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Volume I

Point Thomson Development Project Winter 1982 Geotechnical Investigation

prepared for

EXXON COMPANY, U.S.A.
Production Department Western Divison

№ 012

VOLUME I

POINT THOMSON DEVELOPMENT PROJECT
WINTER 1982 GEOTECHNICAL INVESTIGATION
EXXON COMPANY, U.S.A

HLA JOB NO. 9612,031.08

A Report Prepared for

EXXON COMPANY, U.S.A.
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I SUMMARY

The Point Thomson Development area, located about 50 miles east of Prudhoe Bay, lies between Bullen Point and Brownlow Point, a distance of about 23 miles. The area extends approximately three miles onshore and five miles offshore, and encompasses several barrier islands. Development of the area will require numerous artificial islands for production and injection wells, processing facilities, and water intake for water-flooding. Pipelines will connect the drill pads, islands and onshore facilities. The sales oil and gas will be transported by pipeline to the Alyeska system and, when built, the Alaska Natural Gas Transportation System at the Prudhoe Bay unit. At this time specific locations, numbers or types of production facilities and other improvements have not been defined.

Harding Lawson Associates (HLA) drilled and sampled 23 test borings to depths ranging between 25 and 80 feet within the proposed development area to investigate the soil and permafrost conditions during the winter of 1982. Of the 23 borings, 5 test borings were drilled onshore and 18 test borings were drilled offshore, 14 of which were located over ice and 4 on barrier islands. Ground temperature instrumentation was installed in 3 of the offshore borings, 2 of the onshore borings and 2 of the barrier islands borings. The drilling data, along with the results of an extensive laboratory testing program, were used to analyze preliminary geotechnical aspects of: (a) fill materials, (b) island design and foundation support, (c) offshore pipeline burial, (d) causeway design, (e) onshore pipeline support and (f) roadway and camp design.

Soil samples from the borings were examined to identify their field classification and selected samples were tested to measure their pertinent engineering characteristics. The following classification tests were

performed on cores obtained from each boring: moisture content, dry density, particle size distribution sieve analysis and mechanical analysis using a hydrometer, Atterberg limits, specific gravity, organic content, and pore water salinity and chemistry.

Additional tests included: triaxial shear, unconsolidated-undrained to measure undrained shear strength, triaxial shear, consolidated-undrained with pore pressure measurements and consolidated-drained to measure total and effective stress parameters, consolidation tests with time rates on fine-grained soils to evaluate the degree of consolidation and to compute the magnitude and rate of settlement under static loads, direct shear consolidated-drained tests on cohesionless materials to measure angles of internal friction, pore water conductivity tests to determine the freezing point depression of pore fluids, thermal conductivity tests of both frozen and thawed samples, using the thermal needle method, and thaw consolidation tests on frozen samples.

Climatic and subsurface conditions found in the Point Thomson area are similar to that observed in the Duck Island and Prudhoe Bay areas. Consequently, data acquired over the years from these areas can be directly applied to this study.

The onshore area is flat, treeless, and windswept. The Arctic cold has frozen the ground hundreds of feet deep; it remains frozen except during the hundred days of summer when one to three feet of soil thaws beneath the tundra mat. The permafrost terrain is exemplified by polygonal ground and shallow thaw lakes which drain to the north into the Beaufort Sea.

The boundary between the ocean and land has swept north and south across the project area during the glacial epochs of the last 100,000 years. During low sea level stands the sediments froze and permafrost was formed. The maximum depth of permafrost is estimated to be between a depth of 1,000 and 1,800 feet. Since the last sea level rise, about 4,000 years ago, saltwater has slowly penetrated and degraded the offshore permafrost forming an irregular frozen surface. In the offshore lagoon area between the shoreline and barrier islands, the water is typically 10 to 15 feet deep, while water depths outside the barrier islands are in excess of 30 feet and are ice covered most of the year.

The onshore soil conditions generally consist of a thin layer of fine-grained Holocene silt and organic silt overlying Pleistocene alluvial silts, sands and gravel. The moisture content of the sand and gravel varies from 5 to 15 percent; this corresponds to an in-place dry density of 115 to 130 pcf. The soil was frozen throughout the depths explored, 50 feet, in all the onshore borings.

The offshore sediments consist of a complex sequence of Holocene and Pleistocene sands, silts and clays overlying Pleistocene fluvial and glacio-fluvial sands and gravels. The subsurface soil was unfrozen to the depths explored, 80 feet, in the lagoon area and frozen at depths varying from 0 feet to 39 feet at and outside the barrier islands. In addition, three of the barrier island borings encountered a zone of thawed soil sandwiched between the surface and deep frozen sediments. The Holocene and Pleistocene sands, silts and clays were found to have an effective angle of internal friction of 40 degrees. The Holocene silts and sands had moisture contents which varied between 25 and 35 percent and a dry density between 70 and 90 pcf. The Pleistocene silts and clays had a moisture content which varied between 15 and 25 percent and a dry density between 90 and 110 pcf. The overconsolidation ratio for all soils tested ranged between 1 and 3.

The test borings revealed subsurface conditions typical of the North Slope area currently being developed. Therefore, sound engineering design concepts currently be practiced are applicable to the Point Thomson area.

Oil field development facilities typically are constructed using gravel fill for roads and drill pads. Consequently, development of the Point Thomson area will require extensive fill material depending on final design configurations and the number of structures. The onshore Point Thomson development area has sufficient quantities of sands and gravels for the development of the entire project. In addition, gravel is present in the offshore area. Fine grained silty sand could be dredged from along the shoreline and placed hydraulically. For strength and compressibility, unfrozen onshore and offshore gravels are more desirable than frozen gravel or silty sand.

Subsea sediments will compress under the weight of island fill materials resulting in one to two feet of settlement. Most of the settlement will occur within three months of island construction and should have little effect on the structures installed after that time. The strength of the island fill will depend on whether gravel or silty sand material is used, whether construction is performed during the winter or summer season, whether the fill is frozen and on the brine content, ice content and fill temperature. In general, the silty sands have lower strength and higher compressibility than the sandy gravels. The estimated strengths used to analyze possible types of frozen fill were adjusted for the high ice content gravel observed in the Point Thomson C-1 material site using creep deformation theory.

Structures located on offshore islands, causeways, and barrier islands can be supported on either pile foundations or shallow spread footings. Pile foundations will develop vertical support by friction in the unfrozen soils below the sea floor. If piles penetrate frozen subsea soils, reduced friction values should be used in design. Shallow footings bottomed on gravel fill can be designed using relatively high bearing pressures. Sheet pile walls with pile-supported decks can be used as docks for unloading heavy modules.

In the zone of thaw caused by heat induced from the well drilling apparatus, large island and drill pad settlement will occur. Settlement will result from both thaw of gravel-ice fill and thaw of subsea permafrost. Consequently, structures sensitive to settlement should be located outside the area influenced by drilling or should be designed for releveling.

Subsea pipelines should be designed to withstand the sea floor scour that occurs from various ice processes during break up and summer months. Pipelines outside the barrier islands should be designed to withstand ice gouging and wave-induced ice pounding. Sea ice processes were not within the scope of this work and should be evaluated to determine pipeline burial depths.

It is anticipated that onshore pipelines will extend from the beachline of a causeway into pipeline corridors at Prudhoe Bay. Ice-poor and ice-rich frozen soils are present within the onshore Point Thomson area. Onshore structures and pipelines should be supported above grade on piles designed for both frost heave forces and long-term creep settlement in ice-rich soil. Pile capacity depends upon the bond between the pile surface and frozen soil; consequently, the pile system is referred to as a slurry adfreeze pile. High pore water salinity and ice will reduce the pile adfreeze strength. The minimum embedment depth is dependent upon the anticipated frost heave forces but in all cases should not be less than 11 feet in ice-poor soil and 14 feet in ice-rich soil. Roadways and storage areas within the project site should be constructed of gravel fill at least five feet thick placed over the tundra.

II INTRODUCTION

LIST OF ILLUSTRATIONS

II INTRODUCTION

A. Project Setting

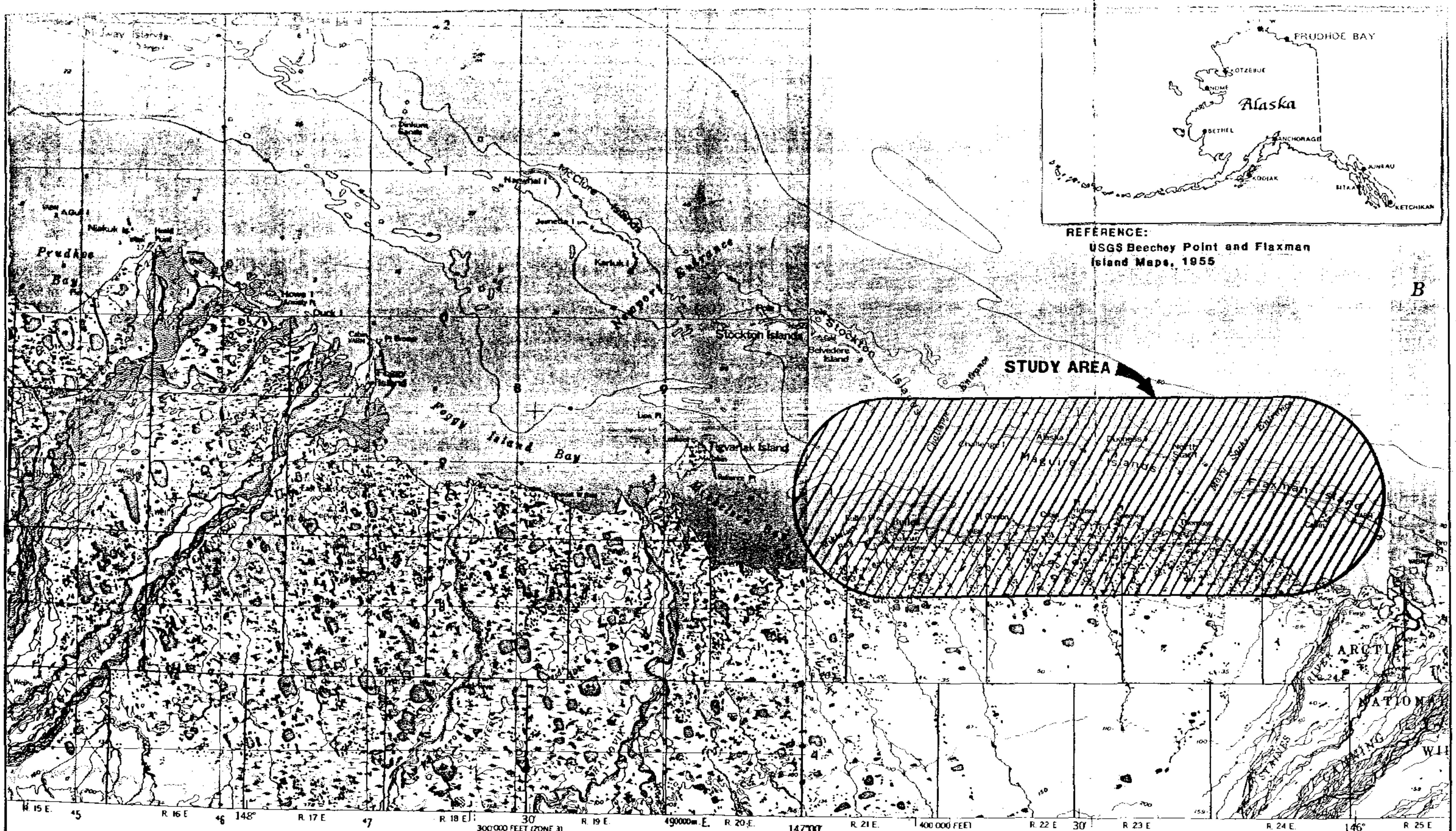
The Point Thomson Development area (PTD) is situated between Bullen Point and Brownlow Point northwest of the Staines and Canning River Delta, and about 50 miles east of Prudhoe Bay. This report presents general geotechnical engineering data needed for regional planning and preliminary design of oil production facilities.

The PTD area shown on Plate II-1 extends approximately 3 miles onshore and 5 miles offshore. Lagoon, shoal and deep water conditions exist within the offshore area, with water depths as great as 35 feet outside the barrier islands and 10 to 15 feet inside the barrier islands. The coastline within the area is a delta front with sandy beaches, mud flats and islands separated by small sandy peninsulas and channels of the Staines and Canning Rivers.

The climate is cold with monthly average air temperatures below freezing nine months of the year. The offshore area is covered with sea ice most of the year. Permafrost, the frozen soil condition associated with arctic cold, is present onshore and offshore and exerts a major influence on both the geologic processes and the engineering properties of soils in the area.

B. Proposed Development

At this time, the type, location and number of specific development facilities have not been defined. We anticipate that the development will include production well facilities requiring onshore gravel pads, offshore gravel islands and gravel pads on the barrier islands, both onshore and offshore pipelines, and support and transportation facilities such as roads, bridges, camps, pump stations, causeways and docks. A substantial requirement for



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5 0 5 10 15 20 25 MILES

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Regional Study Area
Pt. Thomson Development Project
Winter 1982, Geotechnical Study
EXXON Company, U.S.A.

PLATE **II-1**

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gravel fill material to construct both the onshore and offshore facilities is anticipated. Typical production islands may have clusters of 70 to 80 wells that will produce warm crude oil. Wells for gas reinjection and waterflooding will also be needed in the producing areas. A separate island in deeper water or a pad located on one of the barrier islands may be required to produce and treat water for waterflooding.

Fluids from the production wells will be piped to production facilities either onshore or on a barrier island where they will be treated to separate oil, gas, and water. The production facilities may consist of either modular structures, such as those used in Prudhoe Bay, or an integral barge structure using island fill to protect the sunken barge from sea ice. To accommodate both drilling and production facilities, island and pad surfaces could be as large as 30 acres.

The production islands will be interconnected by pipeline systems which will convey crude oil, natural gas, sales oil, and waterflood water. Communication and power supply systems and fuel lines will also interconnect the islands.

Transporting the sales product from the PTD to the Alyeska system and the proposed gas conditioning facility at Prudhoe Bay will probably be by subsea pipelines and causeways from offshore islands to an onshore collecting station. The causeway will protect the pipeline from sea ice and also allow year-round vehicle access from the onshore camps to offshore structures. The pipeline would extend from the PTD coastline to the vicinity of the Duck Island Development (DID) area where it could follow the proposed DID pipeline corridors. An onshore operations camp will be needed for the construction of the pipeline, road, causeway, and island system and for operation of the unit.

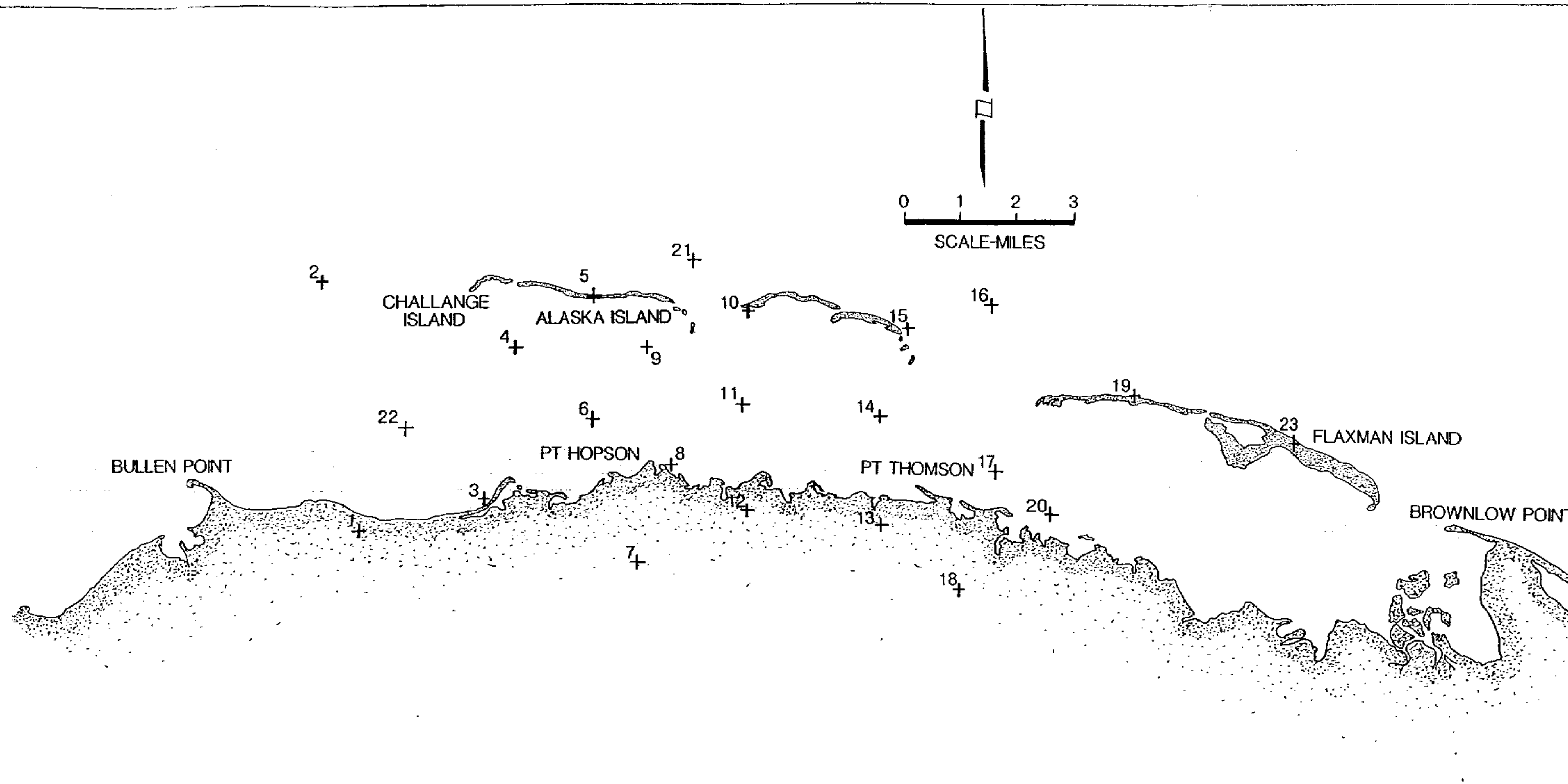
C. Purpose and Scope

This report presents the findings of a geotechnical investigation performed by Harding Lawson Associates for the Point Thomson Development area. The work was performed under Exxon Contract Agreement Number PTD-8201. The purpose of our investigation was to provide baseline geotechnical data, conclusions, and recommendations for regional planning and preliminary design of the project.

