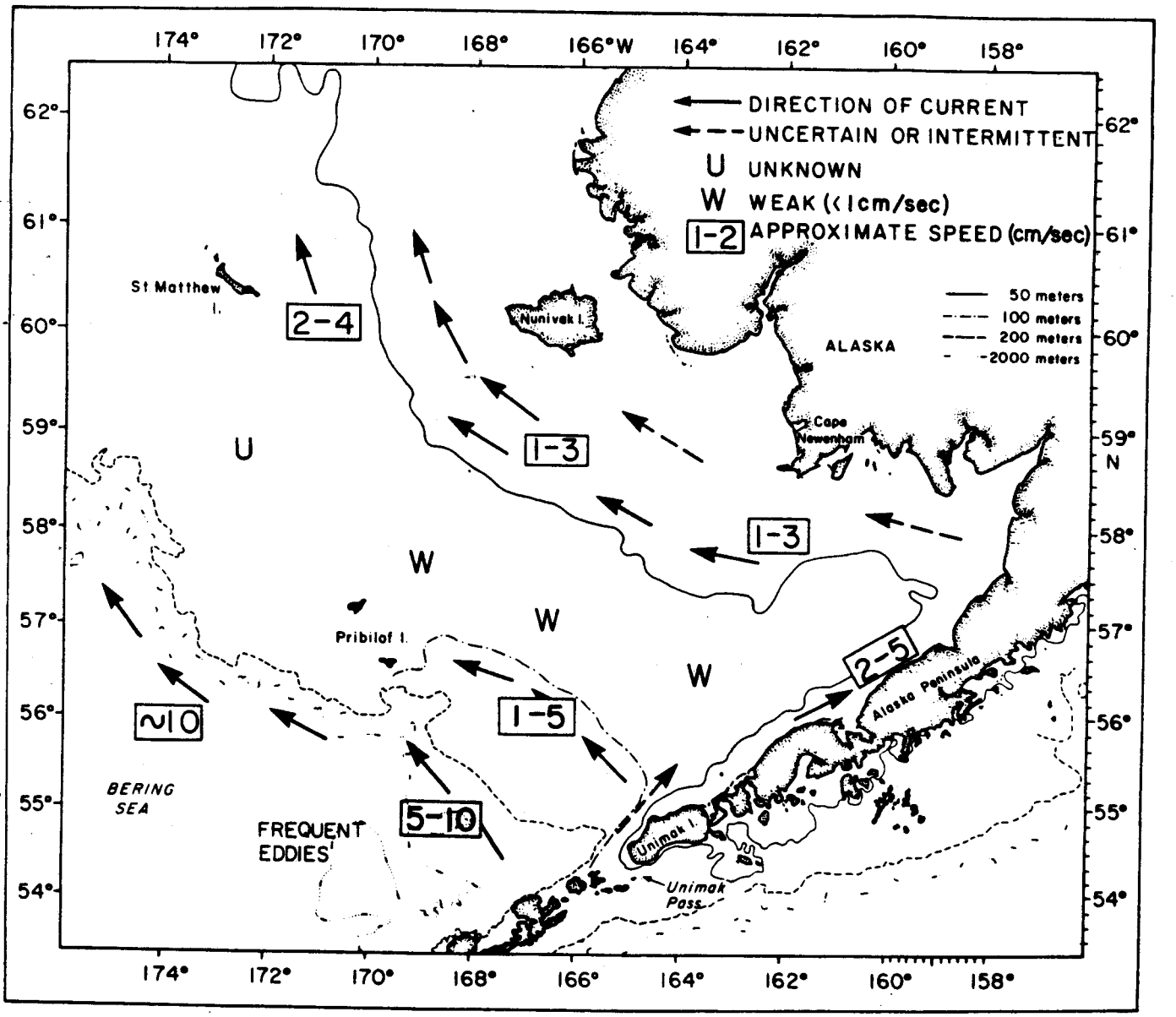


Figure 8.1 Current directions and net speed over the southeastern Bering Sea Shelf (from Kinder and Schumacher 1981a).

Sonntag et al. (1980). Following hypothetical oil spills or well blowouts in their models, oil can be moved by winds and currents, mixed by storms, transported to the benthos by several processes, and made to kill target/commercial species by direct exposure, loss of food and over-competition, or accumulation in tissues and gametes. Oil concentrations in the water column and benthic sediments are modeled as a function of the magnitude of an initial oil spill and its duration (e.g., 100,000 barrels from a tanker or 5,000 barrels/day from a well for several weeks), time of year, location of the mishap, and loss of oil fractions by processes such a volitalization. Model outputs show the trajectory and extent of oil coverage and concentration at various times after each hypothetical mishap. From data and assumptions on lethal levels, distribution and abundance of animals, sensitive life- history stages and physiological events (e.g., molting of crustaceans), predictions are made of the proportion of a year-class or population killed and the eventual ramifications such losses pose to commercial fisheries.

Concerning decapod larvae and in particular crab species, the results of several scenarios modeled at workshops in California (1980) and Alaska (1981) have predicted very slight impacts of oil spills on crab larvae over the St. George Basin (Sonntag et al. 1980) because such small areas, relative to the spatial distribution of larvae, are impacted (Sonntag et al. 1980; Curl and Manen 1982). However, several areas crucial to crab reproduction have been identified at these workshops (Pribilof Islands, North Aleutian Shelf), and oil scenarios have been suggested that could lead to substantial mortality of larvae in these areas (see Fig. 8.2) (Sonntag et al. 1980; Curl 1981; Curl and Manen 1982;

discussed by participants at the St. George Basin Lease Area Synthesis Meeting, April 1981, Anchorage; North Aleutian Shelf Synthesis meeting, March 1982). Predictions from these models may seriously underestimate possible larval mortality caused by an oil mishap (even in the St. George Basin) because of incorrect assumptions concerning larval sensitivity to oil and aspects of larval life history and ecology (these are discussed later in this section).

8.2 Oil Toxicity to Crustacean Larvae

Oil is a highly complex pollutant of water soluble and insoluble fractions and aromatic compounds that may stress organisms over a spectrum of effects from mechanical impacts to subtle biochemical impairments. Its effects on aquatic resources may be manifested in several ways (Curl and Manen 1982): 1) rapid mortality resulting from acute exposures to high doses via external contact, inhalation and asphyxiation, or assimilation of hydrocarbon compounds that become toxic on a cellular and biochemical level; 2) bioaccumulation of sublethal amounts that cause a decline in general vigor evidenced in reduced growth, susceptibility to disease, inhibition of feeding (anorexia) (effects of this nature will likely become lethal to organisms); 3) impaired reproduction, reduced broods and viability of progeny; 4) carcinogenic and mutagenic causes of tumors and morphological abnormalities; and 5) uptake of hydrocarbons causing tainting of commercial crab sold as food.

8.2.1 Effects on Larvae

A wealth of information has been generated on oil toxicity to marine invertebrates (Malins 1977; Wolfe 1977) and many investigators have been specifically concerned with sensitivity of larval crustaceans (Wells and Sprague 1976; Bigford 1977; Caldwell et al. 1977; Tatem 1977; Cucci and Epifanio 1979). Karinen (1981) has reviewed toxicity of oil to Pacific Northwest and Alaskan species of shrimp and crab including Dungeness crab (Cancer magister), king and Tanner crab, and pandalid shrimp. Rice et al. (1975) and Vanderhorst et al. (1976) reported that 96 hr LC_{50} values for juvenile and adult pandalid shrimp range from 0.8-11.0 mg/l as water soluble fractions (WSF). Pandalid larvae, however, are a more sensitive life history stage as evidenced by 96 hr LC_{50} value from 1.0 mg/l WSF down to .3 mg/l as single aromatic compounds such as naphthalene (Mecklenburg et al. 1977; Rice et al. 1975; Rice et al. 1979). Sublethal effects including failure to swim and/or molt inhibition occurred at concentrations from 0.7 to 0.3 mg/l WSF. A 96 hr exposure of pandalid larvae to 0.6 mg/l WSF caused a 70% reduction in molting from S I to S II zoeae (Mecklenburg et al. 1977). Dungeness crab zoeae were susceptible to WSF as low as 0.22 mg/l (Caldwell et al. 1977). Larval king and Tanner crab are equally sensitive to hydrocarbons. Death of Paralithodes camtschatica larvae or failure to swim is caused by WSF of 0.8 to 2.0 mg/l (Brodersen et al. 1977; Mecklenburg et al. 1977), and Chionoecetes bairdi larvae are immobilized by a 96 hr exposure to 1.7 mg/l WSF (Brodersen et al. 1977).

Larval Feeding: Studies with other larval decapods indicate that toxic oil concentrations may be even lower than those just discussed when based on assays of single hydrocarbons, exposures longer than 96 hr, or sensitive sublethal criteria. Larval lobster (Homarus americanus) ceased feeding at 0.19 mg/l WSF and had a 30-day LC_{50} value of 0.14 mg/l (Wells and Sprague 1976). Specific compounds such as naphthalene are very toxic and caused narcotization followed by death of pandalid shrimp and of crab larvae at concentrations of 8-12 g/l during brief exposures of less than 24 hr (Sanborn and Malins 1977). Chemoreceptive organs of juvenile and adult Dungeness crab can detect WSF as low as 10^{-4} mg/l (0.1 g/l), a concentration well within the range of oil spill concentrations (Pearson et al. 1980). This may result in behavioral changes affecting feeding and/or mating and therefore reproduction. The extent of chemoreceptive feeding by crab larvae is unknown but could be seriously impaired by very low oil concentrations, thereby disrupting food consumption by this rapidly growing stage.

Based on these studies the following generalizations can be made: 1) Larvae are more sensitive to hydrocarbons than are juveniles and adults (Johnson 1977; Moore and Dwyer 1974). 2) Toxic oil concentrations range as low as 0.15 mg/l WSF and may be somewhat lower for specific compounds. Moore and Dwyer (1974) give a sublethal range of oil WSF to larvae of 0.001-0.1 mg/l. Wells and Sprague (1976) suggest a multiplier of .03 should be applied to LC_{50} concentrations to establish "safe" levels, which would predict that acceptable concentrations less than 1 µg/l WSF. 3) Molting is an extremely sensitive physiological event for

crustaceans that results in greater toxicity of oil compounds when larvae are exposed for periods of the intermolt cycle. Since larvae molt frequently, relatively short exposures of several days may disrupt normal ecdysis.

8.2.2 Effects of Oil on Reproduction

Oil in the water column or in sediments could affect reproduction in several ways: 1) Sediment and infaunal concentrations of hydrocarbons become so high that feeding of crabs and shrimp is curtailed by either loss of prey (clams, polychaetes, other crustaceans) and/or anorexia. Energetic requirements are not met and gamete production is reduced or curtailed. 2) Hydrocarbons are absorbed and/or ingested with food and deposited in eggs and sperm. At critically high (but as yet unknown) concentrations viability of the gametes is impaired and normal development of embryos arrested, resulting in greatly reduced hatching success. 3) Normal gametes are produced and eggs fertilized and extruded, but sediment hydrocarbons are absorbed directly by the lipid-rich developing embryo and remaining yolk mass. Again, at critically high tissue levels (unknown) development is arrested and a year-class weakened by virtue of poor hatch.

The first hypothesis is predicated on the possibility that extensive mortality of epibenthic and infaunal prey would severely restrict feeding by crabs. Scenarios of oil transport to the benthos (summarized by Manen and Curl 1981) predict accumulation of amounts up to 60 g/m^2

and high resultant mortality. Sonntag et al. (1980) predicted that annual benthic productivity ("benthic food growth rate") would reach zero at sediment oil concentrations of 8 to 16 g oil/m^2, well within the range of possible sediment concentrations predicted by participants of the 1981 Anchorage Workshop. In a realistic spill scenario (about 500,000 barrels of oil; AMOCO CADIZ lost 223,000 mt = 2.47 x 10^6 barrels of oil; IXTOC 1 blowout spilled 30,000 barrels day for several months) several thousand square kilometers could be so impacted and food resources of crabs reduced on a large scale. In addition to outright loss of prey, food consumption could be reduced by a sublethal, anorexic response to increasing tissue levels of oil as shown for lobster larvae (Wells and Sprague 1976).

Reduction of food intake by either cause could trigger an energetic imbalance in which metabolic needs account for the largest expenditure of ingested energy and little remains for tissue and gamete production (Edwards 1978). Sub-optimal temperatures can exacerbate the effect of oil on growth and energy budgets of a species as theorized by Warren (1971). Sublethal oil concentrations can act synergistically with sub-optimal temperatures to reduce energy consumption (Edwards 1978) but at the same time increase respiration even at cold temperatures (Laughlin and Neff 1977), thereby further narrowing the scope for growth (Warren 1971). Similar impairment of bioenergetic demands may affect pelagic larvae exposed to sublethal oil concentrations.

The second hypothesized effect of oil on reproduction is caused by translocation of hydrocarbons ingested and absorbed by adults to gametes. Rapid uptake of petroleum hydrocarbons has been demonstrated in several species of Crustacea (Anderson 1975; Cox et al. 1975; Lee 1975; Tatem 1977). While both adult and larval stages are capable of rapid elimination of hydrocarbons accumulated via the diet, metabolic products appear to be strongly resistant to depuration (Corner et al. 1976; Lee et al. 1976; Sanborn and Malins 1977). Residues amounting to 10% of the initial level were found in adult copepods which had been exposed 34 days earlier as nauplius I to a seawater solution of naphthalene for 24 h (Harris et al. 1977). Neff et al. (cited by Varanasi and Malins 1977) found rapid accumulation of naphthalene derivatives by penaeid shrimp that reached tissue levels of 100 times greater than those in exposure water. Highest and most persistent residues were found in the hepatopancreas that directly supplies nutrient materials to the gonads for gametogenesis. Transfer of naphthalene to eggs was found to occur in the marine polychaete Neanthes arenaceodentata (Rossi and Anderson 1977). Blue crab (Callinectes sapidus) ingesting radiolabeled hydrocarbons assimilated 2 to 10% and stored up to 50% of this amount in the hepatopancreas, which was the only organ assayed that still contained radioactivity after 25 days of depuration (Lee et al. 1976). Again, a direct translocation to and biomagnification of hydrocarbons in lipid-rich gametes is possible, although not well studied to our knowledge. Sufficiently high hydrocarbon levels in egg yolk and developing embryos could cause anomalous development.

The third reproductive effect involving eggs and embryos is uptake of hydrocarbons directly from bottom or interstitial water (female Chionoecetes may bury in the sediment while carrying an egg clutch) where sediment levels are high by virtue of processes such as deposition of oil-laden fecal pellets or storm mixing in shallow waters (Manen and Curl 1981). No studies of direct hydrocarbon uptake by crab or shrimp eggs and embryos could be found, but transferal of naphthalenes to brooding eggs (high in lipids) was reported to occur in the marine polychaete Neanthes arenaceodentata (Rossi and Anderson 1977) while adsorption from seawater occurred independent of adults in eggs of the Pacific herring (Eldridge et al. 1978). The lethal effect such exposure can have on developing embryos was shown by Tatem (1977) who exposed gravid female shrimps (Palaemonetes pugio) to 1.44 mg/l WSF for 72 hr. One week later control females released an average of 45 larvae each while those exposed to oil released only 9 each. Further studies of oil toxicity to developing eggs is warranted in light of possible oil impacts to red and blue king crabs that reproduce in relatively shallow, nearshore areas. Since oil degrades slowly in the sediments of very cold arctic waters (little change in quantity and composition after one year in tests cited by Curl and Manen 1982; Butler and Levy 1978; Mayo et al. 1978), and since female king and Tanner crabs brood eggs for eleven months (Sections 3.0 and 4.0), protracted exposure of eggs to hydrocarbons can result from oil spills that reach extensive areas of reproductive grounds.

An additional mechanism of oil-related stress on crustacean reproduction might involve impairment of copulation that results in a high

proportion of infertile egg masses extruded by females. As described in Sections 3.0 and 4.0, a sexually mature male locates and embraces a female just prior to her molt and they copulate immediately thereafter. Failure to copulate within five days post-ecdysis results in infertile egg masses (whether or not multiparous, older female Tanner crab copulate in later years after the terminal molt is currently under investigation at the University of Alaska). Location of a female partner is based on strong pheromone cues that are detected by chemosensory organs. Pearson et al. (1980) demonstrated that Dungeness crab can detect hydrocarbons at a few g/l. Following an oil spill, water concentrations may exceed 100-200 g/l (Hood and Calder 1981), and might impair chemosensory location of females or otherwise alter behavior to reduce breeding within the population. Following the AMOCO CADIZ spill in the spring of 1978, the numbers of gravid crab and lobster were drastically reduced in that year and 1979 along the affected portion of the Brittany coast (Hood and Calder 1981), suggesting that breeding within the population was impaired.

8.3 Larval Decapod Biology, Sensitivity to Oil, and Oil Scenarios: Misconceptions of Past Models and More Realistic Assumptions

Summaries of biological information and predictions of oil impacts in the southeastern Bering Sea arising from OCSEAP workshops at Asilomar, California (Sonntag et al. 1980) and Anchorage, Alaska (Curl and Manen 1982) were based on available data and best possible assumptions. In reviewing these efforts, several misconceptions and inaccuracies are apparent that, if corrected, may change the predictions of oil toxicity

to and impact on, pelagic and benthic crab populations. These changes include the following points:

1. An entire larval year-class was assumed to hatch during the 3 months of April, May, and June as proportions of 20%, 60%, and 20%, respectively (Sonntag et al. 1980). Based on molt frequency data of our report for larval king crab (Section 3.0), Tanner crab (Section 4.0), and shrimp such as Pandalus borealis (Section 6.0), it appears that the majority of larvae for these species are hatched in a 3-4 week period of April and early May and not over a protracted period of 3 months. Therefore the entire year-class enters the water column during a relatively brief period of time and is not followed weeks later by other cohorts for that year. First stage king crab zoeae that are killed by oil north of Unimak Island in late April, as an example, will not be replaced by other first stage zoeae hatched in June (although they may be replaced by larvae also hatched in April and transported to the affected area). Since hatching seems to be a well-synchronized event among commercial crustaceans, a major oil spill that kills a significant proportion of a larval year-class will not be mitigated by a later hatch of larvae after oil disperses below toxic levels.

2. An oil concentration of 0.2 mg/l and greater that was selected as toxic to crab and shrimp larvae is too high. Virtually all bioassay literature pertaining to Bering Sea species is based on short 96-hr exposures (Wolfe 1977; Karinen 1981). Models assumed that toxic oil concentrations would persist only one to two months, and, for such short periods, must therefore be present at relatively

high concentrations to be toxic. Based on molt frequency data of this report, decapod larvae molt every 3.5 to 4 weeks (as short as 2.5 weeks for crangonid shrimp) and thus over the duration of the hypothetical spills could be exposed 2 to 3 times during the physiologically sensitive events of ecdysis. From the perspective of relatively brief larval development time, a chronic and probably stressful exposure to oil would be one of 2 to 4 weeks duration. Given Moore and Dwyers' (1974) suggested sublethal hydrocarbon range of 1 to 100 µg/l, and Wells and Sprague's (1976) application factor of 0.03 from LC_{50} values to "safe" concentrations, we feel that exposure of crab and shrimp larvae to WSF of oil at >50-100 µg/l (.05-.1 mg/l) for 2 to 4 weeks during a molt cycle would be toxic. The sublethal effects of such exposure could be manifested as reduced feeding, delay of molt (this results in longer development time and pelagic existence, and therefore greater susceptibility to natural mortality factors such as predation), behavioral anomalies (changes in patterns of geotaxis and phototaxis), that together synergistically reduce viability of the larvae. Obviously, models that were predicated on toxic oil levels of 200 g/l (.2 mg/l) did not affect areas as large as those which might be polluted by concentrations 2 to 4 times lower. In this regard the models of Leendertse and Liu (1981) are probably a more accurate representation of oil transport than that of Sonntag et al. (1980). Figures 8.3 and 8.4 show results of the former simulation, and should be studied with respect to dispersion and area affected by lower toxic oil concentrations.