Our work included onshore and offshore test drilling and soil sampling, laboratory testing of the samples recovered during the investigation, geological interpretation of the field data, and engineering analyses to provide conclusions and recommendations for preliminary design. The results of this investigation have been correlated with previous studies.

Twenty-three borings were drilled to depths ranging from 25 to 80 feet below the ground surface/mudline in the PTD area at the locations shown on the Site Plan, Plate II-2. Of the twenty-three borings, fourteen were drilled overwater, four were drilled on the barrier islands and five were drilled onshore. Engineering properties of both frozen and unfrozen samples were determined by laboratory testing. Stabilized temperature profiles were obtained in seven of the borings by installing and reading thermistors.

This report is presented in two volumes. Volume I presents the findings of our field and laboratory investigations and our conclusions and recommendations for preliminary design. Volume II contains the data base for the conclusions presented in Volume I. A summary of previous studies performed in the area is presented in Appendix A. Detailed descriptions of the drilling program are presented in Appendix B along with individual boring logs. Ground temperature measurements and the laboratory testing program are described and the test data are presented in Appendixes C and D respectively.



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Site Plan
Pt. Thomson Development Project
Winter 1982, Geotechnical Study
EXXON Company, U.S.A.

PLATE II-2

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Apendix E presents an explanation of analytical procedures used to define mechanical properties of fill materials, pile settlement and laterally loaded piles in permafrost.

D. Acknowledgements

Project Director was Jay England, Technical Project Manager and Field Project Manager was Donald Bruggers. Authors of the geological section of the report were Craig Rodeick, Lawrence Toimil and Steven Johnson. Field geologists for the drilling were Richard Prescott, Mark Musial and Peter Ondra. Director of the laboratory testing program was Dr. Kai Wong. The engineering analyses and chapters on engineering considerations are credited to Donald Bruggers, Dr. Kai Wong, and Dr. Richard Christensen. Author of Volume II and project engineer was Mark Musial. Technical editor was Martha Jokela.

Day-to-day coordination and support were provided by Leslie Paxton-Rousseau of Exxon Company, U.S.A. Additional support was provided by Dr. Anton Prodanovic of Exxon Production Research Company.

III REGIONAL SETTING

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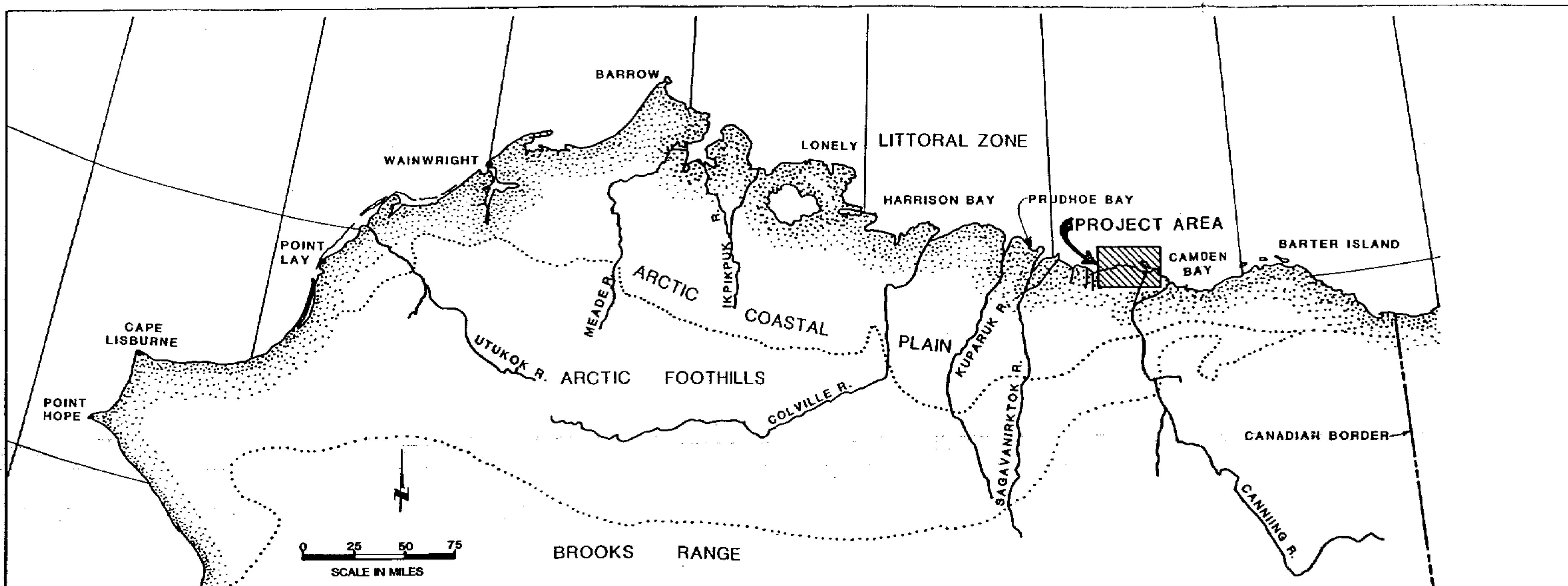
III REGIONAL SETTING

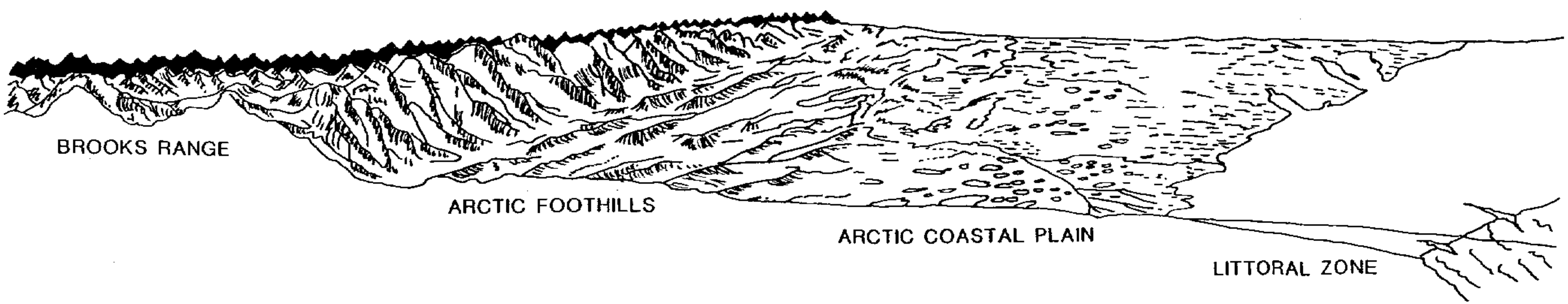
A. Physiography

1. The Arctic Region

The Arctic region of Alaska encompasses the drainage basins of all rivers flowing north from the divide of the Brooks Range into the Chukchi and Beaufort Seas. As shown on Plate III-1, this area stretches more than 600 miles from the Canadian border west to Cape Lisburne and nearly 250 miles north to south from Point Barrow to the crest of the Brooks Range near Howard Pass. The total area of the region is approximately 81,000 square miles, about the size of the state of Idaho. Although it contains approximately 14 percent of Alaska's land, the region has only about 2 percent of its population. Permanent and parttime residents number approximately 8000 (U.S. Army Corps of Engineers, 1980), and the population density is about 0.10 person per square mile.

Wahrhaftig (1965), Hartwell (1973), and others have divided the Arctic region of Alaska into four provinces: the Brooks Range, the Arctic Foothills, the Coastal Plain, and the Littoral Zone. The high rugged peaks of the Brooks Range end abruptly at the Arctic Foothills, which are long arcuate ridges descending to the rolling tundra of the Coastal Plain. The Coastal Plain province which extends from sea level to an elevation of 400 feet, is about 30 miles wide near the project area, but it widens significantly to the west and is over 90 miles wide south of Point Barrow. Offshore, the Continental Shelf continues under the Beaufort and Chukchi Seas to form the Littoral Zone. The shelf is only about 35 to 50 miles wide from Point Barrow eastward but extends several hundred miles offshore to the west. It is





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Physiographic Provinces of the Arctic Region of Alaska
Pt. Thomson Development Project, Winter 1982, Geotechnical Study, EXXON Company, U.S.A.

PLATE **III-1**

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terminated by the relatively steep continental margin which drops off into the Arctic Ocean Basin. Only the Coastal Plain and Littoral Zone are of interest for Point Thomson development and these two are discussed in more detail below.

a. Coastal Plain Province

The Coastal Plain Province in the project area is characterized by subtle topography, thaw lakes, meandering north flowing stream channels, and ice-bonded permafrost soils. The soils are the product of fluvial, glaciofluvial, and marine processes active since Tertiary time (1 to 70 million years ago). Materials eroded from land areas have been deposited near the coast and offshore. These materials include mineral soils ranging in size from clay to boulders and, in some areas, large amounts of organic matter.

Stream, current, wave, and ice processes have winnowed, transported, and deposited a wide range of materials into the sea, forming a coast consisting of prograding delta fans, low truncated bluffs, shallow lagoons, and barrier islands. The shaping of the present coast has taken place over the last 3000 years during a period when the sea level has remained fairly constant.

In the vicinity of the project area, the Coastal Plain Province can be subdivided into the Upland Fan and Coastal Zone regions; these regions differ in their topography, hydrology, and morphology.

(1) Upland Fan

The Upland Fan region is adjacent to northward sloping abandoned deltas of the Staines and Canning Rivers. The topography of the Upland Fan region is very subdued. Elevations range from about 25 feet five miles inland of Point Thomson to zero feet on the beach at Point Thomson. The abandoned delta slopes northward at a gradient of about 1 foot vertical to

1300 feet horizontal. Upland relief is generally minor, with local changes in topography of approximately six feet. Abrupt changes in topography, on the order of 15 feet, are associated with banks along small, north flowing streams.

One of the dominant features of the Upland Fan region is the continuous layer of pereniallly frozen ground known as permafrost. Permafrost is generally defined as ground having a temperature below 0^{0} Celsius (C) continuously for two or more years. Permafrost extends almost to the ground surface except for unfrozen pockets, which are typically located beneath deep lakes and abandoned or active major river channels. Permafrost is found in materials ranging from dense gravel to silts and clays.

Because of the impermeable nature of the shallow permafrost and its low relief, drainage of the Upland Fan is poorly developed. Small, northern flowing streams, most less than four miles long, form the drainage system of the Upland Fan. Thaw lakes along the streams result in a "beaded" drainage pattern. The beaded streams form as a result of the melting of massive ground ice in a process called thermokarst. Water derived from rain, snow melt, and summer thawing of the subsoil accumulates above the permafrost table and this moisture combined with the thaw lakes results in the swampy character of low lying areas during the summer.

The landscape between the thaw lakes is characterized by a variety of patterned ground forms. The most common of these are the high and low centered polygons and frost boils which constitute the principal microrelief.

The major rivers in the study area are the Staines and Canning Rivers. These rivers are of the braided type, i.e., they are characterized by continuously shifting active channels separated by gravel and sand bars. The headwaters of the Staines and the Canning are in the Brooks Range, and they terminate in a delta approximately four miles wide directly east of the project area. The rivers freeze over during the winter but deeper pools, particularly in the Canning, remain unfrozen. The river ice is normally five to six feet thick by the end of winter but overflows can cause the development of aufeis which can considerably thicken the ice cover. Beneath the ice, the river may maintain a discontinuous winter flow. Although freeze-over generally occurs during October, it sometimes takes place as late as mid-November. River breakup generally occurs in early June, and the associated floods are estimated to contain 60 to 80 percent of both rivers' annual flow.

(2) Coastal Zone

The Coastal Zone includes the ancient and modern delta front of the Staines and Canning Rivers and its beaches. The beachline is characterized by numerous small triangular points and high angle bars which have been named Points Gordon, Hopson, Sweeney and Thomson from west to east, respectively.

The shoreline from the Staines River delta west to Bullen Point is characterized by an abrupt break in the slope between the relatively flat Upland Fan and the gently sloping sea floor (Hartwell, 1973). The beach in this area is formed by slumping of the bluffs which are generally about 10 feet high. Slumping results from the thermal and mechanical erosion induced by wave activity along the base of the beach bluffs: blocks of frozen overhanging tundra mats collapse when ice wedges within the tundra melt or are undercut by waves, scattering large clumps of organic material along the beach front.

b. Littoral Zone

(1) Offshore Topography

The Littoral Zone is that portion of the study area offshore of the mainland beach and includes the barrier islands. Seabed slopes between the mainland beach and the barrier islands are relatively flat. An abrupt steepening of the seabed occurs seaward of the barrier islands where seabed gradients are 0.2 percent or a slope ratio of 1 vertical to 500 horizontal (1:500) (Harding Lawson, 1979).

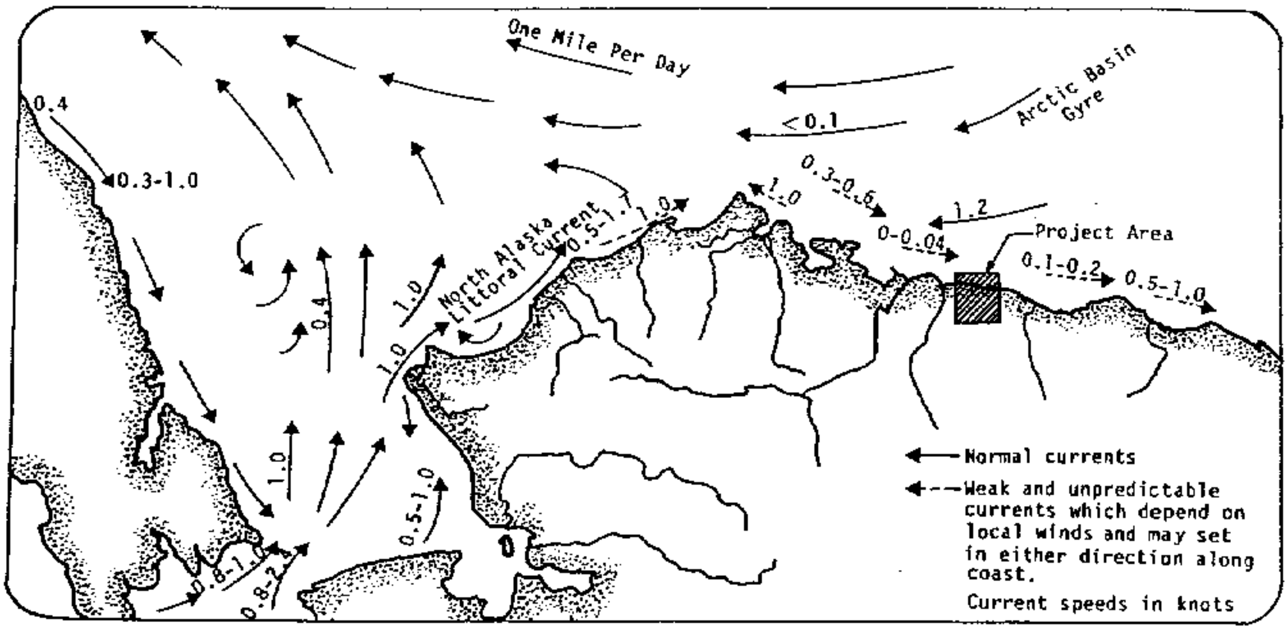
The barrier islands are the dominant topographic features of the Littoral Zone. Two kinds of barrier islands are found in the PTD study area: those that represent the erosional remains of the relict coastline and those recently constructed by physical processes. Flaxman Island is an example of an erosional remnant island. Flaxman Island stands as high as 25 feet above sea level and, along its western end, supports a continuous cover of tundra vegetation and small thaw lakes. The beaches along the western portion of the island are formed by the sloughing of bluffs up to 15 to 20 feet high. Sloughing results from the same mechanical and thermal processes that are eroding the mainland beaches.

The Maguire Islands are examples of more recent constructional features. Nowhere higher than ten feet, these islands are much longer than they are wide, with a maximum length of about three miles and widths ranging from 40 to 150 yards. They are covered with sand and gravel and are separated by frequent inlets. Plant growth is sparse to nonexistent and because vegetation is usually required for dune stabilization, there are no stable dunes. Sand and gravel beach ridges in excess of two feet high have been observed on the western end of Flaxman Island. These ephemeral ridges are the result of "plowing" of the islands by ice during the winter months (Leffingwell, 1919). The constructional islands are all migrating toward the southwest (Wiseman, et. al, 1973).

(2) Tides, Currents, and Waves

Summer water circulation patterns on the Beaufort Shelf offshore of the PTD study area are complex and not completely understood. The surface circulation on the outer Beaufort Shelf is dominated by a clockwise, westward flow associated with a gyre in the Arctic Basin midway between Alaska and the North Pole, as shown on Plate III-2 (Selkregg et al., 1975). Mountain (1974) reports an eastward flow of water along the inner shelf which appears to be associated with local westerly winds produced by storms; these storms occur mainly in late summer and fall and cause higher sea levels. Current reversals have been observed a few hours after a change in wind direction from easterly to westerly or vice versa (Namtvedt et al., 1974). The data indicate that the nearshore currents and sea levels along the Beaufort Sea coast from the Sagavanirktok Delta to the Canning Delta are strongly influenced by local winds.

The mean lunar tidal range for the Beaufort Sea coast in the vicinity of the PTD study area is 6 to 12 inches (Kinney et al., 1972; Reimnitz and Barnes, 1974), and the associated tidal currents are weak. Because lunar tides are relatively insignificant, nontidal factors have an important effect on sea levels, particularly wind. The available data indicate a strong correlation between high tides and strong westerly winds. Storm surges can cause major changes in sea level. In 1970, for example, a major storm surge caused by gale-force westerly winds inundated low-lying



Currents of the Beaufort and Western Chuckchi Seas (After Selkregg, et al., 1975)

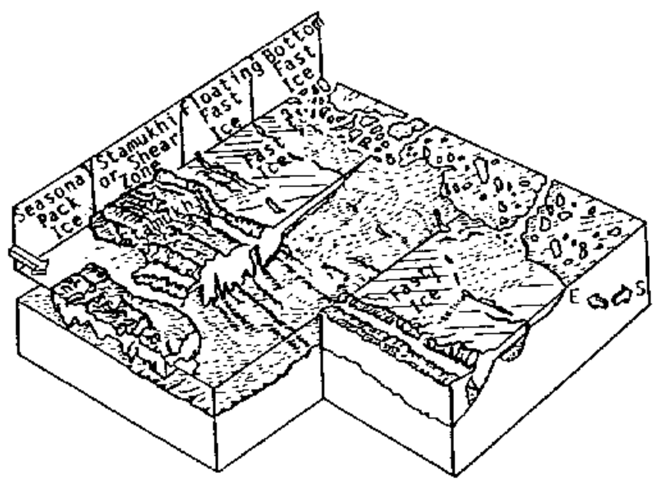


Diagram of an idealized cross section of ice zonation along the Alaskan Beaufort Sea in spring

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OCEAN CURRENTS AND ICE ZONATION

Pt. Thomson Development Project
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PLATE **III-2**

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tundra plains and deltas as far as 15,000 feet inland and left a driftwood line as much as 7 feet above normal sea level in the Bullen Point - Point Gordon area (Reimnitz and Maurer, 1979).

Although major sea level surges are generally associated with the open water season, they can also occur in winter. Winter surges recorded in 1973 at Oliktok Point are reported to have had heights of 3.1, 4.6, and 2.2 feet (Reimnitz and Maurer, 1979). Henry (1975) recorded two surges about 3 feet high in the Canadian Sector of the Beaufort Sea during the winter of 1973-74.

Surface waves are generated only during open-water months in summer. The fetch, or distance across open water, available for wave generation is usually small because of the polar pack ice offshore. Under certain wind conditions the polar pack ice may retreat far to the north, increasing the fetch and permitting swells up to six feet high (Reimnitz and Maurer, 1979). During such periods the constructional barrier islands can be significantly modified. On the coast, where there are no beaches, or where they are poorly developed, storm waves can greatly accelerate erosion of the coastal bluffs.

(3) Sea Ice

For about nine months of the year, the Beaufort Sea is almost completely covered by ice. As shown on Plate III-2, Reimnitz, Toimil, and Barnes (1977) have divided the Beaufort Sea seasonal ice sheet into four distinct zones: bottom fast ice, floating fast ice, stamukhi, and seasonal pack ice.

In the bottom fast ice zone, ice freezes to the sea floor. By winter's end, it is normally about 5 to 6 feet thick and extends as far as 8 miles offshore.

The floating fast ice zone stretches seaward from the boundary of the bottom fast ice to the stamukhi zone. Water in the floating fast ice zone is typically between 3 to 60 feet deep. The ice in this zone is underlain by seawater and is stabilized by the barrier islands and the grounded ice within the stamukhi zone; its canopy, therefore, experiences little deformation throughout the winter.

The stamukhi, or shear zone, consists of a belt of grounded ice ridges and hummocks seaward of the fast ice zone. Commonly occurring near the 60-foot isobath, the stamukhi zone represents a zone of slippage between the floating fast ice and the seasonal and polar pack ice.

The seasonal pack ice zone continues outward 70 to 100 miles seaward of the stamukhi zone to the toe of the Continental Shelf. The ice in this zone is mobile, unstable, and highly deformed. During winter, the seasonal pack ice and polar ice sheet act as a cohesive mass which rotates westward at rates from 1/2 to 2 miles per day.

2. Climate

No long-term climate records are available for the Point Thomson region. However, the study area lies equidistant from Prudhoe Bay on the east and Barter Island on the west. Comparison of climatic records at these two locations should indicate the range in climatic conditions experienced in the Point Thomson area.

Temperature data collected at the ARCO airfield and Barter Island are presented in Table III-1. The data indicate Prudhoe Bay and Barter Island have average annual temperatures of about -13^{o} and $-12^{o}C$ respectively. Summer temperatures at Prudhoe Bay and Barter Island remain relatively cool because of the combined effects of the Arctic Ocean to the north and its

TABLE III-1. MEAN MONTHLY AIR TEMPERATURES FOR PRUDHOE BAY REGION (ARCO AIRFIELD) AND BARTER ISLAND (°C)

Station	Year	Temperature (°C) J	F	M	A	M	J	J	A	S	O	N	D	Yr	Thaw degree days	Distance to coast (km)
Prudhoe Bay at ARCO Airfield	1976	-30.8	-31.9	-29.0	-16.5	-5.9	3.2	6.8	6.6	1.6	-11.4	-16.6	-30.3	-12.7	571	6.0
	1977	-23.1	-28.0	-31.8	-19.2	-5.5	3.7	5.4	8.2	2.5	-4.7	-21.4	-23.4	-11.4	643	
Barter Island	1976	-29.2	-30.7	-27.9	-19.3	-6.7	1.1	3.5	4.3	0.9	-11.0	-15.0	-30.2	-31.1	326	0.1
	1977	-23.4	-27.3	-32.3	-20.1	-5.9	1.4	3.1	5.2	2.1	-4.9	-19.8	-21.7	-12.0	375	
	29-yr means (49-77)	-26.2	-28.6	-25.9	-17.7	-5.4	1.2	1.8	3.8	0.2	-8.7	-17.7	-24.7	-12.2	--	

associated cold air mass and the Brooks Range to the south which blocks the flow of warm air from the interior. Summer temperatures inland are higher because of the reduced cooling effect of the Beaufort Sea. Based on limited temperature data, thawing indexes of about 375^{0}C-days occurring over a time period of 4 months and 550^{0}C-days are estimated for coastal areas and locations 10 miles inland, respectively, in the Point Thomson region.

Extremely low winter temperatures at Prudhoe Bay and Barter Island result from the low level of incoming solar energy. Since sea ice covers the coastal waters after mid-October, winter temperatures along the Beaufort Sea coast are not modified by the ocean. A freezing index of 5200^{0}C-days occurring over a time period of 8 months is estimated for the Point Thomson area (Hartman and Johnson, 1978).

The wind in the Point Thomson area is generally from the east and northeast during the late spring, summer, and early fall. Strong westerly and southwesterly winds with occasional easterly and northeasterly winds are more common during the late fall, winter, and early spring. Based on data from Prudhoe Bay and Barter Island, the mean annual wind velocity is approximately 13 miles per hour, with the highest monthly mean velocities during spring, early summer, and fall. The lowest mean velocities occur in late winter and are associated with extremely low temperatures. The strong westerly winds in winter often occur with snow storms, resulting in ground blizzards. Easterly winds often redistribute the snow.

Precipitation records for the Point Thomson area are not available and precipitation records for Prudhoe Bay prior to 1977 are unreliable because of the difficulty associated with measuring small amounts of precipitation under very windy conditions. A gauge designed for high wind conditions was installed in October 1976; it has recorded precipitation totals considerably higher than those previously recorded at other stations on the Arctic Coastal Plain, as shown on Table III-2 (Walker et al., 1980). The available data indicate that about 65 percent of the total annual precipitation along the Beaufort Sea coast between Prudhoe Bay and Barter Island falls as snow. Most of the snowfall occurs during September and October when there is still open water in the Beaufort Sea to provide a source of moisture.

TABLE III-2. PRECIPITATION (mm) FOR 1977 AND 1978
AT PRUDHOE BAY AND BARTER ISLAND

Year	Prudhoe Bay(1) Rain	Prudhoe Bay(1) Snow(2)	Prudhoe Bay(1) Total	Barter Island(3) Total
1977	81	142	223	85
1978	58	125	183	91

(1) Modified Wyoming snow gauge
(2) Water equivalent
(3) Standard National Weather Service instruments

Drizzle, fog, and light rain are the most common forms of precipitation during the summer months. Fog is common in the mornings along the coast and it often lingers in coastal areas after it has dissipated at Deadhorse and other inland areas.

B. Geology

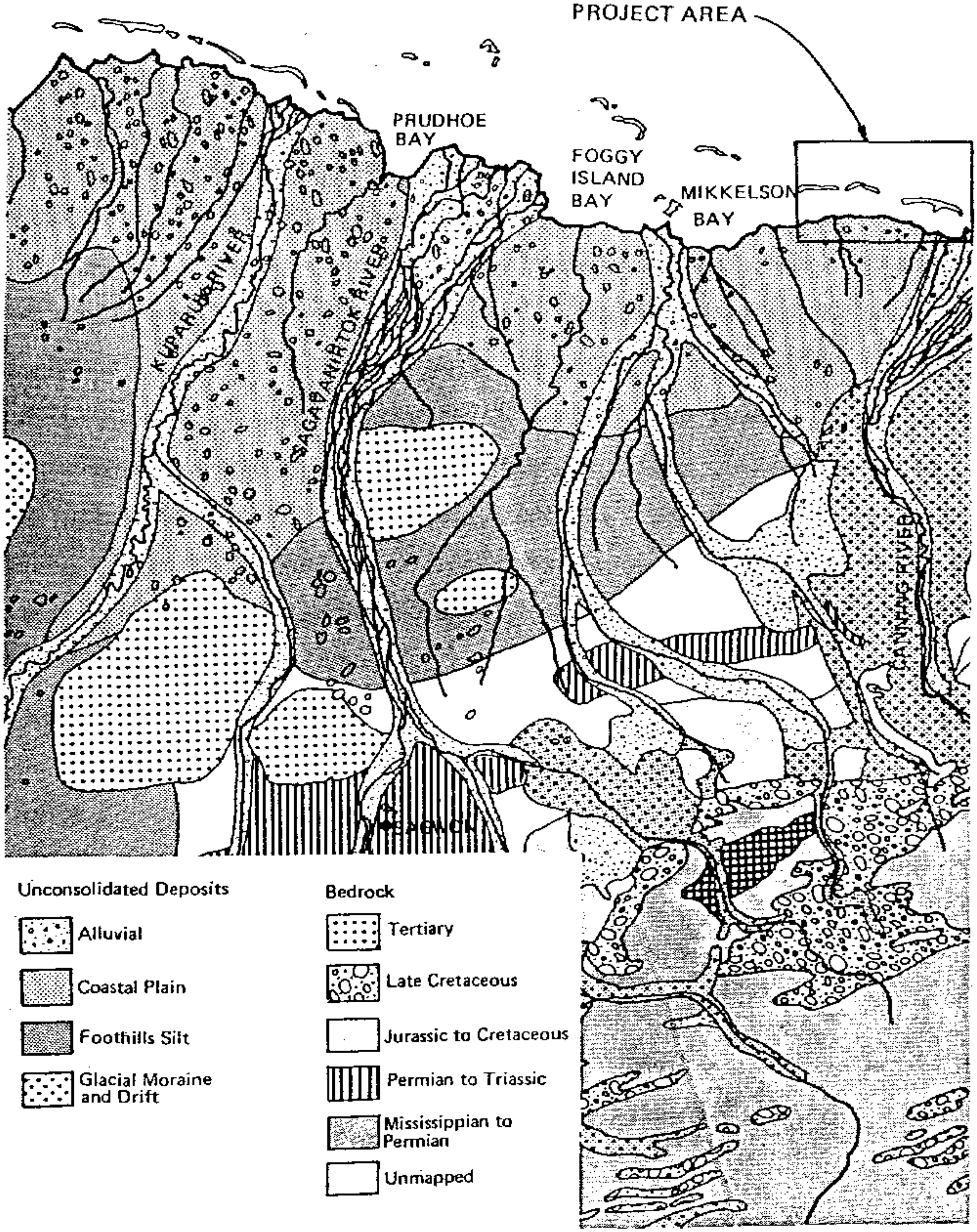
1. History

a. Pre-Quaternary Geology

The surficial geology of the Arctic region from the Brooks Range northward to the Beaufort Sea coast is shown on Plate III-3. The major structural feature underlying the Prudhoe Bay area is the Barrow Arch, which consists of uplifted lower Paleozoic (older than 400 million years) rocks. Above the Barrow Arch lie approximately 12,000 feet of post-Devonian [350 million years Before Present (BP)] sediments consisting of organic-rich shale, sandstone, conglomerate, and dolomitized limestone units of both marine and nonmarine origin. The thickness of the sediments increases southward toward the axis of the Colville Trough.

During late Jurassic (135 to 180 million years BP) and early Cretaceous times (70 to 135 million years BP), the northern part of the Arctic platform and the northern terrain source were pulled (rifted) away, leaving a continental margin facing northward. During the same time period, the Arctic platform was tilted downward to the south and overridden by the emerging Brooks Range. A foreland basin, the Colville Trough, formed north of the Brooks Range. The northern apex of the rifted and tilted Arctic platform formed the Barrow Arch that trends parallel to the Beaufort coast.

Nearly 8000 feet of marine and nonmarine sediments accumulated in the Colville Trough during Cretaceous and Tertiary times. The upper Tertiary bedrock consists of weakly cemented sand, gravel, clay, and silt known as the Sagavanirktok Formation, upon which Quaternary (present to 1 million years) sediments are unconformably deposited.



Harding Lawson Associates
Engineers, Geologists
& Geophysicists

Surficial Geology of a Portion of the Arctic Region

Pt. Thomson Development Project, Winter 1982
Geotechnical Study, EXXON Company, U.S.A.

PLATE **III-3**

DRAWN	JOB NUMBER	APPROVED	DATE	REVISED	DATE
JR	9612,031.08	DFB	4/82		

b. Quaternary Geology

(1) Sea Level Changes

Eustatic sea level changes caused by worldwide glacial epochs have exposed the present onshore and offshore regions of the study area to subaerial erosion and continental and marine deposition. At least six major changes of sea level influenced the stratigraphy of the area during the Pleistocene. A number of these changes appear to have been complex, including more than one episode of high sea level transgression separated by regressions of substantial duration (Hopkins, 1973). There is evidence to suggest that sea level reached its highest position, greater than 60 feet and perhaps as great as 300 feet higher than present, during the middle Pleistocene (0.7 to 1.9 million years B.P.). As recently as 25,000 years ago, the shoreline stood at least as low as the present 60-foot isobath and perhaps as low as the 280-foot isobath.

(2) Quaternary Geologic Units

The definitions and symbols for the geologic units used on the geologic maps and cross sections discussed in the following sections are presented in Table III-3.

TABLE III-3. QUATERNARY GEOLOGIC UNIT DESCRIPTIONS

Geologic Symbol		Name	Unit Description
Holocene	QHt	Thaw Lake Deposits	Organic ice-rich silts with lenses and wedges of massive ground ice. These materials are unstructured in some areas and contain coarse-grained soil because of reworking by frost processes.
	QHs	Shoal Deposits	Constructional units having positive relief and composed of clean, well-sorted sands and minor amounts of gravel.

TABLE III-3. QUATERNARY GEOLOGIC UNIT DESCRIPTIONS
(continued)

Geologic Symbol		Name	Unit Description
Holocene	QH	Lagoon Deposits	Organic-rich silts, clays, and minor lenses of sand which have been deposited in protected lagoon and bay environments.
	QHd	Delta Deposits	Usually consist of interbedded sequences of clayey and sandy silts with occasional interbeds of silty sand. These materials are unstructured in some areas because of reworking by sea ice and strudel scour.
	QHnm	Nearshore Marine Deposits	Unstructured mixtures of silty sands and sandy silts which have been reworked by grounding sea ice and deposited in a nearshore environment. This unit may contain material from underlying units.
	Qf	Flaxman Lag	A lag deposit, which consists of gravel, cobbles, and boulders resulting from the erosion of the Pleistocene Flaxman formation.
Pleistocene	QPf	Flaxman Unit of Gubik Formation	A marine unit consisting of inter bedded sandy silt and clay with ice-rafted glacial boulders. The unit may contain boulders up to 9 feet in diameter but, most are less than 2-1/2 feet in diameter.
	QPnm	Nearshore Marine Deposits	Includes soft to medium-stiff silts and clayey silts. Similar to QHnm; locally contains ice-rafted glacial boulders up to 3 feet in diameter. Where boulders are present, referred to as Flaxman Formation.
	QPm	Marine Deposits	Interglacial marine clays and clayey silts with thin seams of fibrous organic material. Overconsolidated, becoming stiff to hard in some test borings.