3. Oil was mixed to a 50-m depth in previous models (Sonntag et al. 1980) which is quite feasible but not necessary to affect crustacean larvae. Curl and Manen (1982) also discussed mixture of oil to depths of 60 m by storms as a mechanism for transport to the benthos. In the biological sections of this report (3.0-7.0) larvae of various decapod groups are shown to be distributed in the upper 60 m of water and often are most abundant in the upper 40-20 m (e.g., Tanner crab larvae). Later zoeal stages are capable of strong swimming bursts exceeding a centimeter per second. Over several days, larvae can easily move tens of meters vertically and in so doing approach or reach the surface. Megalopae of Chionoecetes spp., for example, were frequently caught after dark in neuston nets sampling the upper 20 cm, indicating that much of the population spends considerable time at the surface (Armstrong and Incze, unpublished data from 1981 PROBES cruise, Leg 4). Larvae of several other decapod groups studied for this report are situated high in the water column and apparently undergo diel vertical migrations (see Sections 6.0, 7.0). Thus, if spilled oil is initially mixed only to 20 m but is spread over a greater area it will still likely stress most decapod larvae of the water column as they invariably move near the surface during 10-14 days of oil residence time, but in this case the spatial effect is much greater and the population more severely impacted. To reiterate, it may not be necessary that oil is mixed much below the surface to contaminate and stress crab and shrimp larvae. Megalopae might routinely visit the surface where highest concentrations of oil would usually be found. Models should consider scenarios that spread a given volume

of oil rapidly over the surface (Leendertse and Liu 1981) and only to a depth of 20 m to derive area affected.

4. The model of Sonntag et al. (1980) did not consider any direct toxic effects of oil to benthic crab and shrimp but only indirect effects through losses of food. Curl and Manen (1982) discuss the possibility of some adult mortality in heavily impacted areas, but neither model considers toxicity of oil-contaminated sediments to developing eggs and embryos of benthic crustaceans. Armstrong et al. (1983) reviewed literature on oil impact and recovery of marine benthic communities and highlighted evidence of great perturbations to crustacean populations exposed to oil spills (Le Moal and Quillien-Monot 1981; Krebs and Burns 1978). Maurin (1981) reported that a year following the AMOCO CADIZ spill there were reduced crab catches, implying mortality of benthic stages, and fewer ovigerous female lobster suggesting effects on reproduction. We could find no literature reporting systematic studies of oil toxicity to early developmental stages of crustacean eggs, yet if hydrocarbons pass egg membranes and are sequestered in the lipid-rich yolk then the risk to rapidly cleaving embryos is probably high. Armstrong and Millemann (1974) found that embryos of the mussel Mytilus edulis are most sensitive to an insecticide during early cleavage stages, and they reviewed literature on protein and spindle apparatus poisons that affect both nucleic acid synthesis and normal blastomere division [it is possible that certain oil hydrocarbons act in a similar manner and Malins (1977) reviews literature on toxic derivatives of hydrocarbon metabolism that affect DNA structures and

synthesis as mutagenic/teratogenic agents]. Eggs of fish and polychaetes absorb hydrocarbons such as naphthalene (Rossi and Anderson 1977; Eldridge et al. 1978), and Tatem (1977) showed the lethal effects of a brief 72-hr exposure of gravid female shrimp to WSF when larval hatch was subsequently reduced 80%.

The longevity of oil bound to sediments in the Bering Sea could result in a chronic exposure of eggs during the 11-month development time for king and Tanner crab as hydrocarbons continuously desorb to interstitial and bottom water in accord with solubility, and mass balance properties. Sonntag et al. (1980) predicted that 8-16 g oil/m^2 would significantly inhibit annual benthic production. Curl and Manen (1982) discussed oil transport to the benthos via storms and fecal pellet rain, and, based on OCSEAP spill scenarios in the St. George Basin, predicted that 10 g/m^2 mixed 1 cm deep would result in a crude oil concentration of 3-4 ppt. Since larval stages are invariably more sensitive to pollution than are adults, we consider the same to be true of embryos, especially during chronic exposures. Therefore sediment levels of 5-10 g/m^2 (perhaps lower) could be toxic to crab and shrimp eggs over months of exposure and kill significant proportions of a following year-class as eggs, while a current year-class is killed as zoeae in the water column.

5. Both modeling efforts concluded that oil spills so severe as to eliminate an entire larval year-class would not constitute a significant effect on benthic stocks (and in turn the fishery) because longevity and fecundity of the species would mask this loss. We

strongly disagree with this hypothesis and believe that any significant reduction or a complete loss of a year-class could adversely affect the fishery 7-8 years later. As noted in Section 3.0, greater than 60% of any year's fishery may be comprised of new recruits from a single year-class. Otto et al. (1982) summarized population estimates for red king crab over the last 10 years and noted a significant decline in pre-recruit males in 1980 through 1982. Both the 1981 groundfish survey and commercial fishery have verified the existence of very weak year-classes, and the fishery in this and next year will be very poor (Section 3.0). Such reduction in commercial stocks probably results from poor survival during early life-history stages of larvae and new instars that is caused by poorly understood sources of natural mortality (exceptionally cold years of 1975-76 and excessive predatory pressures on small benthic instars are hypotheszied to be contributory causes; Section 3.0). Large-scale mortality of larvae caused by oil pollution could eventually be just as critical to the fishery as are unusually high losses due to natural causes. This would be particularly true of C. opilio Tanner crab because of the apparently sporadic recruitment success of this species under natural conditions (see Section 4.0; Incze 1983; Somerton 1981). Obviously, consecutive years of oil pollution or scenarios described in Item 4 of this subsection where pelagic larvae of one year are killed and benthic eggs for the following year's hatch simultaneously poisoned, would cause even greater harm to the fishery.

One or two very weak year-classes resulting from oil pollution may have important, though unknown, ecological ramifications via impacts on epibenthic and infaunal communities. Jewett and Feder (1981) reported that commercial crabs comprise 55% and 82% of epifaunal biomass on the middle (40-100 m) and outer (>100 m) shelves, respectively. Reduction of this enormous predator/prey group by catastrophic loss of larvae could radically alter the community composition, perhaps by an increase of echinoderms (sea stars) that are also abundant. The effect of this may be to slow recovery of crab stocks faced with large populations of competitors that increase to replace one or two years of crabs lost to oil. Populations of the crab Uca pugnax were still adversely affected 7 years after a small oil spill at West Falmouth, Massachusetts, that reduced the overall population, lowered female to male ratios, reduced juvenile settlement, and caused heavy winter mortalities and behavioral anomalies (Krebs and Burns 1978).

8.4 Extent of Area Affected by Oil

Scenarios considered by participants of the 1981 Anchorage OCSEAP Workshop included only spills or blowouts that released 50,000 barrels which, in retrospect, is a quantity far less than might be expected from mishaps involving modern tankers. Oil spill scenarios used during the North Aleutian Shelf Synthesis meeting in Anchorage (March 1982) were even smaller for the southeastern Bering Sea. Exceedingly small spills of 10,000 barrels were modelled by Pelto (1983) and covered relatively small areas of the Bering Sea (20 km by less than 1 km). The AMOCO CADIZ released 223,000 mt = 2.47×10^6 barrels of oil (1 barrel = 35

gal; specific gravity of oil about 0.85), of which 660,000 barrels reached the coastline. The Ixtoc blowout spilled 30,000 barrels/day into the Gulf of Mexico, and the eventual 500,000 mt released (Hood and Calder 1981) was equivalent to 2.5×10^6 barrels.

Spill scenarios modeled by the 1980 Asilomar Workshop included both a 100,000 mt (= 1.11×10^6 barrels) spill over two days and a release of 5,000 mt/day (55,500 barrels) for 20 days (Sonntag et al. 1980). After mixing oil to 50 m and accounting for loss of a 25% volatile fraction, an area of 7,500 km^2 was polluted at or above 0.2 mg/l (considered a lethal threshold in that model). If as suggested in this report the same volume of oil is mixed to 20-30 m and 0.05-0.1 mg/l is considered toxic, then an area of 15,000 km^2 might be affected. Curl and Manen (1982) predicted that a 50,000 barrel spill in the St. George Basin would be lethal over a 100-300 km^2 area (0.2 mg/l threshold; mixed to 50 m), and a more realistic spill of 500,000 barrels (half the value considered by Sonntag et al. above) would pollute an area 10 x greater. If these various scenarios are modified by mixing oil less deeply and considering oil concentrations of 0.05-.1 mg/l WSF to be toxic, then water over an area of 10,000- 15,000 km^2 might be polluted by concentrations lethal to decapod larvae following a large spill.

Oil contamination of the benthos can also impact crab and shrimp populations by deleteriously affecting egg and embryonic development and stressing all benthic age-classes, especially very young juveniles. In the small scenario of 50,000 barrels, over 100 km^2 received oil levels of several ppt by storm mixing and fecal deposition, and hundreds of km^2

were covered by lower concentrations (Curl and Manen 1982). After larger spills of 500,000 to one million barrels, several thousand km^2 of benthos could be covered by 5-10 g oil/m^2; a level we previously suggested might be toxic to crustacean embryos during chronic exposures. Extensive coverage would be most likely and most critical nearshore in shallow water. The same magnitude of scaling up could be applied to the NAS as well, which was considered only in terms of very small, 10,000 barrel (bbl), spills (Armstrong et al. 1983), which might cover an 8 x 20 km area with toxic oil concentrations. A large spill of 100,000-500,000 bbl north of Unimak Island, for instance, could be transported several hundred kilometers in nearshore currents to Cape Seniavin and also mixed to the benthos in these shallow waters.

8.5 Predictions of Oil Impact on Decapod Larvae

Rather than work from a specific oil scenario in this section and ask if larvae would be impacted, each major decapod group will be discussed from the vantage of how severe an oil spill must be to significantly impact a year-class. Figure 8.2 shows proposed lease sale areas of the St. George Basin and North Aleutian Shelf, and serves as reference to the following discussions.

8.5.1 Direction of Oil Transport

Physical oceanogrpahy and its relation to transport and distribution of oil in the water column was reviewed by Schumacher (1982) as part of the St. George Basin Synthesis meeting. Results of computer simulations by Leendertse and Liu (1981) were used to formulate scenarios of oil spills and direction of surface trajectories (Figs. 8.3 and

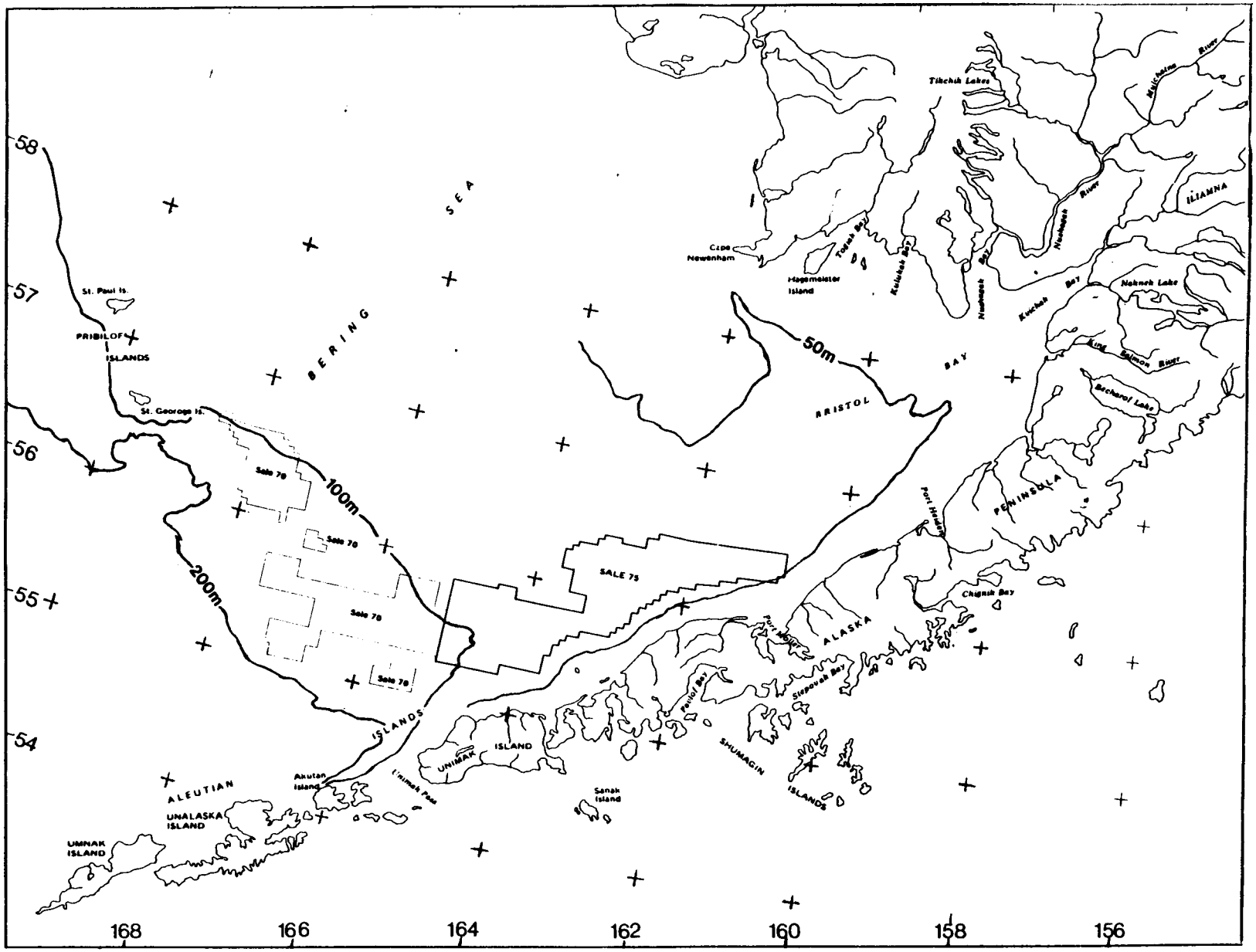


Figure 8.2 Lease sale areas in the St. George Basin between the 100 m and 200 m isobath, and along the North Aleutian Shelf.

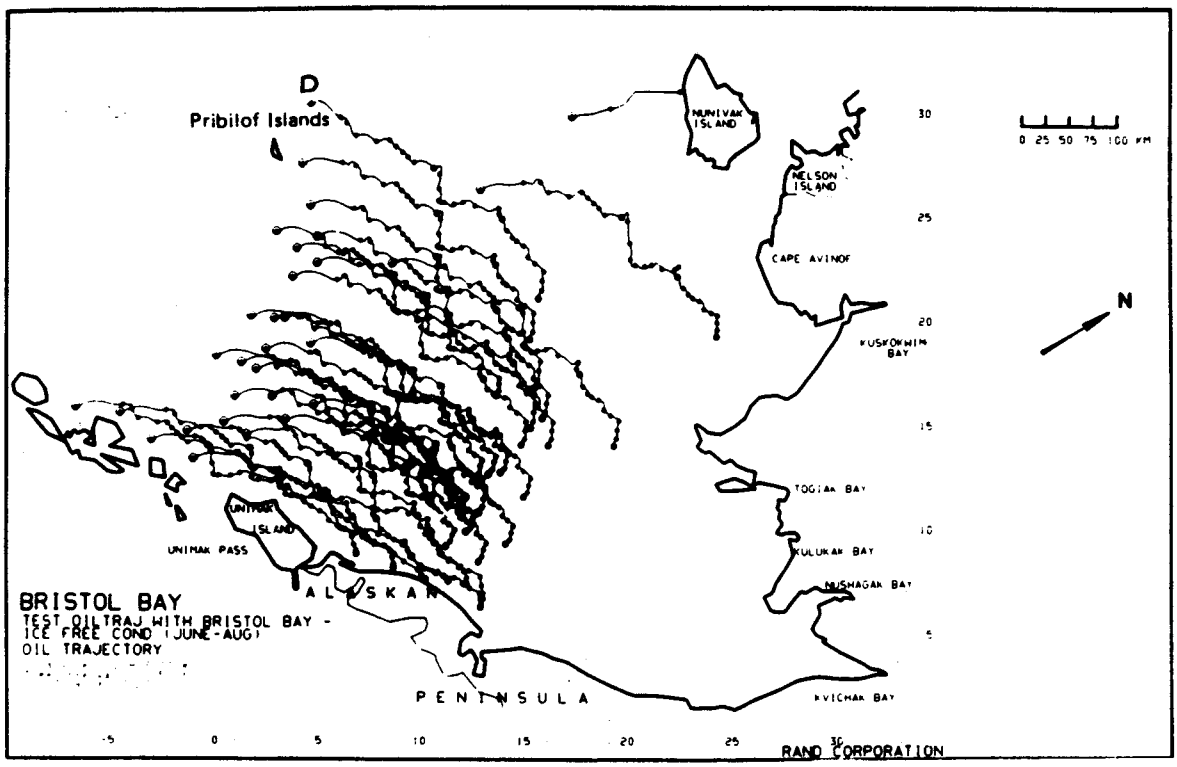


Figure 8.3 Surface oil trajectories during summer from spill points within the St. George Basin. Note easterly movement (from Leendertse and Liu 1981).