TABLE III-3. QUATERNARY GEOLOGIC UNIT DESCRIPTIONS
(continued)

Geologic Symbol		Name	Unit Description
Pleistocene	QPb	Beach Deposits	The base of the Pleistocene marine section primarily composed of gravelly sand, but in some boreholes it consists of silty sand.
	QPo	Outwash Deposits	Fluvial and glaciofluvial interbedded gravelly and silty sands. Thins onshore, grading into QPb in some areas.
	QPa	Alluvium	Fluvial and glaciofluvial material consisting predominantly of interbedded sand and gravel, which may contain lenses of fine-grained material.

(3) Onshore Geology

A generalized map of the surficial geology of the PTD project area is presented on Plate III-4. During episodes of Pleistocene sea level regression, the Canning River transported massive quantities of fluvial and glaciofluvial materials to the coast to form the Upland Fan Shelf. These materials now form a thick mantle of Quaternary deposits that overlie the Tertiary Sagavanirktok formation. Most of these Quaternary deposits are unconsolidated sands and gravels (geologic symbol QPa) composed of reworked Tertiary materials and materials derived from the Brooks Range to the south. These deposits are similar to the terrace and floodplain deposits of the present-day Canning and Staines Rivers.

The Flaxman Unit (geologic symbol QPf) of the Gubik Formation outcrops as a thin band along the shoreline of the mainland and on Flaxman Island. The formation is named from Flaxman Island where it is well exposed. The unit contains sporadic gravel, cobbles and boulders, a diagnostic feature of the unit.

At Flaxman Island and along the coastal bluffs surrounding the study area, scattered gravel, cobbles, and boulders are incorporated in the QPf deposits. Sightings of boulders incorporated within QPf units of the Gubik Formation have been recorded by Leffingwell (1919), MacCarthy (1958), and Rodeick (1975). The boulders, commonly called Flaxman boulders, are characterized by rock types foreign to the geology of northern Alaska and include red granite, granulite-facies, metamorphic rocks, pyroxenite, diabase, pink quartzite, and large amounts of dolomite. It is generally believed that the Flaxman boulders represent glacial dropstones that were ice-rafted to their present positions during periods of elevated sea level, most likely during the Sangamon interglacial period (70,000 to 100,000 years BP) or perhaps when the coast of northern Alaska was isostatically depressed (Hopkins, 1979).

Overlying the QPa and QPf on the Upland Fan are from two to twenty feet of ice-rich silts (geologic symbol QHt) with variable amounts of organic matter. The silts are probably equivalent to the Barrow member of the Gubik Formation (Black, 1964). Because they would obscure the surficial geology, the upper few feet of Holocene sediments are not shown on the geologic map.

Thaw lakes have modified the landscape of the PTD study area during Holocene time (last 10,000 years) through the combined processes of thermokarst and thermo-erosion (Everett and Parkinson, 1977). The thaw lake cycle and intense frost activity have reworked the upper two to eight feet of ice-rich silts. Melting of the ground ice has lowered the land surface in some areas by as much as several tens of feet. Eolian and frost activity have been locally important in reworking the Holocene lake deposits.

These processes are discussed in more detail in the following sections.

(4) Offshore Geology

(a) Geologic History

The geologic history of the offshore area from Bullen Point to Brownlow Point and the Canning River Delta area is similar to the offshore area around the Duck Island Development area. Sedimentation has been primarily controlled by eustatic changes in sea level during the Pleistocene.

Numerous glacial periods in the foothills and Brooks Range have supplied vast quantities of material to the arctic coastal plain and offshore continental shelf. The oldest deposits encountered (described in detail below) are sand and gravel of fluvial and glaciofluvial origin (map symbol QPa). The ubiquitous nature of these deposits, often just below the surface near the coast, attests to the volume of water and material supplied by melting glaciers. The top of this unit dips to the north away from the coast. The deposit is more than 400 feet thick beneath Reindeer Island.

These coarse-grained deposits were subsequently inundated by rising sea level and overlain by a marine clay and silt unit possibly 175,000 years BP during the pre-Illinoisan interglacial period. The fine-grained deposits are normally less than 28 feet thick in the lagoon, except near the east end where deposits may be in excess of 60 feet thick. Seaward of the barrier islands, USGS/HLA Test Boring 18 was drilled 300 feet below mudline and did not encounter the bottom of this fine-grained unit. Most of these deposits are overconsolidated, a condition caused by subsequent subaerial erosion during the next glacial period. That period was one of major modification for the marine clays and in some places the clays were stripped away completely.

Approximately 70,000 to 100,000 years ago, the sea level rose about 12 meters higher than present. During that time, a thick deposit of silt accumulated over much of the PTD study area. Ice fragments, calved from glaciers in the Canadian Archipelago and carrying gravel to boulder sized material, grounded in Alaskan waters and deposited rocks dissimilar to those found in the Alaskan Brooks Range. Years of accumulation formed a sandy silt deposit containing coarse material foreign to Alaskan geology. Known as the Flaxman Unit of the Gubik Formation, it is up to 37 feet thick in the study area.

Subsequent to the deposition of the Flaxman Unit, sea level fell during the Wisconsin glacial epoch to the present 60-foot isobath and perhaps as low as the 280-foot isobath. During this period major rivers and small melt water streams carried material onto the continental shelf, cutting through the Flaxman Unit and the older marine clay. Further modification of existing deposits occurred during another transgression and regression in the middle and late Wisconsin and the final Holocene rise to modern day sea level, which was established approximately 5000 years BP.

(b) Pleistocene Units

Plate III-4 shows a surficial geologic map of the offshore portion of the study area. The top meter of sediment has been stripped off to show near-surface deposits that differ from the lagoon sediments. The relationship of all identified geologic units is shown on the Fence Diagram, Plate III-5.

The Flaxman Unit (QPf) of the Gubik formation consists predominantly of sandy silt with subordinate layers of sand and silty clay.

The silt varies from soft to hard, but is generally stiff to very stiff and overconsolidated. Occasional lenses of fibrous organic materials have been noted on the boring logs. The thickest section of QPf encountered in the borings was a 36-foot-thick layer in Boring 19 (Appendix B) which did not penetrate the entire section. QPf appears to have at one time completely mantled older Pleistocene clay (QPm) and alluvial deposits (QPa) throughout the study area as shown by the ubiquitous distribution of Flaxman lag deposits (Qf).

The lowermost marine unit (QPm) consists of clay, silty clay, and minor amounts of silt and sand. The deposits are normally stiff to hard and overconsolidated although normally consolidated clay and silt deposits are present locally. The QPm unit appears fairly continuous except near the coast. In some cases QPm consists of sand, especially near the coast.

The QPm unit rests disconformably on Pleistocene fluvial deposits and its upper surface is probably erosional. Seismic reflection profiles from the Duck Island Development study (1981) show the upper surface of this unit as an erosional unconformity implying that it has been subjected to at least one episode of subaerial exposure before deposition of the overlying QPf silts.

The Fence Diagram, Plate III-5, shows that QPm pinches out against Pleistocene alluvium (QPa) before reaching the southern coastline. There are outcrops of the overlying QPf along the coast, but no evidence of QPm.

The combined thickness of fine-grained sediments probably does not exceed a thickness of 55 to 60 feet inside the lagoon, with the possible exception of the very east end near the eastern tip of Flaxman Island. In the offshore area, fine-grained soils in excess of 300 feet thick were encountered in USGS/HLA Boring 18, in excess of 150 feet in USGS/HLA Boring 17, and in excess of 126 feet in USGS/HLA Boring 16 (Appendix A).

Pleistocene alluvium (QPa) underlies most of the PTD study area. It is at the surface onshore and becomes progressively deeper to the north. The Fence Diagram shows that QPa dips more steeply to the north near the east end of the lagoon. The material was placed as ancient rivers meandered back and forth across the coastal plain. The material is probably a combination of fluvial and ancient glacial outwash material. QPa consists of sandy gravel and gravelly sand with a chert and limestone lithology common to the Alaskan Brooks Range.

(c) Holocene Units

Holocene deposits within the PTD study area consist of materials deposited in lagoon, beach, and nearshore marine environments. Areally the most extensive Holocene sediments are lagoon deposits (map symbol QH). The QH deposits consist predominantly of soft to medium stiff silts, often organic-rich silts, minor clay and sand deposited in a protected lagoon. The thickest QH deposits were drilled at Test Borings 2 and 4 (Appendix B) where the QH section extends to a depth of 25 feet below the mudline.

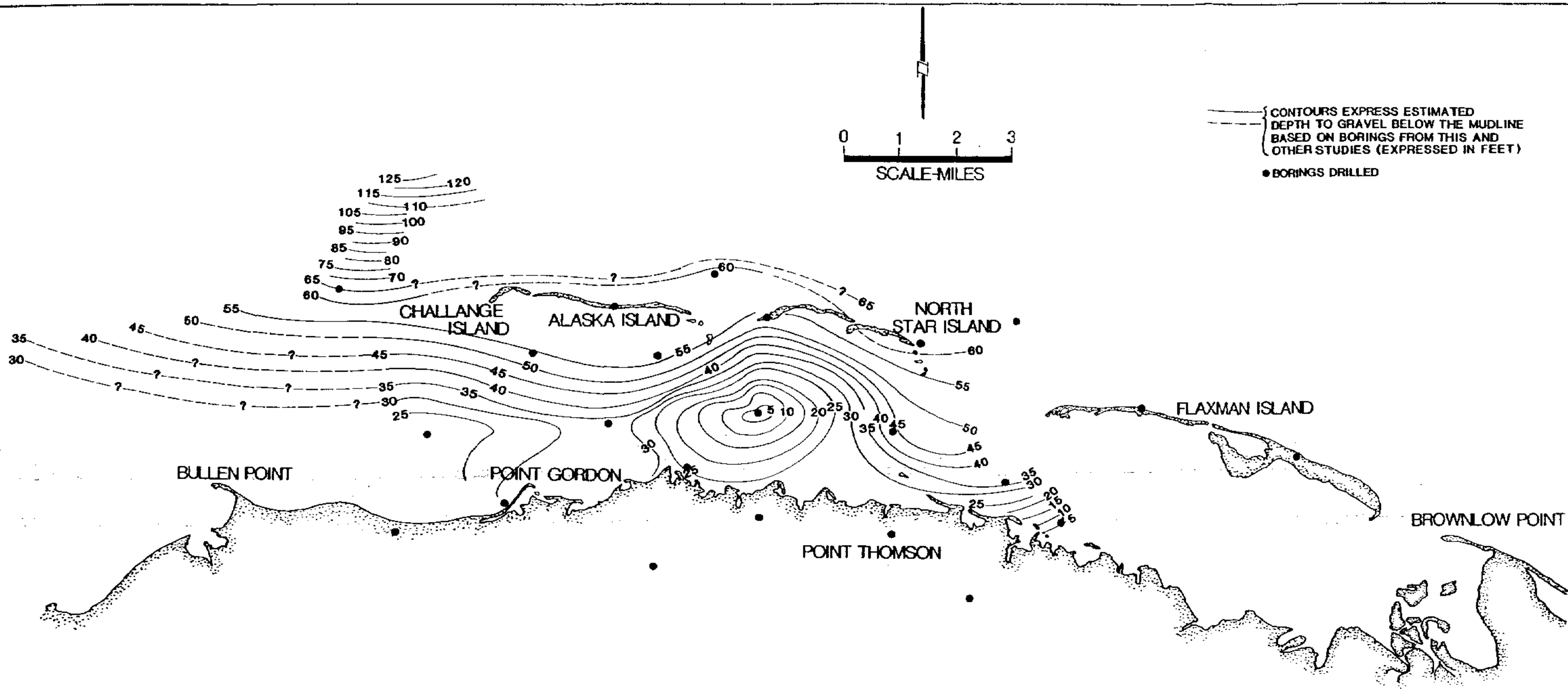
Holocene beach deposits (map symbol QHb) consist of medium- to coarse-grained sand and gravelly sand. In HLAs' "Interpretation of Geophysical, Geologic and Engineering Data" (1979) the beach deposits in the lagoon area were considered to be a lag deposit (map symbol Qf) created by the winnowing of an older unit. The beach deposit thickness of up to 14 feet suggests more recent sand has been transported to the study area by the Staines and Canning Rivers. Therefore, QHb may contain Qf material. QHb has been used to designate two different Holocene beach deposits. At USGS/HLA Test Boring 15 (Appendix A), QHb is the basal transgressive deposit, a beach that was created during the last rise in sea level and subsequently inundated, whereas the beaches of the Maguire Islands and the sand spit of Flaxman Island are more recent features.

Holocene nearshore marine deposits (map symbol QHnm) consist of loose sand, silty sand and soft clay. They are present as a thin veneer in the offshore study area and have been subjected to reworking by ice gouging in an open marine environment.

Surficial concentrations of gravel, cobbles, and boulders are present on many of the beaches within the study area and are also exposed on the seabed. These Holocene lag deposits (Qf) are the remains, after erosion, of the boulder-rich Flaxman Unit (QPf) of the Gubik Formation. The boulders rest upon eroded outcrops of the Gubik and may be up to 14 feet thick locally; however, this unit is generally less than 3 to 4 feet thick.

(5) Offshore Gravel Resources

Plate III-6 shows our interpretation of the depth to gravel in the lagoon based on the test boring data. The two most promising sites for ground extraction are in the vicinity of Borings 11 and 20 (Appendix B). The water depths at these borings are 9.5 and 8.8 feet, respectively.



Harding Lawson Associates Engineers, Geologists & Geophysicists	**Depth to Gravel Map** Pt. Thomson Development Project Winter 1982, Geotechnical Study EXXON Company, U.S.A.	PLATE **III-6**

DRAWN	JOB NUMBER	APPROVED	DATE	REVISED	DATE
	9612,031.08		4/82		

Gravel in Boring 11 is part of the QPa unit discussed above, as shown by the typical Alaska chert lithology of the gravel. The gravel at Boring 20 is probably Qf and separated from QPa by a 7-foot-thick layer of QPf. Thus, the better gravel site is the vicinity of Boring 11 where an uninterrupted sequence of sand and gravel is present to at least 50 feet below mudline.

Conservative estimates, based on our Depth to Gravel Map, Plate III-6, suggest that within a 1/2 mile radius from Boring 11 there may be in excess of 10 million cubic yards of gravel available within 50 feet of the mudline.

2. <u>Seismicity</u>

The Point Thomson area is within seismic risk Zone 1 of the Uniform Building Code. The risk of the project area being affected by a significant (greater than 5.0 Richter magnitude) seismic event is considered low. The only recorded seismic event greater than magnitude 5.0 occurred in 1937 northeast of Herschel Island in MacKenzie Bay, approximately 200 miles east of the PTD project site (Woodward-Clyde, 1978). The closest known active fault to the project site is the Kobuk Fault which borders the southern foothills of the Brooks Range about 230 miles south of Point Thomson. The mapped length of the Kobuk Fault extends more than 300 miles; however, only a portion of the fault displays evidence of Quaternary activity (Patton, 1973).

Alyeska Pipeline Service Company used the following ground motion parameters for the design of facilities at Prudhoe Bay: maximum contingency level acceleration of 0.12g, maximum contingency lèvel velocity of six inches per second, maximum operating level acceleration of 0.06g, maximum operating velocity of three inches per second and a duration of 5 seconds (Corps of Engineers, 1980).