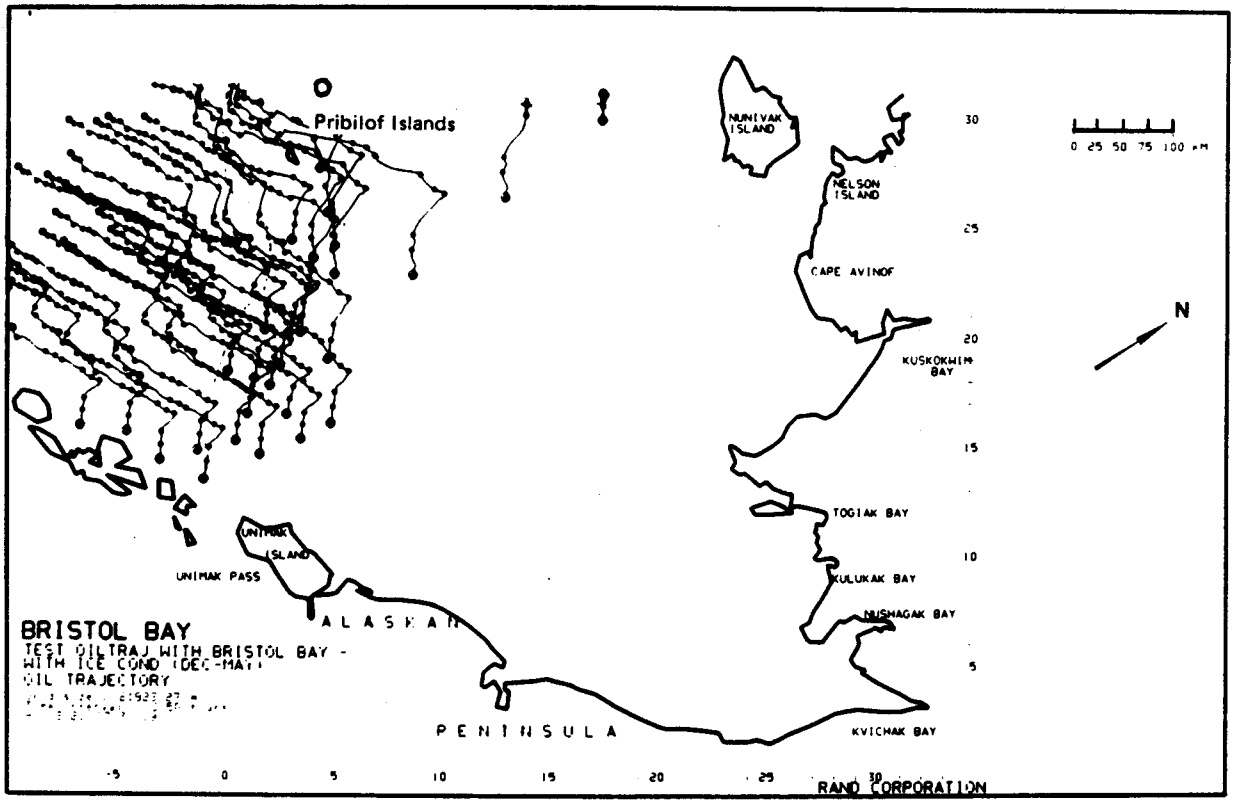


Figure 8.4 Surface oil trajectories during winter from spill points within the St. George Basin. Note westerly movements (from Leendertse and Liu 1981).

8.4). During summer and fall, oil from spills in the St. George Basin would be moved by prevailing winds east over the middle shelf and south to the North Aleutian Shelf coast at Unimak Island eastward for 200 km. In the winter, oil would be transported northwest and in both cases a spill would cover about 250 km^2 after 10 days. Most significantly, the rate of movement in summer is predicted to be about 8.5 km/day, much faster than the net current transport of crab larvae along the NAS which would be about 1.7-3.4 km/day. An oil spill in space and time that follows peak larval hatch could, theoretically, overtake a portion of the population even if initially some distance removed. However, extensive distribution of the larval population (e.g., Tanner crab) and dilution/volatilization of the oil might shield the year-class from extensive losses.

8.5.2 King Crab Larvae

As shown in Section 3.0, there are very few larvae of Paralithodes spp. over the St. George Basin, and consequently even an extensive oil disaster that is confined to the area between 100 m and 200 m would have no foreseeable effect on king crab populations. However, it is most probable that an enormous spill or blowout at numerous points within the lease sale area or along future tanker routes from St. George Basin, and certainly a spill along the NAS would be spread to areas critical for larval king crab development.

Blue king crab (P. platypus) and its fishery are centered about the Pribilof Islands. The Rand model of transport and fate of oil following a spill in the St. George Basin shows that winter-spring trajectories

are to the west-southwest (Fig. 8.4). If a major mishap in the northern lease tract (Fig. 8.1) occurs in April or May, then oil will likely reach and surround both St. George and St. Paul Islands and affect waters in between where larvae of this species are abundant. The northern lease area is about 125 km from St. George Island. A 50 x 150 km area of oil pollution emanating from a point around 56°45'N, 168°30'W would cover an area of 7500 km^2 (feasible in the model of Sonntag et al. 1980) including nearshore waters around the islands. In addition to killing a large percentage of the larval year-class, oil mixed to the bottom and transported to sublittoral areas around both islands could stress and kill juvenile crabs and poison eggs as previously discussed. The potential for severe decimation of blue king crab stocks by oil perturbations is high. Nearshore distribution and ecology of blue king crab is poorly understood but their dependence on the habitat must be high given the insular distribution (see results of NMFS surveys, Fig. 3.5).

Red king crab larvae (P. camtschatica) are distributed along the North Aleutian Shelf (see Section 3.0). Major oil spills by tankers at Unimak Pass or blowouts in southern lease-sale tracts around 55°30'N, 165°W or within the NAS lease sale area (Fig. 8.2) during summer months would result in oil being transported to king crab nursery areas according to trajectories of the Rand model for this season (Curl and Manen 1982; Armstrong et al. 1983; Fig. 8.3). The area from the west tip of Unimak Island to the eastern edge of Port Moller out to the 50-m isobath covers about 10,500 km^2. A large spill at Unimak Island could cover

most of this region and, as suggested by Curl and Manen (1982) and Armstrong et al. (1983), kill virtually all of the larval year-class in this area.

More detailed station coverage of the NAS in 1982 indicates a major portion of the larval population occurs along the 50 m isobath (Section 3.0), and probably is transported by long-shore currents to the northeast as hypothesized by Hebard (1959) and Haynes (1974). Although the frontal system depicted by Kinder and Schumacher (1981a) is not as well studied along the NAS as in upper Bristol Bay, its integrity may be such to entrain subsurface oil at the front with resultant transport in the direction of larval crab movement. Cline et al. (1981) concluded from methane profiles originating from Port Moller that material rarely penetrated more than 20 km offshore and was essentially entrained shoreward of the 50 m front while moving to the northeast, thus substantiating the notion of a strong front in this region. While movement of oil as a surface film by winds results in extensive coverage within brief time periods in models of Leendertse and Liu (1981) and Pelto (1981), mixing of oil into the water column along the 50-m isobath might pose a more serious threat to red king crab larvae along the NAS for 10-20 days after a spill. It is known from work by Haynes (1974) that king crab larvae are abundant east of Port Moller up to Port Heiden and into Bristol Bay in July and August. If these larvae escape pollution then the damage done by a Unimak-Port Moller disaster might be somewhat attenuated. However, distribution and abundance of larvae east of Port Moller is poorly known and requires further study (now funded by OCSEAP in FY 83).

Large volumes of oil reaching shallow water of the North Aleutian Shelf would be mixed to the benthos and would directly affect juvenile and adult crabs, deplete food, and stress and kill developing eggs of gravid females. Because major populations of sexually mature females are invariably found off Unimak Island, in the area of Amak Island, and off Port Moller (based on NMFS surveys; see Section 3.0), and because extensive lagoons and estuaries support abundant bird and mammal populations as well as supply nutrients for productive nearshore pelagic and benthic communities (see discussions in Hood and Calder, Vol. 2, 1981), threats of oil pollution to the North Aleutian Shelf should be considered paramount in future research and management plans. A significant loss of any year-class should be viewed as damaging to the fishery 7-8 years later.

An important but poorly studied life history stage in the southeastern Bering Sea is newly settled juveniles up to two years old. Their susceptibility to oil pollution may be very high, in part, because of highly restricted distribution in critical but scarce habitat. Very young juvenile king crabs less than two years old in the Kodiak region prefer rocky, cobble habitat that affords shelter from predators (Feder et al., 1980; Jewett and Powell 1981). Very little habitat of this type exists along the NAS (Michel et al. 1982) and young-of-the-year (0+) juveniles that settle on open bottom are probably vulnerable to heavy predation (Murray Hayes, NMFS, Seattle, pers. communication). Thus any habitat that offers protection to young crabs is critical to benthic survival. During an intensive search for 0+ and 1+ juvenile king crabs along the NAS in June, August, and October 1982, the only specimens

found from Unimak Island to Cape Seniavin were gathered by divers at Amak Island (trawl, video camera, and divers used to locate; Walt Pearson, Battelle Laboratory, Sequim Wa., pers. communication). Heavy oiling of the shallow sublittoral area around Amak could destroy a substantial portion of one or two juvenile king crab year-classes that metamorphosed in that area. (Distribution of small juveniles into upper Bristol Bay is currently under investigation through OCSEAP in FY 83).

8.5.3 Tanner Crab Larvae

Larvae of both C. bairdi and C. opilio are ubiquitously distributed over the St. George Basin, and C. opilio populations are also large to the north and northeast over the middle shelf (Figs. 4.10-4.15). A very large oil spill might cover 10-15% of the Basin (Sonntag et al. 1980; Manen and Curl 1981) and could have a significant impact depending on the following points:

1. Location. If a large spill was generally dispersed along 200 km of the 100-m isobath in a 50 km wide band, then the high densities of larvae associated with this depth in the years of our study (Fig. 4.7) could result in a high percentage of the year-class being affected.

2. Month. A spill that coincides with the megalops larval stage would probably be more destructive than an earlier spill when zoeae are present. Larvae of both Chionoecetes spp. are molting into the megalops stage by early July, and large numbers of megalopae may be found through September. Megalopae may spend a considerable amount

of time in the neuston layer. If their occurrence at the surface is part of a diurnal migration, then most megalopae could be expected to be exposed to surface films of oil. Further, since megalopae are the last larval stage before metamorphosis, they represent the survivors of larval development during which natural mortality has substantially reduced populations from initial densities of SI zoeae hatched. Extensive mortality of the megalops stage could exacerbate natural mortality rates and threaten recruitment to the benthos.

3. Year. Somerton (1981) shows that C. opilio in the area of the St. George Basin have successfully recruited juveniles to benthic populations only three times in 10-11 years. If a major oil disaster occurs in what is otherwise an auspicious year for C. opilio larvae, then extensive mortality could imperil an infrequent, yet crucial year-class for this species' reproductive effort in the area of the St. George Basin.

Because of the widespread distribution of Tanner crab over the southeastern shelf, a major oil spill would be required to significantly affect a larval year-class. However, because megalopae may aggregate near the surface, a widespread spill of shallow depth could affect larvae over a very large area. Since adults of these species are primarily in water deeper than 70 m, direct impacts on adult crabs are unlikely. The results of work reported by Incze (1983) indicate that events affecting the larval stage may be responsible for much of the sporadic nature of recruitment in this species.

8.5.4 Other Brachyuran Larvae

Larvae of Erimacrus isenbeckii are not abundant over large areas of the St. George Basin, and highest densities were found just north of Unimak Island (Fig. 5.1). An oil mishap over the Basin proper would not threaten the species, but oil transported along the North Aleutian Shelf from Unimak Pass could impact areas of high E. isenbeckii abundance. Although the commercial fishery (very small at present) is centered around the Pribilof Islands, few larvae were found in that area making it difficult to equate potential loss of larvae with impact on a fishery. Ongoing OCSEAP research should help clarify Erimacrus susceptibility to oil around the Pribilof Islands.

Larvae of Hyas spp., Oregonia spp. and of the family Pinnotheridae are widely distributed over the St. George Basin. Any reduction in benthic populations through mortality of larvae might have some ecological repercussion (no fisheries for these groups). However, as noted for Tanner crab, the area affected by even a large spill might be only 10-15% of the Basin and therefore of little threat to populations of these crabs as a whole. Again, if oil from a spill is dispersed along the 100 m isobath (roughly the middle front) for about 200 km then a greater proportion of the larval population might be killed since densities are high in this region (Section 5.0).

8.5.5 Shrimp Larvae

Larvae of Pandalus borealis and species of hippolytid and crangonid shrimp are ubiquitously distributed over the St. George Basin (Section 6.0). There is presently no commercial fishery for any shrimp species

in this area and so deleterious effects from oil-related mortality of larvae would be ecological in nature. The combined reduction of larvae and, in turn, benthic recruitment of several major shrimp groups could impact the benthic community through predator-prey relationships discussed in Section 6.0. Again, the relatively small area of the Basin polluted by even large spills would preclude impoverishment of benthic communities to the extent various finfish and crustacean fisheries are threatened through loss of food. Nearshore surveys in 1982 along the NAS revealed very high densities of both larval and adult crangonid shrimp. Although these data have not been fully analyzed, the magnitude of populations may be such as to suggest high predator utilization of crangonids in this region by crabs and fish (Armstrong unpublished data; VTN Inc., Portland, OR, pers. communication).

8.5.6 Hermit Crab Larvae

Larvae of the family Paguridae were widely distributed over the St. George Basin and middle shelf, and higher densities were usually found east of the 100-m isobath (Section 7.0). It does not seem likely that oil would significantly impact hermit crabs as a group because of broad spatial distribution and protracted period of hatch, factors that would tend to restore larvae in oil-impacted areas after toxic concentrations had diminished.

8.6 Summary of Major Conclusions

At the conclusion of this two-year study a number of features have been elucidated regarding general biology and population dynamics of decapod larvae in the southeastern Bering Sea. Although much more re-

search is called for on this group (OCSEAP FY 83 programs on crab biology will be very useful), several important predictions and observations pertaining to oil impact on decapod larvae in the S.E. Bering Sea can be made. These include:

1. Larvae of both red and blue king crab seem most likely to be deleteriously impacted by oil pollution because distribution is nearshore and relatively restricted over the expansive shelf. There is a high probability that significant portions of an entire year-classes could be killed by oil dispersed from a major spill, with a subsequent impact on the commercial fishery.

2. Larval Tanner crab populations could suffer extensive mortality depending on location, magnitude, season, and year of a spill as well as larval stage affected. Further modeling should be done with these species based on modified assumptions outlined in this section, particularly in regards to the last larval (megalops) stage. Many oil spills, however, might be relatively benign in their impact since these larvae are abundant over large areas of the St. George Basin and over the middle shelf near the NAS lease sales.

3. Larvae of many species of shrimp, hermit crab, and other true crabs are abundant and widely dispersed over the Basin. Most oil spills would not significantly imperil benthic populations, although the combined loss of all decapod larvae over 10-15% of the Basin could have regional consequences through impacts on predator/prey relationships in the benthic community.

4. Exposure of developing eggs and embryos of commercial crab stocks to contaminated sediments should be considered an important potential source of mortality in nearshore, nursery locations. There is no available literature on sensitivity of decapod eggs to ambient oil and research on this topic is warranted.

5. Further modeling of oil impacts to crab larvae should be done using the Leendertse and Liu and/or Sonntag models after modification of certain assumptions have been made including: a) shorter periods of hatch; b) 2-4 week molt cycles; c) greater toxicity of oil with threshold concenrations at 0.05-.1 mg/l; d) shallower mixing (20-30 m) but greater horizontal dispersion; e) stress and death of egg masses when sediment loads exceed 5-10 g/m^2; f) large spill scenarios of 5×10^5 - 1×10^6 barrels emanating from areas of the proposed lease sale near the Pribilof Islands, along the 100-m isobath, near Unimak Island, and along the NAS during April through July.

6. Significant reductions in larval populations caused by oil should be expected to adversely affect a year-class and, later, the commercial fishery when that year-class is recruited to legal size.

8.7 Research Recommendations

Areas of greatest susceptibility to oil in the southeastern Bering Sea are the Pribilof Islands and NAS which support much of the blue and red king crab populations, respectively. The following points should be given high research priorities:

1. Impact of oil via water and sediment on egg development and embryo maturation of commercial crabs, based on both short and long-term exposures.

2. Distribution and critical habitat of blue king crab larvae, young juveniles and mature females nearshore about the Pribilof Islands.

3. Extent and timing of larval red king crab hatch in upper Bristol Bay compared to nearshore along the NAS from Unimak Island to Port Moller.

4. Area of settlement and successful juvenile development of red king crab along the NAS into Bristol Bay.

As of this writing, the latter three points are research programs sponsored by OCSEAP and scheduled for completion in summer, 1984.

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APPENDICES:

A: S.E. Bering Sea Shrimp - Species List

B: References Used for Identification of Shrimp Larvae in the S.E. Bering Sea

C: Paguridae and Lithodidae Found in the Bering Sea

D: Distinguishing Between Chionoecetes bairdi and C. Opilio Zoeae Collected in the Southeast Bering Sea

APPENDIX A: S.E. Bering Sea shrimp - Species list.

Order Decapoda

Family Pasiphaeidae

Pasiphaea pacifica

Family Pandalidae

Pandalus borealis Kroyer
Pandalus goniurus Stimpson
Pandalus montagui tridens Rathbun
Pandalus stenolepis
Pandalopsis dispar

Family Hippolytidae

Spirontocaris lamellicornis (Dana)
Spirontocaris ochotensis (Brandt)
**Spirontocaris prionota*
**Spirontocaris arcuata*
Eualus macilenta (Kroyer)
Eualus gaimardii belcheri
**Eualus fabricii*
**Eualus barbatus*
**Eualus pusiolus*
**Eualus avinus*
**Eualus townsendi*
**Lebbeus groenlandicus*
**Lebbeus grandimanus* (formerly *L. polaris*)
**Heptacarpus camtschaticus*
**Heptacarpus moseri*

Family Crangonidae

Crangon dalli Rathbun
Crangon communis Rathbun
**Crangon alaskensis*
***Sclerocrangon boreas*
Argis dentata (Rathbun)
**Argis lar*
**Argis alaskensis*
**Argis crassa*

Family Oplophoridae

**Hymenodora frontalis*
**Hymenodora facialis*

This list is based on Feder & Jewett 1980 from NMFS/NOAA 1975 and 1976 survey cruise.
*Additions to list from species ranges given by Butler 1980.
**Larvae attached to adult; not expected to appear in plankton.

APPENDIX B. References used for identification of shrimp larvae in the S.E. Bering Sea, and location of source material used by each author.

Larval Descriptions

Author	Species or group, location
Pandalidae	
Berkeley, A., 1930	*Pandalopsis dispar* British Columbia
Haynes, E., 1976	*Pandalus hypsinotus* Kachemak Bay, Alaska
Haynes, E., 1978	*P. goniurus* Kachemak Bay, Alaska
Haynes, E., 1979	*P. borealis* Kachemak Bay, Alaska
Haynes, E., 1980	*P. tridens* Kachemak Bay, Alaska
Ivanov, B., 1971	*P. tridens* Kamtchatka
Kurata, H., 1964c	*P. borealis* and other pandalids Hokkaido, Japan
Needler, A. B., 1938	*P. stenolepis* British Columbia
Pike and Williamson, 1962	Pandalid sp. British Columbia
Rothlisberg, P., 1980	Pandalid sp. West Coast of U.S.A.
Williamson, D., 1967	Pandlid sp. British Columbia
Hippolytidae	
Haynes, E., 1978b	*Lebbeus groenlandicus* Kachemak Bay, Alaska
Ivanov, B., 1971	*Eualus macilenta*, *E. barbatus*, *Spirontocaris* sp., and *L. groenlandicus* (Stage I's) Kamtchatka Penn.
Needler, A. B., 1933	Hippolytid larvae British Columbia
Pike, R. B. and Williamson, D. I., 1960	*Spirontocaris* and related genera (includes *L. polaris* = *L. grandimanus*, *L. groenlandicus*, *E. gaimardii*, and *E. gaimardii belcheri*, *E. pusiolus*, *E. fabricii*, British Columbia

APPENDIX B. References used for identification of shrimp larvae in the S.E. Bering Sea, and location of source material used by each author. - Continued.