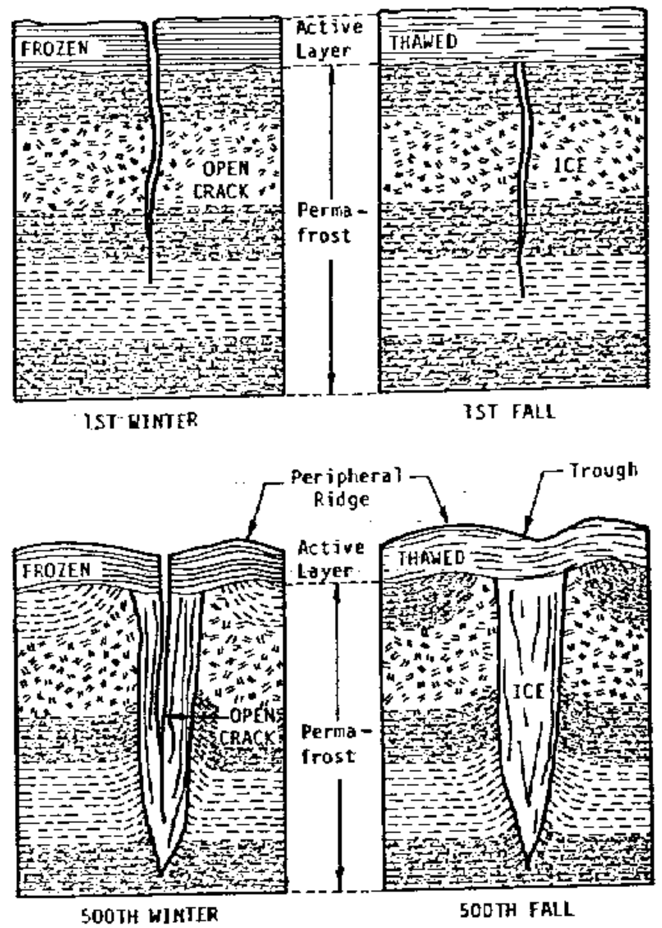
3. Permafrost

a. Onshore Permafrost

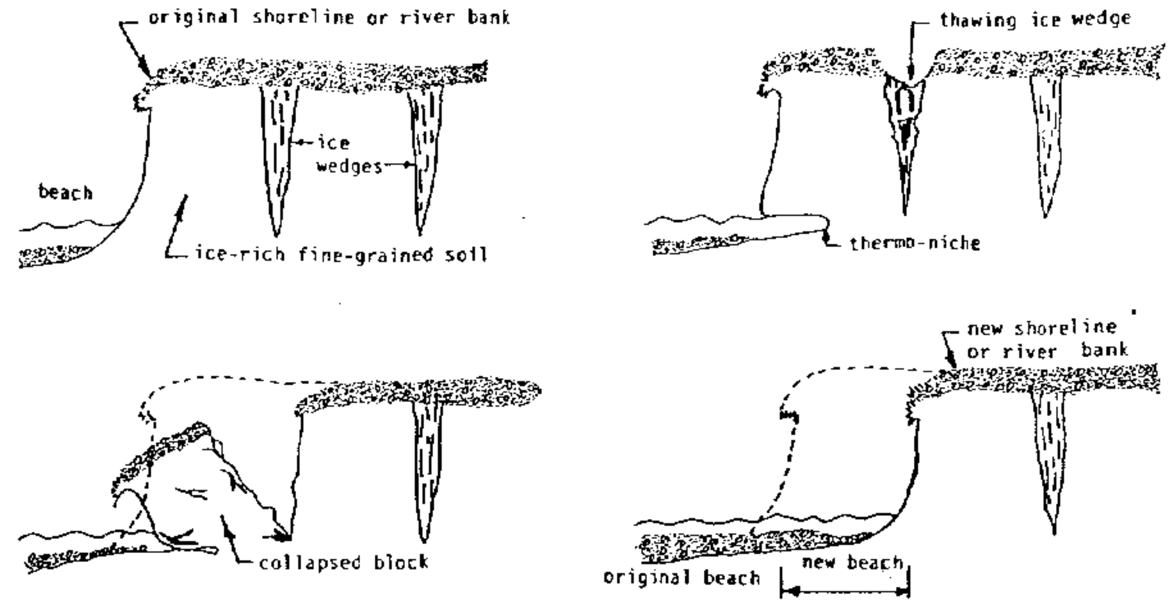
The dominant feature of the Upland Fan region is the continuous layer of perenially frozen ground known as permafrost. The maximum depth of permafrost at Prudhoe Bay is approximately 1800 feet (Howitt, 1971) and similar depths are expected in the Point Thomson Development area. Permafrost extends almost to the ground surface, except for thaw pockets typically located beneath deep lakes and abandoned or active major river channels.

Permafrost may be ice free at $0^{o}C$ or below, depending on the salinity of the interstitial water. When permafrost occurs in clay beds, substantial amounts of unfrozen moisture can persist at temperatures several degrees below $0^{o}C$ due to the freezing point depression produced by capillary forces (Ferrians, Kachadoorian, and Green, 1969).

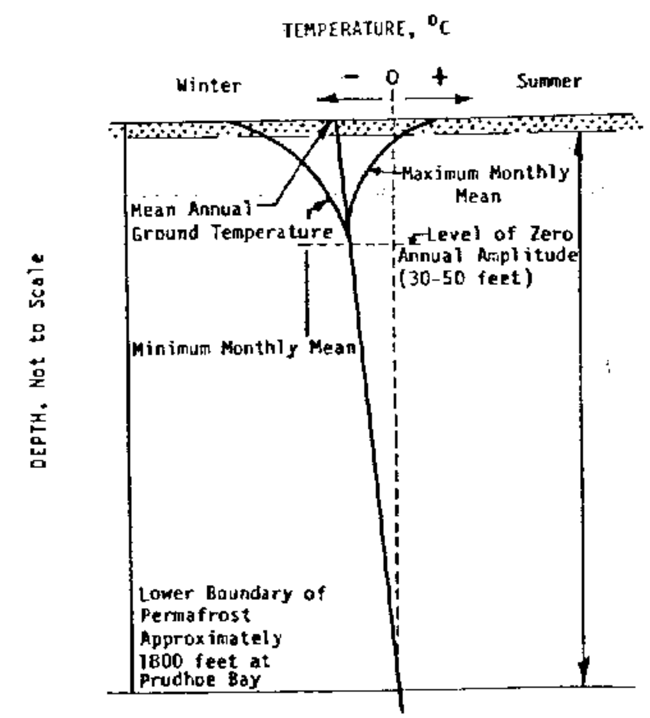
As shown on Plate III-7 the temperature of the permafrost zone is lowest near the ground surface during the winter months and gradually increases with depth until it reaches $0^{o}C$. The depth of the permafrost is controlled by heat flow from the inner core of the earth. Beneath a depth of 30 to 100 feet below the ground surface the temperature remains almost constant. We would expect ground temperatures at a depth of about 25 feet to vary annually from $-8^{o}C$ to $-12^{o}C$. The temperature lag relative to air temperatures at this depth is five to six months (Lachenbruch, 1959). Warmer temperatures are found near bodies of water such as lakes, rivers, and the ocean. Ground temperatures observed during the Point Thomson study are presented in Chapter IV.



Schematic representation of the evolution of an ice wedge according to the contraction-crack theory (After Lachenbruch, 1963)



Schematic of thermo-erosional niche



Schematic of typical ground temperature regime in permafrost areas

Harding Lawson Associates
Engineers, Geologists & Geophysicists

ICE WEDGE EVOLUTION, THERMO-EROSIONAL NICHING, AND GROUND TEMPERATURE REGIME

Pt. Thomson Development Project, Winter 1982,
Geotechnical Study, EXXON Company, U.S.A.

PLATE **III-7**

DRAWN	JOB NUMBER	APPROVED	DATE	REVISED	DATE
SP	9612,031.08	DEB	4/82		

Permafrost is overlain by a shallow "active layer" which thaws in the summer and freezes in the winter. Away from the influence of streams and lakes, the active layer is generally between several inches and several feet thick, depending upon the amount of incoming solar radiation, the texture and water content of the soil, the depth of snow, and the thickness of the vegetative cover.

Tundra vegetation provides a good insulating mat and in the PTD study area the active layer beneath the mat is relatively thin (1.5 to 3.5 feet). The high moisture content of the tundra soils also contributes to the slowing of heat exchange between the atmosphere and the soils, making the soils relatively cool in summer. Sands and gravels, such as are found in the active and abandoned floodplains of the Canning River, generally thaw to depths of five feet if not covered with a vegetative mat. Thaw depths as much as eight feet have been encountered in similar gravels along the Sagavanirktok River.

b. Offshore Permafrost

The mean annual bottom water temperature for the inner shelf of the Beaufort Sea is between $-1.09^{o}C$ and $-1.50^{o}C$. Bottom water temperatures below $0^{o}C$ are expected in water less than 500 to 1000 feet deep (Selkregg et al., 1975). Therefore, all sediments within the offshore project area meet the broad definition of permafrost.

In the following discussion, the term relict permafrost is used to describe old bonded permafrost that probably has remained from the last subaerial exposure of the seabed, as opposed to shallow, probably recently formed, permafrost. The following explanation for the existence of relict ice-bonded permafrost beneath the Beaufort Sea has been proposed by Hopkins and Hartz (1978):

> The position of the shoreline in the Beaufort Sea 18,000 years ago, lay somewhere seaward of the 20-meter isobath and borehole data thus suggest, in fact, that relative sea level fell at least 90 meters below present in the Beaufort Sea. The mantle of marine silt and clay, deposited during Sangamon time (approximately 120,000 years ago), became frozen as did the underlying gravels. The total thickness of bonded permafrost formed at any particular place, depended partly upon the duration of exposure to sub-aerial temperatures, the thicknesses of several hundred meters were formed in most areas of the shelf landward of the present 20-meter isobath. (sic)

The distribution of relict permafrost in the offshore project area was investigated during the HLA/USGS test boring program of 1979 (HLA 1979) and the test boring program performed during the winter of 1982 for this study. The data from these studies suggest that the ice-bonded permafrost in the offshore project area is relict, having formed during the last low sea level standstill, and that the depths to the ice-bonded layer are highly variable. Seasonal ice bonding and development of new permafrost in surficial sediments take place only within bottom fast ice zones in very shallow waters (about 2.5 feet deep).

The data obtained from the two test boring programs indicate that beyond a depth of about six feet below sea level and away from the immediate vicinity of the barrier islands, relict ice-bonded permafrost is restricted to the Pleistocene units of the Gubik Formation. The depths to ice-bonded permafrost in the project area are shown on the cross sections, Plates IV-4 through IV-11 and the Regional Soil Map, Plate IV-1 presented in Chapter IV.

Temperature measurements obtained in all of the borings indicate that both ice-bonded and unbonded sediments have temperatures well below $0^{o}C$. It was also found that all of the borings have negative thermal gradients, indicating that ice-bonded permafrost may be present at depths not reached by the borings.

4. Onshore Geologic Processes

a. Ice Wedging

Polygonal or patterned ground is the most conspicuous surface feature of the Upland Fan area. The polygonal patterns are formed by temperature-induced contraction cracks similar to those encountered on dry mud flats. These cracks fill with water and freeze. Continued cracking, filling, and freezing along the same lines eventually produces a network of ice wedges several yards deep and tens of feet apart.

A schematic representation of the evolution of an ice wedge is presented on Plate III-7 (Lachenbruch, 1963). The size of polygons and the spacing of ice wedges varies from less than 20 to more than 300 feet across. The depth of the wedges varies from 3 feet to more than 25 feet. Ice wedges may be from a few inches to up to 10 feet wide at the top, and they commonly taper with depth.

The compression of the ground adjacent to ice wedges causes peripheral ridges. The ridges can prevent drainage from the center of the polygon, resulting in small shallow ponds in the polygon centers.

b. Thaw Lake Cycle

There are thousands of thaw lakes, ponds, and pools dotting the Upland Fan area. The lake basins originate in areas of restricted drainage where warm surface temperatures cause the underlying ground ice to thaw, resulting in subsidence. Most of these small ponds are less than three feet deep. The lakes may be regular or irregular in shape, but there is a strong tendency for the larger lakes (approaching one mile long) to be elongated or elliptical and oriented parallel to one another.

The thaw lakes go through a cycle of development, expansion, drainage, and revegetation. Development of an oriented thaw lake begins with climatic change or disruption of the vegetation and organic cover of the polygonal tundra. Thawing of the ice-rich near-surface materials and melting of ice wedges result in standing water which eventually becomes a thaw lake. If the pond is large enough, the permafrost beneath it and along its sides thaws, resulting in expansion of the water body.

Thawing occurs most rapidly below the water level, eroding the surrounding tundra and rapidly melting and truncating ice wedges to produce an irregular shoreline. Eventually, thawed and frozen blocks of tundra collapse into the growing lake. The lake grows most rapidly along the axis perpendicular to the wind, partially because of increased current velocities and seasonally higher temperatures of the water at the ends of the lake (Carson and Hussey, 1962). Eventually, the lake intersects a natural outlet and drains. In time, vegetation recolonizes the lake bottom, and the thawed depression fills with peat and other organic materials. Ice wedges form new polygons, and the cycle begins again.

c. Beaded Stream Erosion Cycle

Beaded streams form the small, northward flowing drainages common in the PTD study area. A beaded stream consists of a series of elliptical or irregularly-shaped pools varying in depth from three to nine feet. They can vary from a few tens of feet to hundreds of yards in width and length.

The beaded streams are formed from the melting of the ice wedges which underlie the polygon rims. Warm surface waters melt the ice and form a depression on the tundra surface. A series of these thermokarst depressions along a drainage route forms a beaded stream (Lewellen, 1972).

Rex (1953) proposes four phases of development. Phases 1 through 3 are characteristic of most of the beaded streams in the area:

Phase 1 - A marshy feeder area of polygon trough intersected with pools usually located at the polygon intersections.

Phase 2 - A stream channel marked by a string of pools. The pools are circular if located at the ice wedge intersections or elongated if located between two polygons.

Phase 3 - A clearly defined and often entrenched stream between large circular pods; sometimes the stream surrounds a polygon.

Phase 4 - Several large bonded pools joining to form a thaw lake.

Chapman (1964) reports the headward erosion along the gully of a melting ice wedge that intersected a lake which subsequently drained. A good example of the headward erosion is shown on Plate III-8. This figure was obtained from the aerial photos of the project area immediately south of Point Gordon where a beaded stream has drained a large lake located in Sections 17 and 18, T9N, R22E.