Larval Descriptions
Continued

Author	Species or group, location
Crangonidae	
Haynes, E., 1980b	Crangon franciscorus augustimana (Stage I) Kachemak Bay, Alaska
Kurata, H., 1964d	Crangonidae and Glyphocrangonidae, Hokkaido, Japan
Loveland, H. A., 1968	Crangon alaskensis San Juan Is., Washington
Makarov, R., 1966	Crangon dalli, Sclerocrangon boreas, Argis lar, A. crassa, Paracrangon echinata (spiny larvae)
Makarov, R., 1968	Sclerocrangon sp. Ochotsk Sea
Squires, H. J., 1965	Argis dentata N. Quebec, Ungava Bay
Williamson, D. I., 1960	Crangonid larvae North Sea, Barents Sea
Pasiphaeidae	
Elofsson, R., 1961	Pasiphaea multidenta and P. tarda, western Norway
Williamson, D. I., 1960	P. multidentata and P. tarda British Isles
Williamson, D. I., 1962	Oplophoridae and Pasiphaeidae larvae North Sea, British Isles and Barents Sea

APPENDIX C. Paguridae and Lithodidae found in the Bering Sea (compiled from McLaughlin 1963, 1974; Pereyra et al. 1976; Feder and Jewett 1980).

Family Paguridae
- Pagurus aleuticus
- P. beringanus
- P. brandtii
- P. capillatus
- P. confragosus
- P. cornutus
- P. dalli
- P. hirsutiusculus
- P. kennerlyi
- P. mertensii
- P. middendorffii
- P. ochotensis
- P. rathbuni
- P. tanneri
- P. townsendi
- P. trigonocheirus
- P. undosus
- Elassochirus cavimanus
- E. gilli
- E. tenuimanus
- Labidochirus splendescens

Family Lithodidae
- Dermaturus mandtii
- Haplogaster grebnitzkii
- Lithodes aequispina
- Phyllolithodes papillosus
- Placetron woznessenskii
- Pristopus verilli
- Sculptolithodes derjugini
- Paralithodes camtschatica
- P. platypus

Distinguishing Between *Chionoecetes Bairdi* and *C. Opilio* Zoeae Collected in the Southeast Bering Sea

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DISTINGUISHING BETWEEN *CHIONOECETES BAIRDI* AND *C. OPILIO* ZOEAE COLLECTED IN THE S.E. BERING SEA

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ABSTRACT

Three morphological characteristics which enable separation of zoea larvae of *Chionoecetes bairdi* and *C. opilio* are discussed; two are described here for the first time. Use of all three characteristics enables species identification of most *Chionoecetes* zoeae found in plankton samples from the southeastern Bering Sea.

INTRODUCTION

Zoeae of *Chionoecetes bairdi* and *C. opilio* are morphologically very similar, being larvae of two very closely related species which apparently still interbreed in nature (Johnson 1976, Pereyra et al. 1976). Several descriptions of zoea larvae of the two species have been published: *C. bairdi* and *C. opilio* Stage I zoeae from the S.E. Bering Sea (Haynes 1973), *C. bairdi* Stage II zoeae from Cook Inlet, Alaska waters (Haynes 1981) and *C. opilio* Stage I and II zoeae from the waters of Japan (Motoh 1973, Kurata 1963[1], Kuwatani et al. 1971). Haynes (1973, 1981) compared zoeae of both species from U.S. and Japanese waters in order to define morphological characteristics which could be used to distinguish between zoeae of the two species in areas where both exist.

Based on examination in our study of several thousand zoeae of both *Chionoecetes* species from the southeastern Bering Sea (*C. opilio and C. bairdi)* and also specimens from the western Beaufort Sea (*C. opilio*) and the Gulf of Alaska (*C. bairdi*), we have found that: (1) the principal criterion employed by Haynes in papers describing the morphological differences between zoeae of *C. opilio* from Japan and *C. bairdi* from U.S. waters (Haynes 1981) is more useful than the criteria he employed earlier to describe differences between Stage I

zoeae of these two species from the southeastern Bering Sea, but (2) additional characteristics are necessary for distinguishing between the species because of variability in the diagnostic length relationships recommended.
In this paper we compare our findings from plankton samples (mostly from the southeastern Bering Sea) with Haynes' findings (Haynes 1973, 1981) and describe two additional characteristics of the zoeae which extend Haynes' (1981) diagnosis of species differences.

Plankton samples from the southeastern Bering Sea are those of Incze et al. (this volume). Samples from Kodiak Is., Alaska were provided to us by A.J. Paul, Institute of Marine Science, University of Alaska, Seward; Lower Cook Inlet, Alaska samples were provided by Dr. T.S. English, School of Oceanography, University of Washington, Seattle; and western Beaufort Sea samples were provided by Dr. R. Horner, Seattle. Specimens were initially preserved in 3-4% buffered formalin and later transferred to 70% ethanol: water with glycerin.

DISTINGUISHING BETWEEN *C. BAIRDI* AND *C. OPILIO*

Observations on Length of Posterior Lateral Spine

Haynes (1973) described morphological features of Stage I zoeae of *C. bairdi* and *C. opilio* hatched from ovigerous females collected in the southeastern Bering Sea. Although the larvae described in his study were very similar, Haynes felt that they could be distinguished on the basis of subtle morphological differences:

> "Stage I zoeae [of the two species] are identical except for a few subtle differences in abdominal morphology. The most obvious difference is in the length of the posterior lateral spines on the third and fourth abdominal segments. In *C. bairdi*, the spines overlap the adjacent segments by about one-third the length of the spines. In *C. opilio*, the spines on the third segment barely extend past the posterior margin of the fourth segment, and those on the fourth segment do not quite reach the posterior margin of the fifth segment."

However, relative length of the posterior lateral spine (PLS) of specimens collected in this study usually did not provide clear evidence of the species according to the criteria outlined above. From examination of several thousand specimens it has become clear that a wide range of PLS lengths exist.

Measurements were made of PLS length relative to the posterior margin of abdominal segments for *C. bairdi* and *C. opilio* from Haynes' (1973) published figures to assist us in comparing Haynes' criteria with the measurements made of zoeae collected in our study. From Haynes' figures the following were calculated: (1) the percent of the third abdominal PLS that extends past the posterior margin of the fourth abdominal segment and (2) the percent of the fourth abdominal segment PLS that extends past, or doesn't quite reach, the posterior margin of the fifth abdominal segment. Our measurements made of Haynes' figures are shown in Fig. 1. Similar measurements were made on a number of Stage I zoeae of *C. bairdi* obtained from two sources: ovigerous females collected off Kodiak Is., Alaska and plankton samples collected in Lower Cook Inlet, Alaska (*C. opilio* has never been reported from these areas). The posterior lateral spines on either side of an abdomen of these zoeae frequently differed in length, as they did in Haynes' (1973) figures. In all cases illustrated in Fig. 1, the measurement of the longer spine was used when the PLS passed the posterior margin of the following segment and the shorter was used when the PLS did not reach this margin. Still, it can be seen (Fig. 1) that the relationships of PLS length to the margin of the following segment in known *C. bairdi* zoeae can vary substantially and can be quite similar to relationships illustrated for *C. opilio* by Haynes (1973). For *Chionoecetes* spp. collected from the plankton of the southeast Bering Sea, where both species exist, the relative lengths of the PLS show a continuum of values which make it virtually impossible to separate zoeae in all but extreme cases.

Further Observations on Abdominal Morphology

Haynes (1973) also observed that Stage I zoeae of *C. opilio* from Japanese waters described by Kurata (1963) primarily differed from his Stage I zoeae in the length of the curved lateral processes on the third abdominal segment. In a subsequent paper, Haynes (1981) compared both stages of *C. opilio*, which he had obtained from Japan, with corresponding stages of *C. bairdi* from Alaska waters, and on the basis of these later observations he concluded:

> "For both stages, zoeae of *C. bairdi* are morphologically identical with zoeae of *C. opilio* from Hokkaido and the Sea of Japan, except for the length of the curved lateral processes on the third abdominal somite. In Stage I and II zoeae of *C. opilio* from Hokkaido and the Sea of Japan,

> the curved lateral processes reach the posterior margin of the third abdominal somite, but in Stage I and II zoeae of *C. bairdi*, they are markedly shorter."

Haynes' later paper thus emphasized the use of the curved lateral process on the third abdominal segment [the length of which was previously described for *C. opilio* by Kurata (1963)] as a principal diagnostic feature for distinguishing between both zoeal stages of the two species: one from the eastern Pacific (*C. bairdi*) and one from the western Pacific *(C. opilio)*. However, Haynes (1981) acknowledged:

> "Stage II zoea of *C. opilio* from the eastern Pacific Ocean have not been identified, and it is not known if they can be distinguished from Stage II zoeae of *C. bairdi* by the length of their lateral processes."

Therefore, it remained unknown at that time how well these observations would apply to specimens collected in the southeastern Bering Sea.

Using the relationship of the length of lateral process on the third abdominal segment to the posterior margin of that segment (Haynes 1981), we were able to separate numerous *Chionoecetes* zoeae from the southeast Bering Sea into two groups, presumably corresponding to the two species of interest. In many instances, then, the relationship recommended by Haynes (1981) appears applicable when specimens of *C. opilio* are from the eastern Pacific, as well. However, we have found considerable variability in the relative length of the lateral process and it frequently is not possible to distinguish between the two species using this character alone. Specifically, the more slender, longer processes do not always reach the posterior margin of the segment, yet they clearly differ in shape and length from the shorter processes on other zoeae. We searched for additional characteristics in specimens from the clearly separated zoeal groups (using the above lateral process criterion of Haynes) to see if other morphological features could be used to distinguish between the two species when the lateral process length relationship did not clearly indicate one species or the other. Two additional characteristics have proven helpful in this respect: (1) length from the distal end of the rostral spine to the distal end of the dorsal spine and (2) the shape and relative length of the carapace lateral spines. These characteristics are described in the following section.