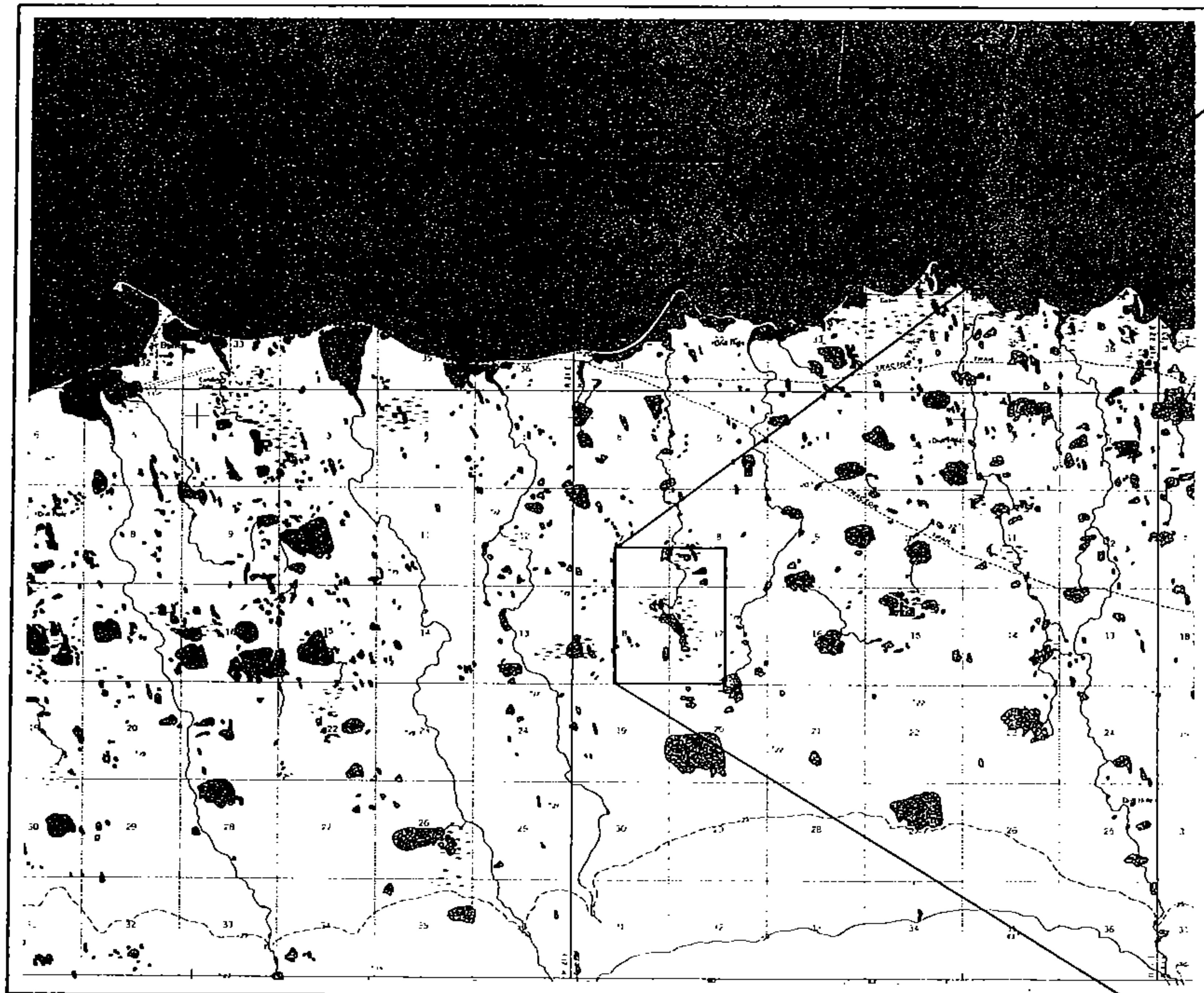


Figure 1 USGS area map

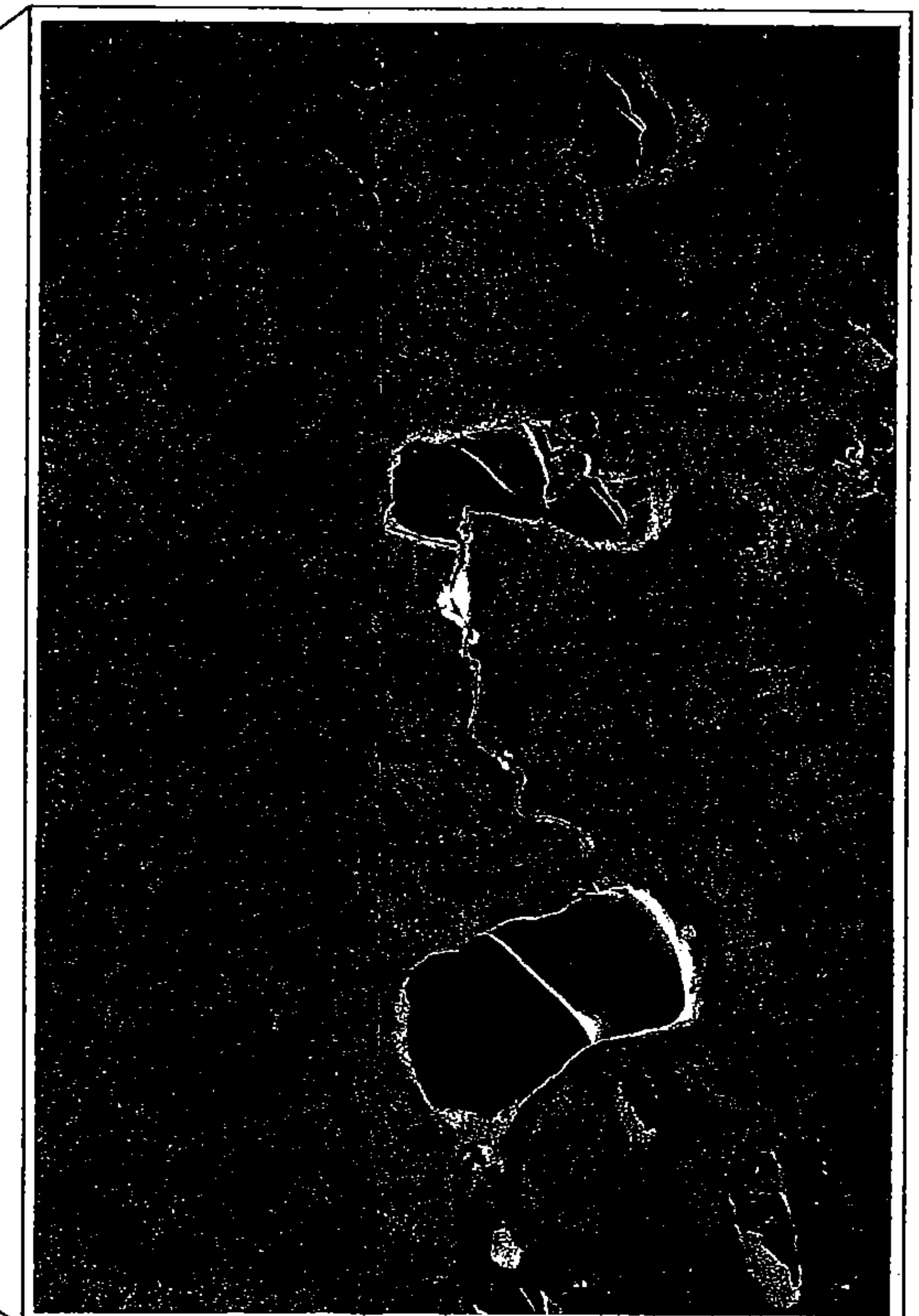


Figure 2 Beaded stream and erosion of lakes (from aerial photo 6-6, Exxon, 1980, Point Thomson.)

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Beaded Stream Erosion Cycle
Pt. Thomson Development Project
Winter 1982, Geotechnical Study
EXXON Company, U.S.A.

PLATE **III-8**

DRAWN	JOB NUMBER	APPROVED	DATE	REVISED	DATE
JP	9612,031.08		6/82		

d. Frost Action

In the project area, frost action within the fine-grained active zone soils is intense. Pressures generated during the freezing of the active zone tend to jack the gravel-sized soil fractions to the surface, forming frost boils and stone rings. This process also causes frost churning or cryoturbation of the active zone soils. The depth of soils experiencing cryoturbation varies with soil gradation and moisture content.

e. Thermo-Erosional Niching and Shoreline Retreat

(1) Thermo-Erosional Niching

Thermo-erosional niching, the undercutting of river banks or coastal bluffs by the thermal action of flowing water, is the most active erosive agent along the beaches in the project area. Thermo-erosional niching is defined as lateral erosion resulting from melting of ground and interstitial ice accompanied by lateral current transport of the liberated fine materials (Hopkins and Hartz, 1978). Plate III-7 shows the stages of thermo-erosional niching of a wedge of fine-grained permafrost and its ultimate collapse and lateral transport.

(2) Coastal Erosion

Based on aerial photographs from the late 1940's to present, the coast within the project area is retreating at an average rate of six to nine feet per year (Hopkins et al., 1977). The coastline from Point Thomson to Brownlow Point is reported by Lewellen (1977) and Hartz (1978) to be retreating at rates of 22 and 12 feet per year, respectively. Leffingwell (1919) estimated that Brownlow Point was being eroded at the much higher rate of almost 30 feet per year.

The rapid retreat of the coast is a result of the process of thermo-erosional niching acting on beach bluffs composed primarily of fine-grained, ice-rich sediments. The erosion rates depend on the local morphology, the orientation and exposure of the coast, and, according to Lewellen (1977), the ice content and grain size of the coastal sediments being eroded.

Drawings of Flaxman Island prepared by Lewellen (1970) from aerial photographs taken during the period 1949 through 1968 (U.S. Army, 1949, 1955, 1968) are presented on Plate III-9. Comparison of Lewellen's drawings to outlines of the island taken from airphotos dated 1980 indicate the north face of the island has retreated approximately 70 feet in 12 years for an average annual rate of about 6 feet per year. Based on these data, the north face of the island has retreated approximately 360 feet for an average annual rate of about 12 feet per year. This rate of retreat compares well with Lewellen's estimates (Plate III-9) and suggests that the coastal promontories and barrier islands are undergoing higher annual rates of erosion than the rest of the coast in the project area.

5. Offshore Geologic Processes

The major processes affecting the seabed in the lagoon are strudel scour, ice gouging, and the longshore transport of sediments by ocean currents. The dearth of available data on the lagoon and shallow offshore environment makes it difficult to accurately assess the impact of these processes in the study area. However, some conclusions can be drawn by comparison to other similar settings.

a. Strudel Scour

Scouring of the sea floor occurs each spring when north flowing rivers break up sending their fresh waters flowing across the sea ice. The water drains through holes and cracks in the sea-ice canopy and acts as a jet of water to scour the seabed.

Major seabed modification by this phenomenon is restricted to areas around river mouths. As such, strudel scour should be restricted to the eastern part of the PTD project area within four to six miles of the mouth of the Staines River. Severe scouring will probably be restricted to that portion of the lagoon west of the center of Flaxman Island. Water depths east of the center of Flaxman Island are generally less than six feet and the ice canopy is normally frozen to the lagoon bottom by late spring. As strudel scouring is most effective where there is water under the ice canopy, the area east of the center of Flaxman Island will probably be protected from severe strudel scour.

No data are available on the depth of scour in the lagoon. However, Toimil (1979) reports strudel scours of undetermined depth in water eight to ten feet deep three miles east of Point Thomson.

b. Ice Gouging

Ice gouging is not expected to be a major hazard in the lagoon. The lagoon is shallow, well protected from large multi-year ice keels, and major shear zones are restricted to the seaward side of the barrier islands. The shelter offered by the barrier islands suggests gouging will be less intense in the lagoon than that found in Stefansson Sound. Gouge orientation is random rather than concentrated and the maximum gouge depths do not exceed two to three feet.

Seaward of the barrier islands ice modification of the sea floor is probably intense. The major winter shear zone forms close to the barrier islands and a gouge density of 50 gouges per kilometer with sub-seabed penetration up to 1 meter are expected. The extremely irregular bathymetry seaward of the barrier islands probably owes its origin to ice gouging.

c. Sediment Transport

The dominant direction of sediment drift along the Beaufort Sea coast is westward; however, there are many local variations. West of Brownlow Point longshore transport is to the west and east of Brownlow Point it is to the east. Thus, the majority of sediment supplied to the marine environment by the Canning River is funneled into Camden Bay and the smaller Staines River is the major supplier to the lagoon.

Our borings logs indicate sand and silt are being supplied to the lagoon. The most probable sources of this sediment are the Staines River and the eroding beach bluffs surrounding it. They also indicate little recent material is being supplied to the offshore shallow marine environment.

Relatively large amounts of sediment flow into the lagoon during spring break up. The flow tapers off throughout the summer season and is negligible during the winter months. Since the boring logs show sand is the most prevalent surface material, much of the silt and clay size material either remains in suspension or is put into suspension during summer storms and transported out of the lagoon.

6. Terrain Units

Terrain unit mapping was performed using color aerial photographs taken by North Pacific Aerial Surveys dated September 1980. Aerial photos covering Flaxman Island are at a scale of 1 inch equals 700 feet. The remainder of the project area was mapped using color aerial photos at a scale of 1 inch equals 500 feet. The terrain unit map is presented on Plate III-10.

a. Low Centered Polygons

Low centered polygons (map symbol LCP) are one of the most easily recognized landforms in the Point Thomson region. These polygons are caused by repeated intense freezing and thawing in fine-grained soils, resulting in the growth of intersecting ice-wedges, which form the polygon rims. Ice-wedge growth is discussed in Section 4 and is shown graphically on Plate III-7.

Low centered polygons generally occur in areas of poor surface and subsurface drainage. During the thaw season, the depressed central portion of the polygon can contain up to 1-1/2 feet of standing water. Low centered polygons with wet centers are common along the coast and in the Upland Fan adjacent to thaw lakes.

Soil conditions typical of low centered polygon areas were encountered in Boring 18 (Appendix B). In areas with low centered polygons, ice-rich silts (moisture contents greater than 50 percent) and massive ice predominate in the upper 10 to 15 feet and are commonly underlain by granular soils with a lower ice content than the silt. The ice in the granular soils generally occurs as grain coatings and as random crystals.

b. High Centered Polygons

High centered polygons (map symbol HCP) can be recognized by the deep troughs which form their perimeters. Within the study area typical exposures of high centered polygons occur on the coast at the break in slope between the Upland Fan and the beach and along the shores of the drained lakes immediately east of the Staines River.

High centered polygons are caused by thermo-erosion of the ice and ice-rich soils that form the perimeter of low centered polygons. The process is initiated by an improvement in the surface and subsurface drainage in an area containing low centered polygons. Melt water escaping from the ice wedges within the polygon perimeters causes the perimeter troughs to deepen, exposing the soil on the polygon rim to thermo-erosion. As this process is repeated over a number of years, the rim soils become so eroded that they form troughs around the polygon centers.

Soil conditions in high centered polygon areas are the same as those in low centered polygon areas. However, there are smaller amounts of massive ice in the rim soils of the high centered polygons because of thermo-erosion.

c. Reticulate Ground

Reticulate ground (map symbol RG) appears as a network of slightly convex polygons up to 5 feet in diameter. The center of each polygon is generally formed by frost-boil tundra having a hummocky micro-relief. The frost boils consist of irregularly shaped masses of bare soil up to three feet across. Because of frost activity, rocks are commonly segregated from the soil, forming stone rings around the perimeter of the frost boils.

Reticulate ground normally occurs in the upland areas adjacent to drainage ways, such as active and abandoned stream channels and thaw lakes. Soils in these areas consist of a thin mat of peat or organic silts underlain by gravelly sand.

The mineral soil exposed on the surface of the frost boil is exposed to the drying and erosive action of the wind. Removal of the fine grained soils by the wind often results in dish shaped scars in the tundra surface up to a few feet deep. In some areas the scars may be as much as 50 feet in diameter.

Frost boil tundra, in conjunction with high and low centered polygons, is the predominant terrain unit in the Upland Fan.

f. Thermokarst Terrain

Thermokarst terrain (map symbol TK) is a composite terrain consisting of high centered polygons and low center polygons undergoing topographic reversal and conversion to high centered polygons. Small, irregularly shaped thaw lakes are common, occurring at the intersections of the polygon rims. The micro-relief of this landform is quite high with topographic differences of four to six feet occurring between polygon rims and perimeters.

Thermokarst terrain is most common inland from Point Thomson westward to the Staines River and probably represents incomplete topographic adjustment to improved drainage northward to the coast and westward to the Staines River.

g. Low Energy Beaches

Low energy beaches (map symbol LEB) are rarely wider than 60 feet and are usually backed by coastal bluffs less than 15 feet high. They are composed primarily of sand and silt derived from erosion of the coastal bluffs. In areas where the Flaxman Formation outcrops in the bluffs, some coarse material in the form of gravel and occasional boulders may be present.

Wave activity along the low energy beaches is generally not sufficient to winnow out the silt and sand site material. As a result, the coarse gravels and boulders occur within a matrix of fine sand and silt size material.

Low energy beaches predominate along the mainland of the PTD study area and on the southern shore of Flaxman Island.

h. High Energy Beaches

Coarse grained materials predominate in high energy beaches where the winnowing action of the waves has removed the fine grained material leaving behind the coarse sand and gravel fractions. The high energy beaches are very dynamic and can undergo considerable variation in width and length on a seasonal basis. Due to their exposure to wind and waves they support very little vegetation.

High energy beaches form the bars at Bullen Point and Points Gordon, Hopson, Sweeney and Thomson. They are also well developed along the Maguire Islands and the western end of Flaxman Island. The high energy beaches along the seaward side of the eastern end of Flaxman Island are backed by coastal bluffs up to 20 feet high.

IV SOIL AND PERMAFROST CONDITIONS

LIST OF ILLUSTRATIONS

IV SOIL AND PERMAFROST CONDITIONS

A. Stratigraphy

1. Introduction

Soil and permafrost conditions were investigated by drilling and sampling 23 test borings in the PTD area. Representative samples from the borings were tested in our laboratory to measure their engineering properties. The soil conditions encountered in the 23 borings are summarized in Table IV-1 and are shown on the Regional Soil Map, Plate IV-1. Logs of the borings along with laboratory test results are presented in Volume II of this report. Plate IV-2 presents locations of cross sections. Geologic cross sections depicting soil conditions along east-west and north-south alignments are presented on Plates IV-3 through IV-10.

2. Onshore Soil Conditions

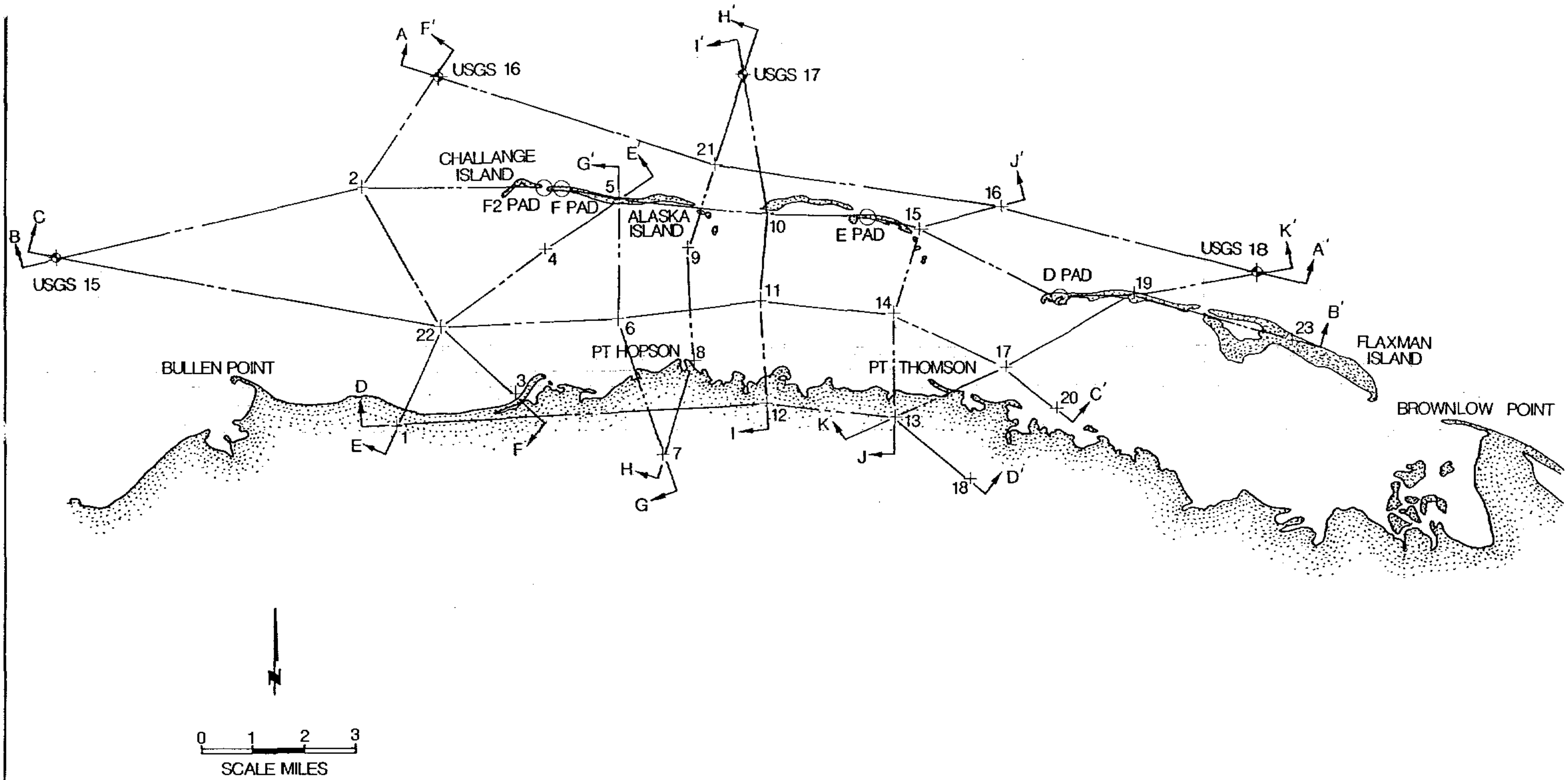
a. Soil Types

The onshore soil conditions in the PTD area generally consist of a thin layer of fine-grained Holocene silts and organic silts overlaying Pleistocene alluvial silts, sands and gravels. With the exception of the active layer, the soils are frozen throughout the year. As shown on Plate IV-11, the alluvial material comprises the bulk of the soils in the onshore area.