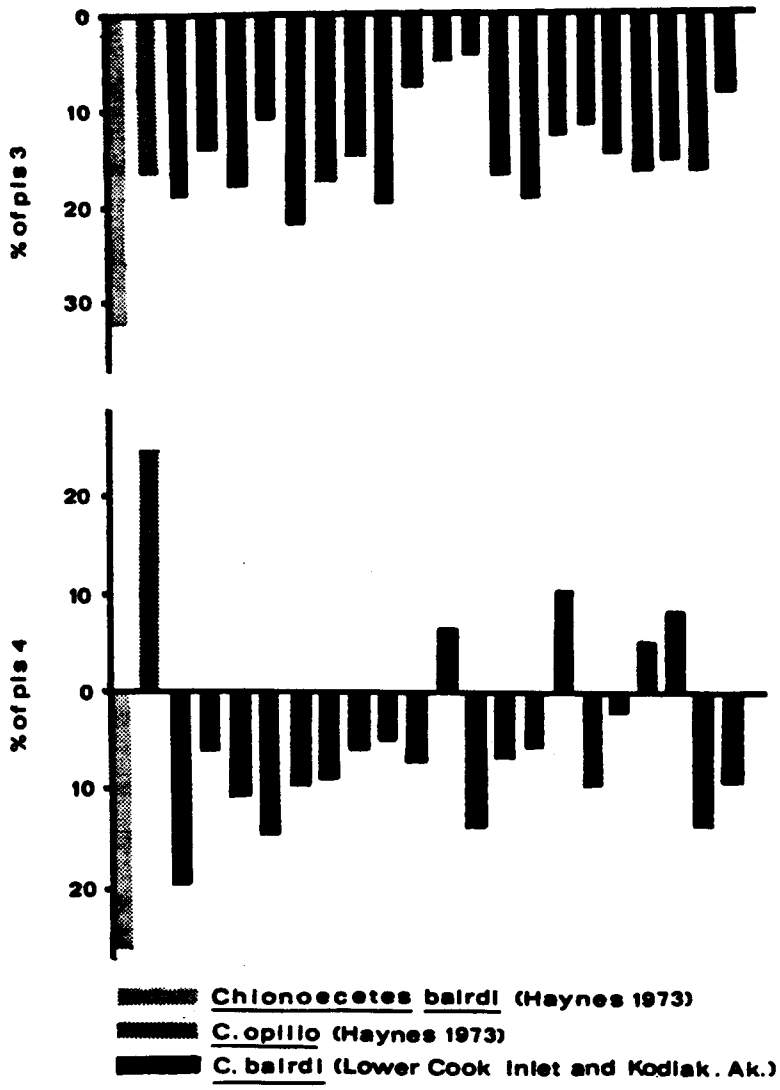

Figure 1. Comparison of PLS length in specimens illustrated by Haynes (1973) and in specimens examined in this study. Figure illustrates: (1) percent of the length of the third abdominal segment PLS that extends past the posterior margin of the fourth abdominal segment (upper chart); (2) percent of the length of the fourth abdominal segment PLS that extends past (downward in this figure) or does not quite reach (upward in this figure) the posterior margin of the fifth abdominal segment (lower graph).

Additional Morphological Features Useful in Species Identification

Measurements of length from the tip of the rostral spine to the tip of the dorsal spine (rostral-dorsal length = RDL) of Stage I and II zoeae from the southeastern Bering Sea with longer lateral processes [hereafter referred to as knobs, after Kurata (1963)] were always in the range of RDL values given by Motoh (1973, 1976) and Kurata (1963, 1969) for *C. opilio* from Japan (Table 1). That is, specimens diagnosed as *C. opilio* according to Haynes' (1981) lateral process (knob) criterion always had RDL measurements greater than or equal to 4.5 mm. Haynes (1973, 1981) did not specify a difference in RDL measurements between the two species. Those *Chionoecetes* zoeae collected from the southeast Bering Sea which had shorter knobs had RDLs in the range given by Haynes (1973, 1981) for *C. bairdi*, i.e. less than 4.6 mm for Stage I and less than 6.4 mm for Stage II. In addition, we also found that Stage II zoeae with shorter knobs had shorter RDLs than those reported by Haynes (Table 1). Measurements of these RDLs ranged from 5.5 - 5.95 mm. We thus found a consistent relationship of RDL to knob length in specimens for both groups of zoeae: those with obviously short and those with obviously long knobs (lateral processes).

The zoeae from the southeast Bering Sea that constitute these two categories also differed from each other in the shape and length of their carapace lateral spines (CLS). The CLS of zoeae with long knobs appeared straight, while the CLS of zoeae with short knobs appeared to droop downward (ventrally). As a general rule, the straighter CLS were shorter relative to the zoea's RDL, whereas the drooping CLS were longer relative to the RDL. These characteristics in addition to the one proposed by Haynes (1981) were used in our study to distinguish between zoeae of *Chionoecetes* spp. and are summarized in Table 2.

When these characteristics were used, most zoeae of *Chionoecetes* spp. from shelf waters of the southeastern Bering Sea could be tentatively identified as *C. bairdi* and *C. opilio*. This included the numerous specimens in which the knob length relationship did not provide conclusive evidence for species identification. Our identifications were then "tested" against data from plankton studies and information on the distribution and relative abundance of adults of the two species.

Table 1. Rostral-dorsal lengths of *Chionoecetes bairdi* and *C. opilio* Stage I and II zoeae tabulated from the current literature.

	C. opilio Kurata (1963,1969)	*C. opilio* Motoh (1973,1976)	*C. bairdi* Haynes (1973,1981)
Stage I	4.5 - 4.9 mm	4.8 - 5.4 mm	3.96 - 4.55 mm
Stage II	6.0 - 6.9 mm	6.2 - 7.1 mm	5.95 - 6.37 mm

Table 2. Summary of diagnostic features used to identify Stage I and II zoeae of *C. bairdi* and *C. opilio* collected in plankton samples from the southeast Bering Sea: Knob (curved lateral process), RDL (rostral - dorsal length) and CLS (carapace lateral spines) (see text for details).

	C. bairdi	*C. opilio*
Knob	Shorter	Longer
Stage I	3.96 - 4.55 mm	4.5 - 5.4 mm
RDL		
Stage II	5.50 - 6.37 mm	6.0 - 7.1 mm
CLS	Generally long and drooping ventrally	Generally short and straight

APPLICATION OF FINDINGS TO FIELD STUDIES

Certain aspects of the timing of appearance of the larvae in the plankton and spatial patterns of distribution and abundance provided evidence needed to corroborate the species identifications we had made using the above characteristics to extend Haynes' (1981) description. The larvae with the longer RDL and shorter, straighter CLS were found in the plankton earlier in the season than the larvae of opposite characteristics (see Incze et al., this volume). This was consistent with information provided to us by D. Somerton (see D. Somerton's larval paper, this volume), namely, that the state of maturation of egg masses of female Tanner crabs observed during National Marine Fisheries Service surveys in the area indicated that *C. opilio* hatched earlier than *C. bairdi*. The larval species description was further substantiated by specimens collected in areas where the bottom crab fauna was clearly dominated by one species or the other. Finally, areas of the Bering Sea which contained zoeae of only one description during a sampling season eventually gave rise to megalops larvae which were identified to species according to Jewett and Haight (1977); the megalops identifications confirmed our zoea identifications. All the above lines of evidence were in agreement with our zoea species identifications from four years of plankton samples.

Some *Chionoecetes* zoeae from the southeastern Bering Sea could not be categorized by the criteria described above. The RDL of these zoeae, found in water shallower than 200 m, often was in the area of range overlap of RDL for *C. opilio* and *C. bairdi* (Table 1); the knob character was often intermediate; and the CLS character occasionally did not match the knobs even when the latter were distinct. For these specimens, which were not abundant, no species designation could be made. It is possible that these were F_1 progeny of inter-specific matings between *C. opilio* and *C. bairdi*, but it would not be possible to determine this with morphological evidence alone. Since the relationship of genetic phenotype dominance among the various characters is unknown, it is also possible that F_1 progeny were included in one or the other (or both) of the species groups we have established above. Because the degree of inter-specific breeding is unknown, the extent of this error cannot be estimated.

Some plankton samples collected from regions overlying the continental slope contained zoeae which did not conform in appearance to any of the zoeae described above (*C. bairdi*, *C. opilio* or the unidentified *Chionoecetes* zoeae found over the shelf). These may have been the larvae of deeper dwelling species of *Chionoecetes*. As in the case of the shallower unknown zoeae, however, such specimens were not numerous.

We also compared our diagnostic features to zoeae from other areas. *C. bairdi* zoeae from Lower Cook Inlet, Alaska and Kodiak Is., Alaska exhibited all three characteristics listed in Table 2 for *C. bairdi* Stage I zoeae. Stage II *C. bairdi* which we obtained from plankton samples collected from Lower Cook Inlet, Alaska also exhibited all three of the characteristics listed in Table 2 for that stage. *C. opilio* zoeae (only 10 obtained) from the western Beaufort Sea (where *C. bairdi* does not occur) exhibited all the characteristics listed in Table 2 for *C. opilio* Stage I and II zoeae. We thus feel that the additional species characters described in this paper have general applicability to the species descriptions. In our study we found it necessary to use these characters in addition to the diagnostic feature suggested by Haynes (1981) to distinguish between zoeal larvae of *C. bairdi* and *C. opilio*.

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FOOTNOTES

1. Kurata (1963) described Stage I and II zoeae of what he called *C. opilio elongatus* based upon Rathbun's (1924) disignation of the subspecies. According to references cited by Haynes (1981) the sub-specific designation is not warranted, therefore, we have used the species designation *C. opilio* for zoeae described by Kurata.