TABLE IV-1. SUMMARY OF SUBSURFACE SOIL CONDITIONS

Boring Number	Water Depth	Boring Depth	Depth to Bonded Permafrost	Thickness of Holocene		Depth to Top of Pleistocene	
				Silt/Clay	Sand/Gravel	Clay/Silt	Sand/Gravel
Offshore							
2	12.3	74.5	NE	26	4	30	55
3	5.8	51.0	38	4	--	--	4
4	11.8	51.5	NE	24	5	29	44
6	16.2	51.5	NE	4	8	12	33
8	8.5	51.5	37	2	8	10	25
9	9.5	61.5	NE	21	5	26	50
11	9.5	50.0	NE	--	2	--	2
14	9.6	51.5	NE	11	5	16	44
15	16.5	56.5	39	11	10	20	--
16	31.0	25.5	2.5	--	2.5	2.5	NE
17	9.0	51.0	NE	8	9	17	38
20	8.8	52.0	NE	2.5	13.5	16	24
21	25.0	65.0		2.5	--	2.5	NE
22	15.0	51.0	NE	10	--	--	10
Barrier Islands							
5	3.0	51.5	0	--	12.5	12.5	--
10	--	51.5	0	--	17.5	17.5	--
19	--	50.5	0	--	15	15	--
23	--	50.5	0	2	--	2	--
Onshore							
1	--	48.5	0	1.5	4 (Ice & ML)	--	5.5
7	--	49	0	2	4 (Ice & ML)	--	6
12	--	50.5	0	2	5 (Ice)	30	7
13	--	50	0	3	--	15	3/25
18	--	48.5	0	1.5	1.5 (Ice)	--	17

Note: NE = not encountered. All depths in feet.
*Unexpected shallow permafrost in deep water



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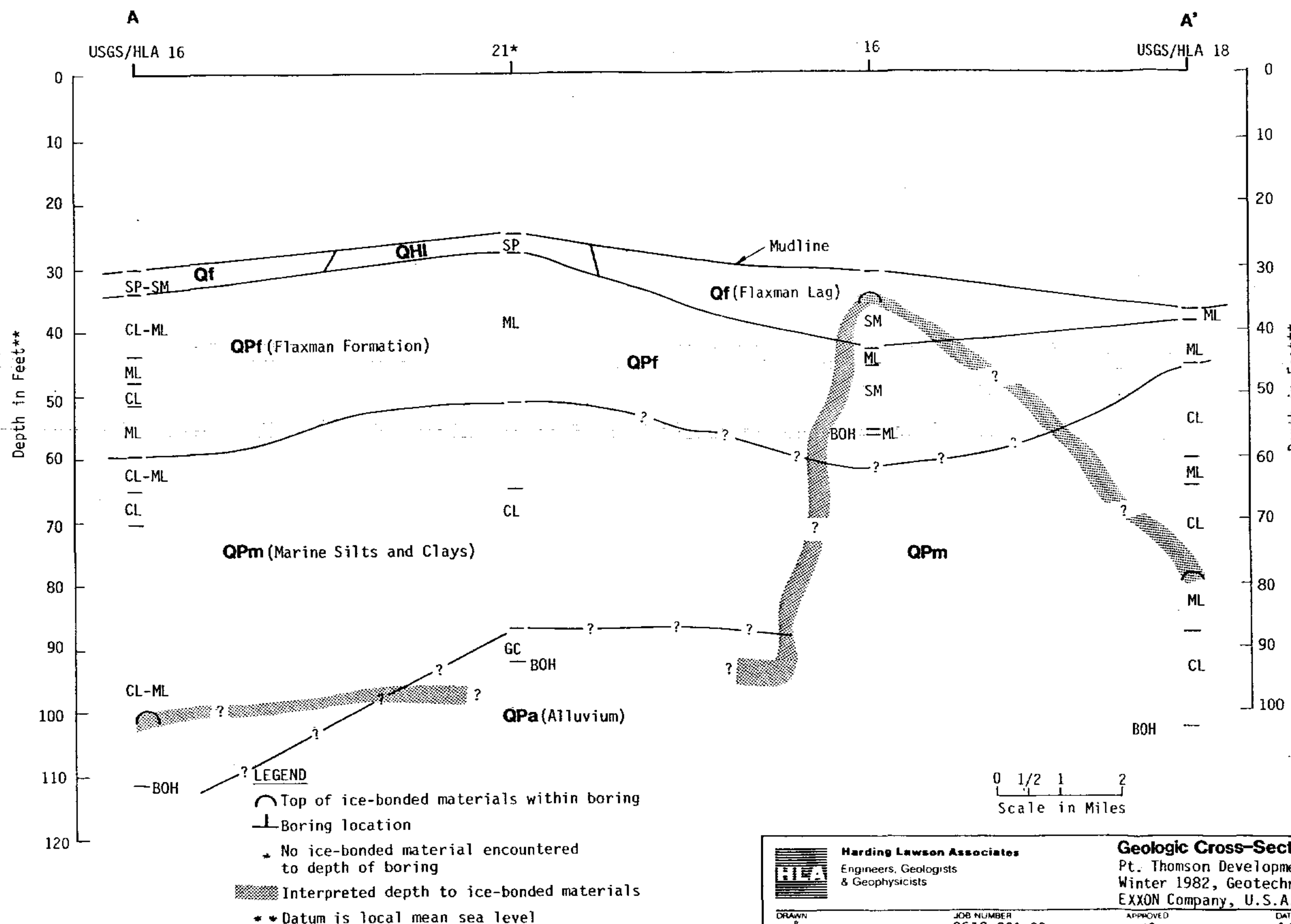
Locations of Geologic Cross Sections
Pt. Thomson Development Project
Winter 1982, Geotechnical Study
EXXON Company, U.S.A.

PLATE **IV-2**

DRAWN	JOB NUMBER	APPROVED	DATE	REVISED	DATE
	9612,031.08		4/82		



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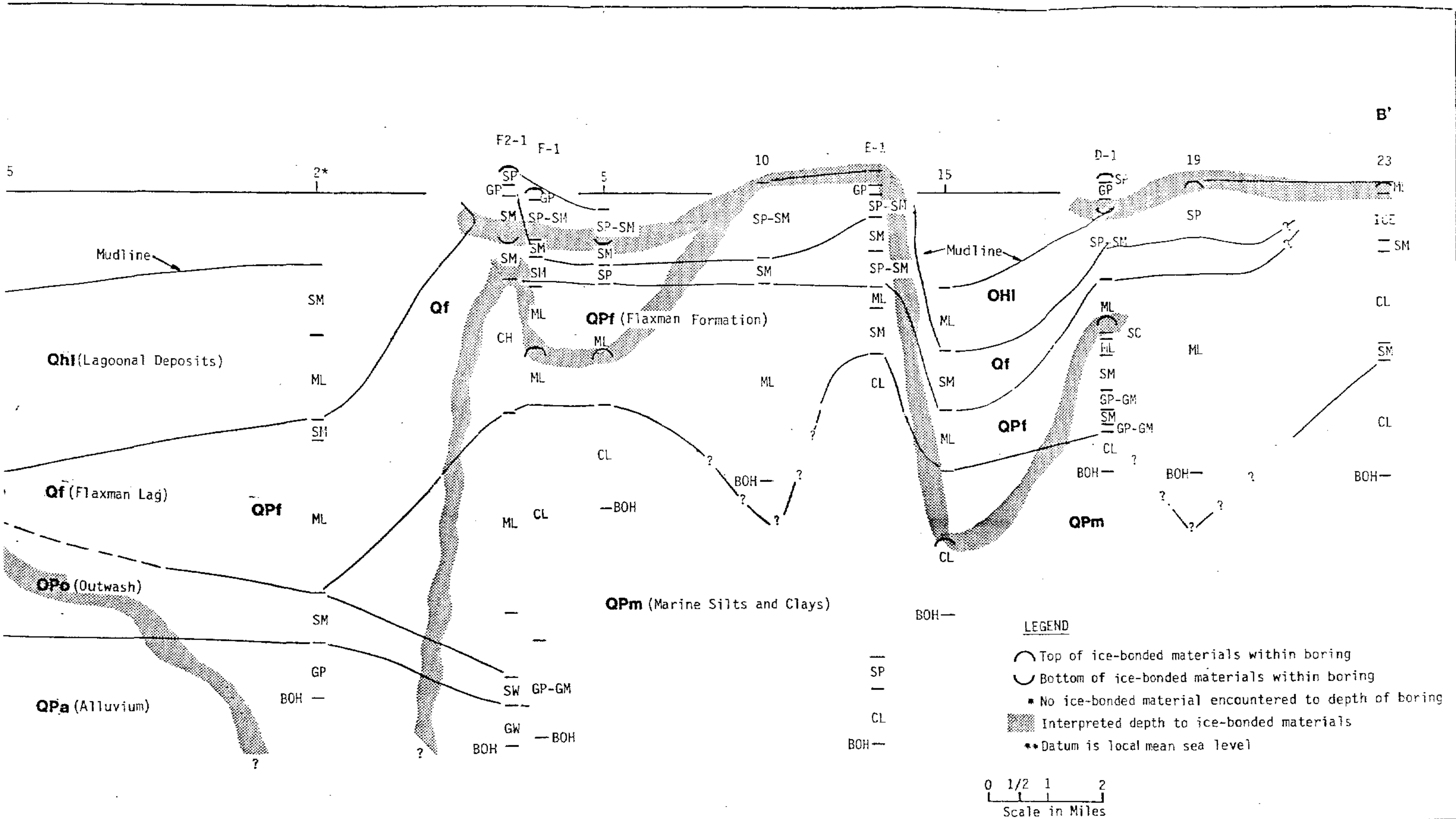
Geologic Cross-Section A-A'
Pt. Thomson Development Project
Winter 1982, Geotechnical Study
EXXON Company, U.S.A.

PLATE **IV-3**

DRAWN	JOB NUMBER	APPROVED	DATE	REVISED	DATE
	9612,031.08		4/82		



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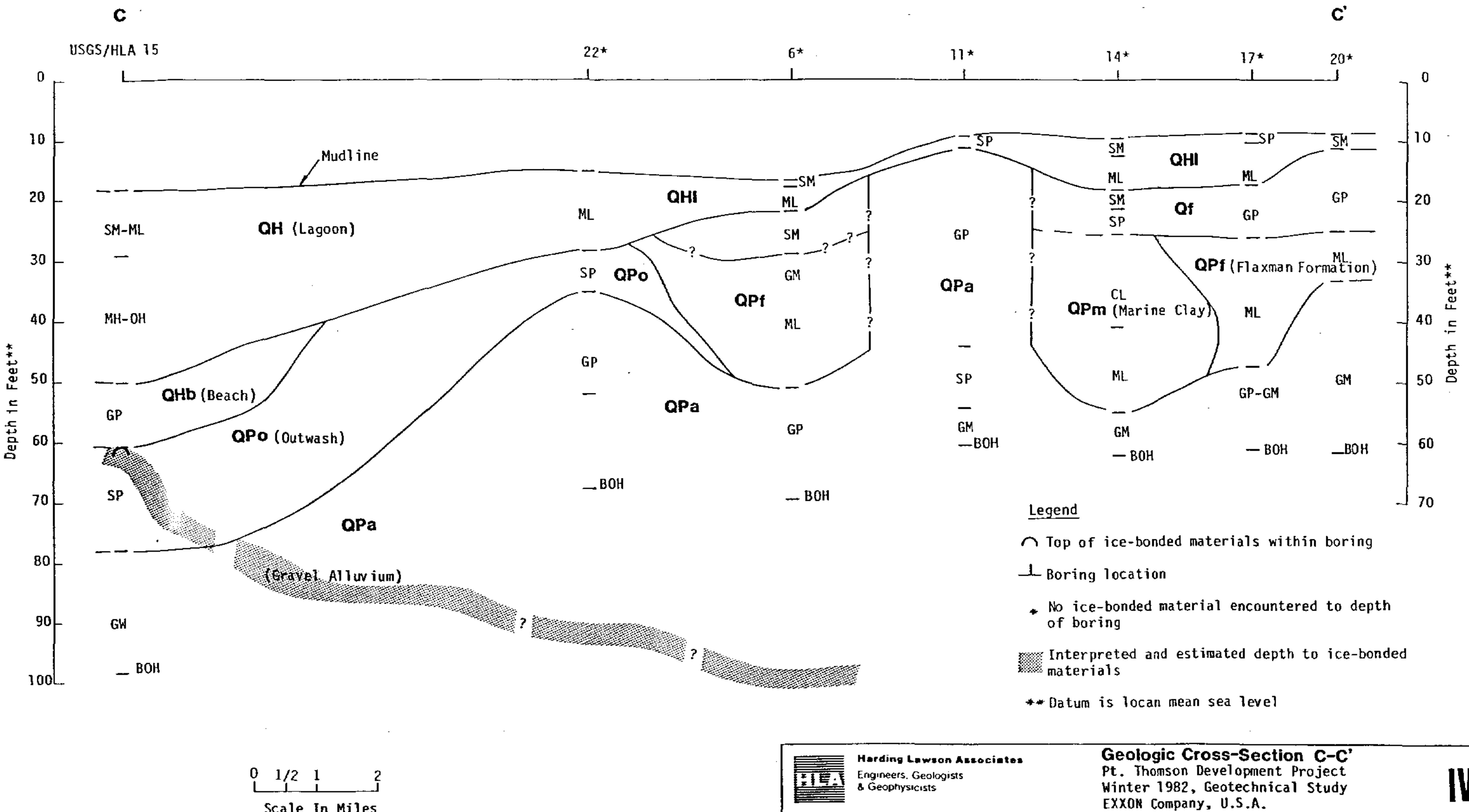
Geologic Cross-Section B-B'
Pt. Thomson Development Project
Winter 1982, Geotechnical Study
EXXON Company, U.S.A.

PLATE **IV-4**

DRAWN	JOB NUMBER	APPROVED	DATE	REVISED	DATE
SP	9612,031.08	DEB	4/82		



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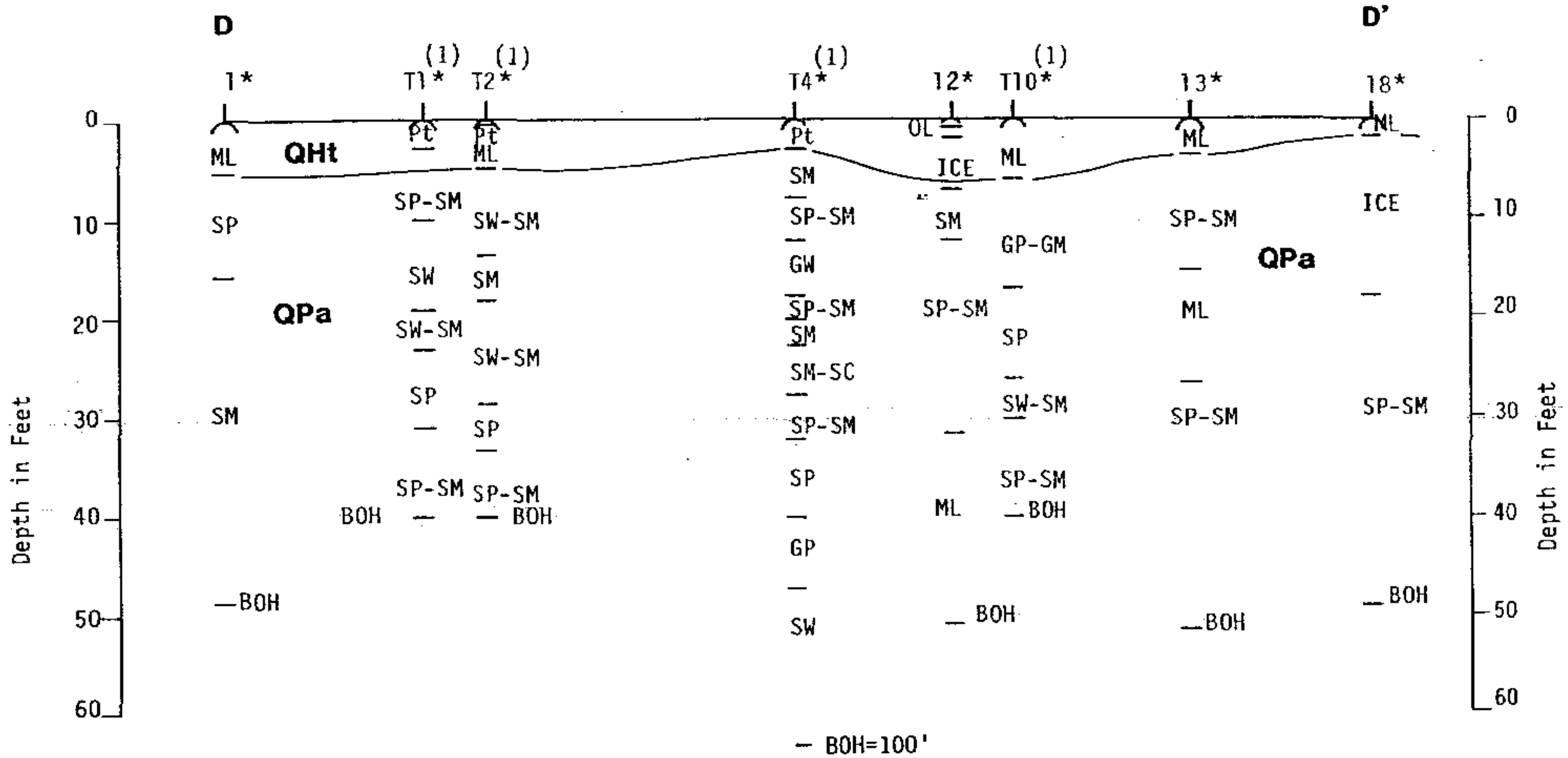
Geologic Cross-Section C-C'
Pt. Thomson Development Project
Winter 1982, Geotechnical Study
EXXON Company, U.S.A.

PLATE **IV-5**

DRAWN	JOB NUMBER	APPROVED	DATE	REVISED	DATE
JP	9612,031.08	DCB	4/82		



Legend

⌒ Top of ice-bonded materials within boring

⊥ Boring location

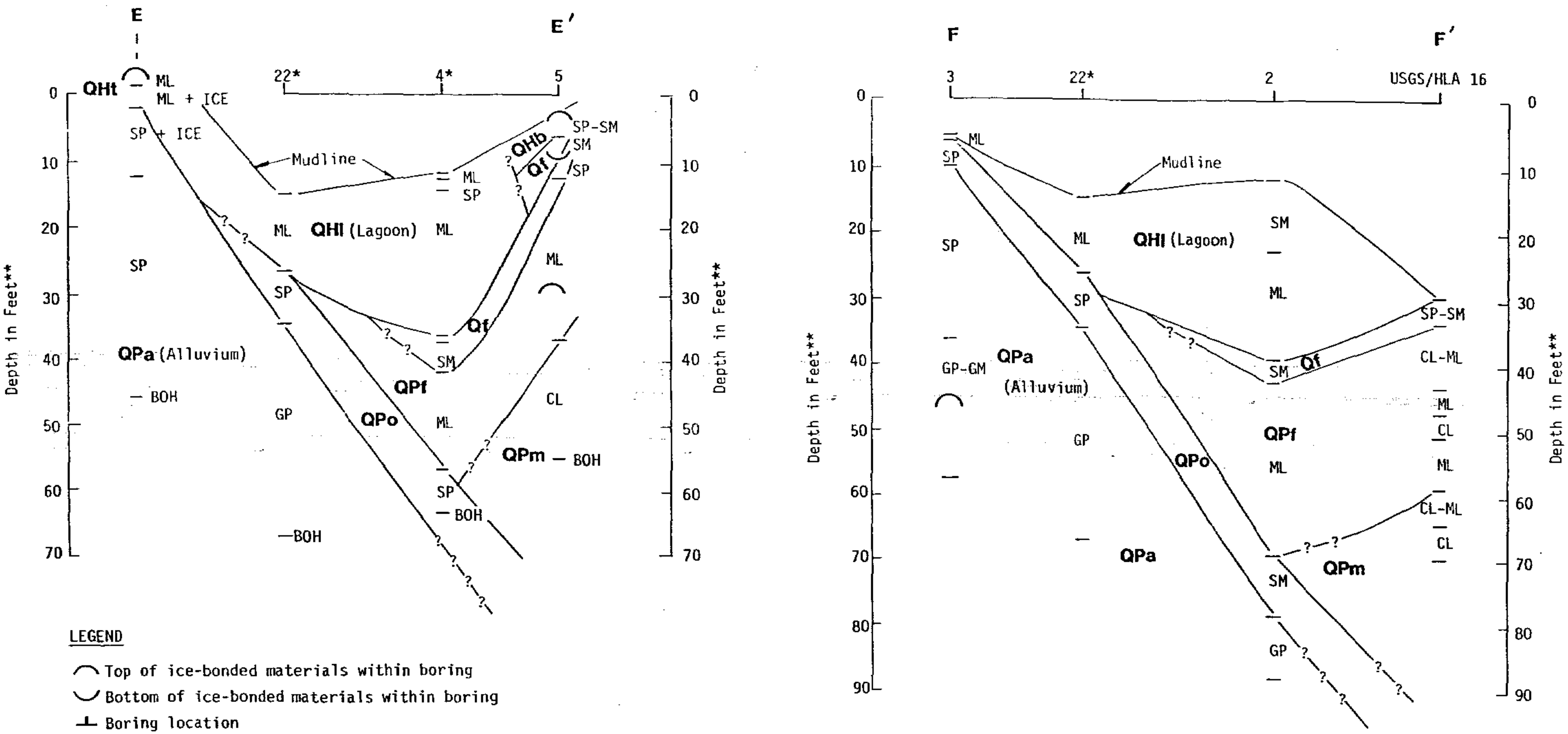
* Ice-bonded material encountered to full depth of boring

(1) Borings from Exxon Gravel Study, 1980.

0 1/2 1 2

Scale In Miles

Harding Lawson Associates Engineers, Geologists & Geophysicists		**Geologic Cross-Section D-D'** Pt. Thomson Development Project Winter 1982, Geotechnical Study EXXON Company, U.S.A.	PLATE **IV-6**
DRAWN	JOB NUMBER 9612,031.08	APPROVED DEB	DATE 4/82	REVISED	DATE



LEGEND

- Top of ice-bonded materials within boring
- Bottom of ice-bonded materials within boring
- Boring location
- * No ice-bonded material encountered to depth of boring
- Interpreted depth of ice-bonded materials
- ** Datum is local mean sea level

0 1/2 1 2

Scale in Miles

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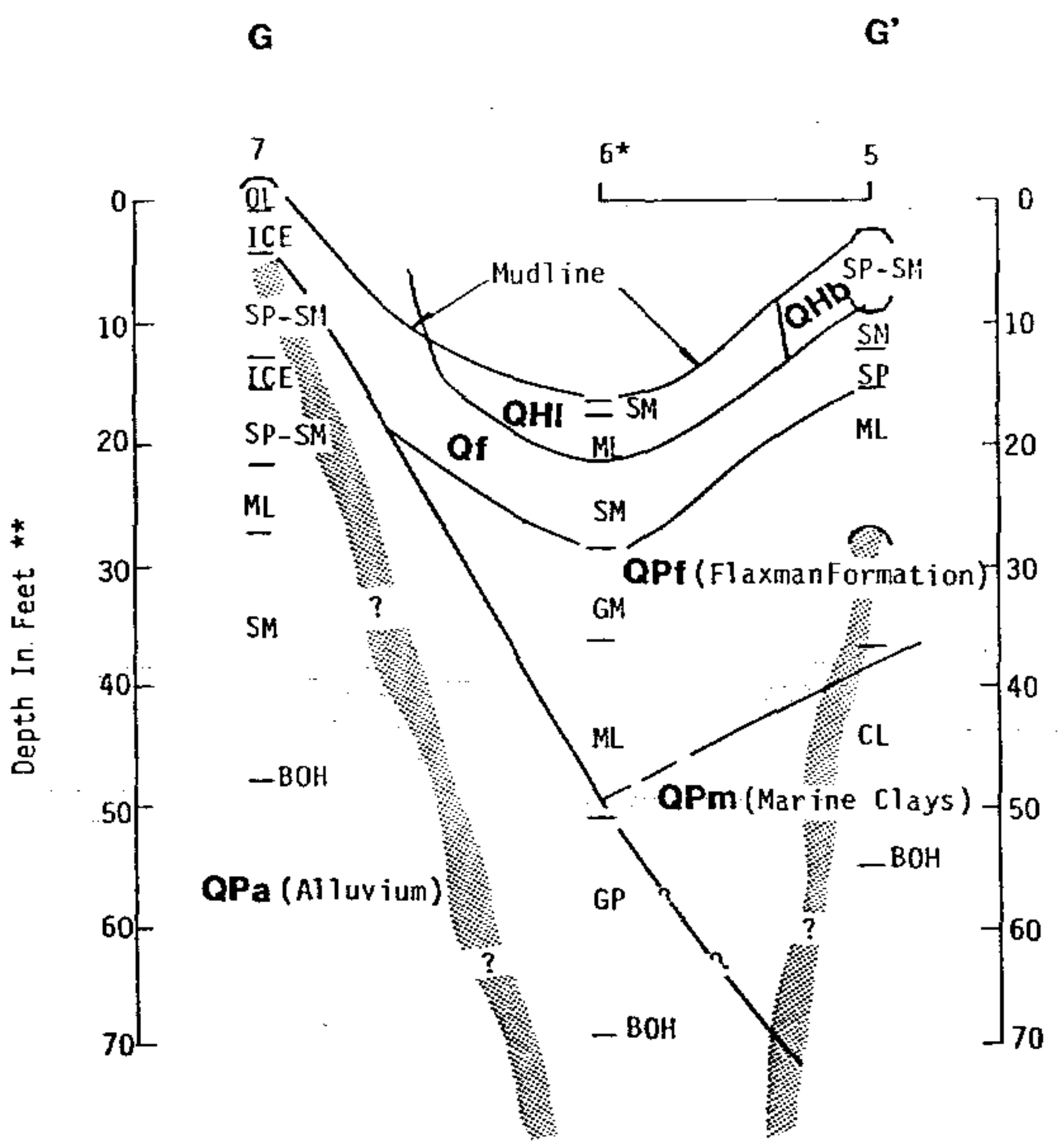
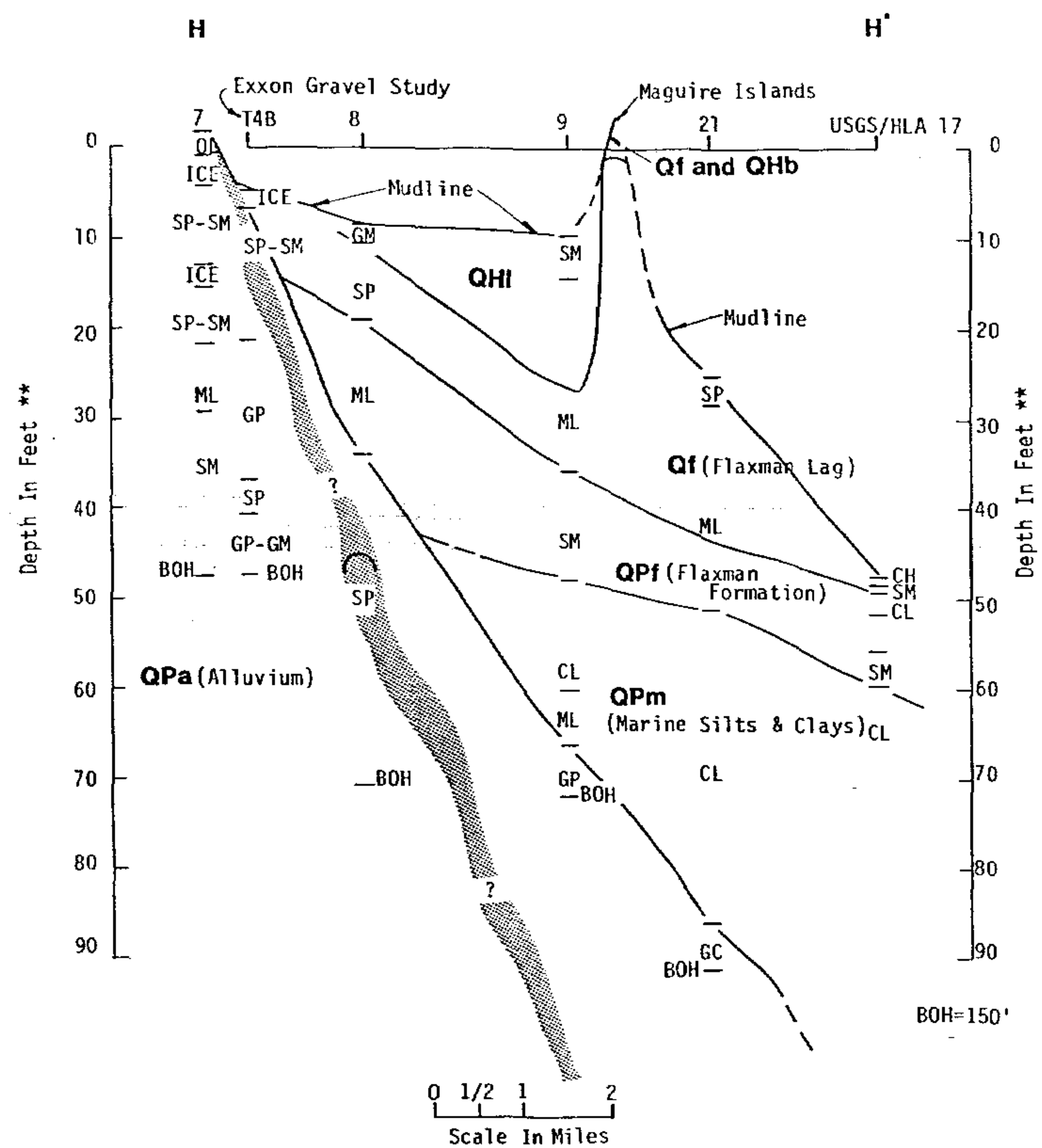
Geologic Cross-Sections E-E′ and F-F′
Pt. Thomson Development Project
Winter 1982, Geotechnical Study
EXXON Company, U.S.A.

PLATE **IV-7**

DRAWN	JOB NUMBER	APPROVED	DATE	REVISED	DATE
	9612,031.08		4/82		





Legend

- Top of ice-bonded materials within boring
- Bottom of ice-bonded materials within boring
- Boring Location
- No ice-bonded material encountered to depth of boring

* *Interpreted depth to ice-bonded materials

* Datum is local mean sea level

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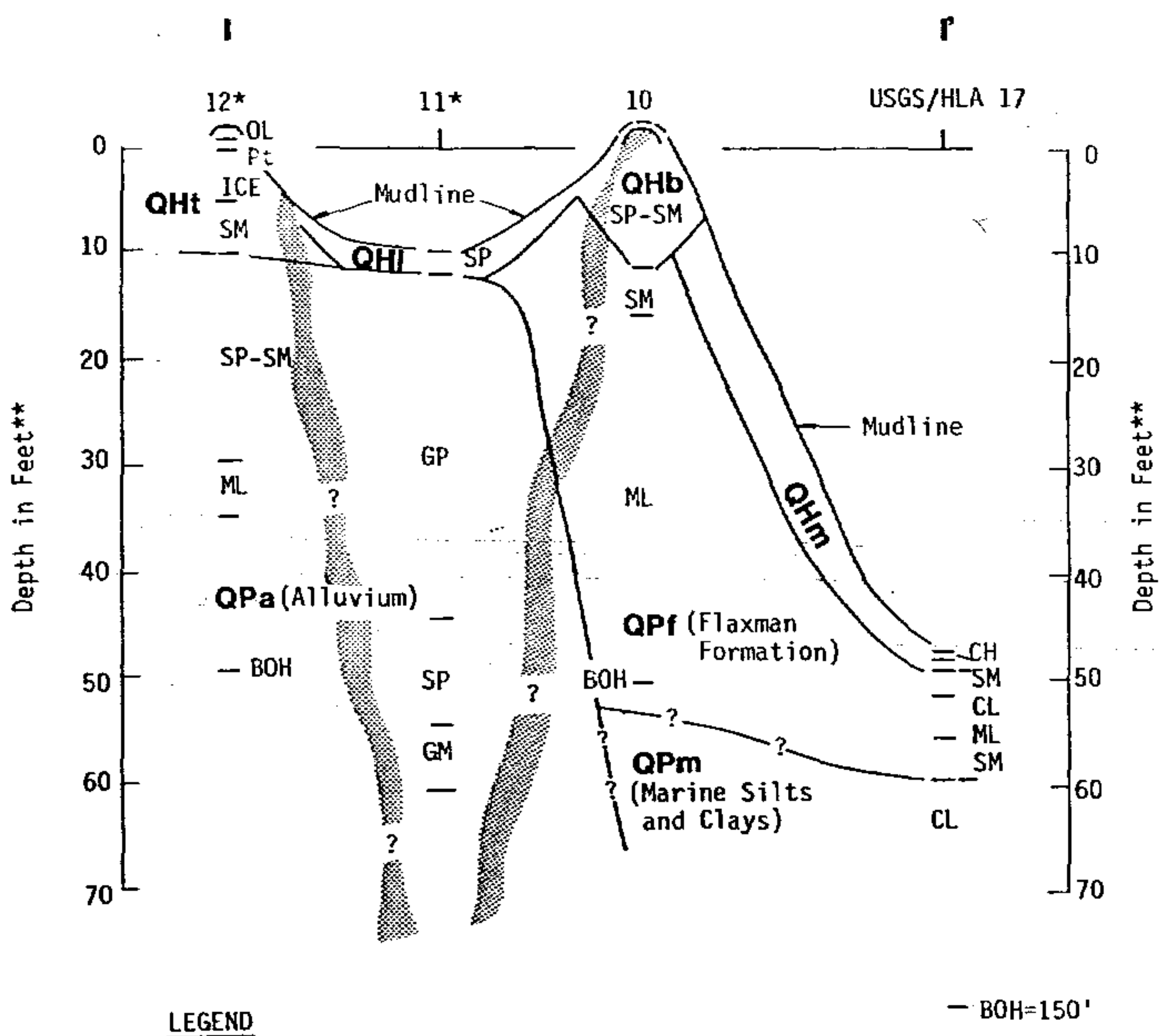
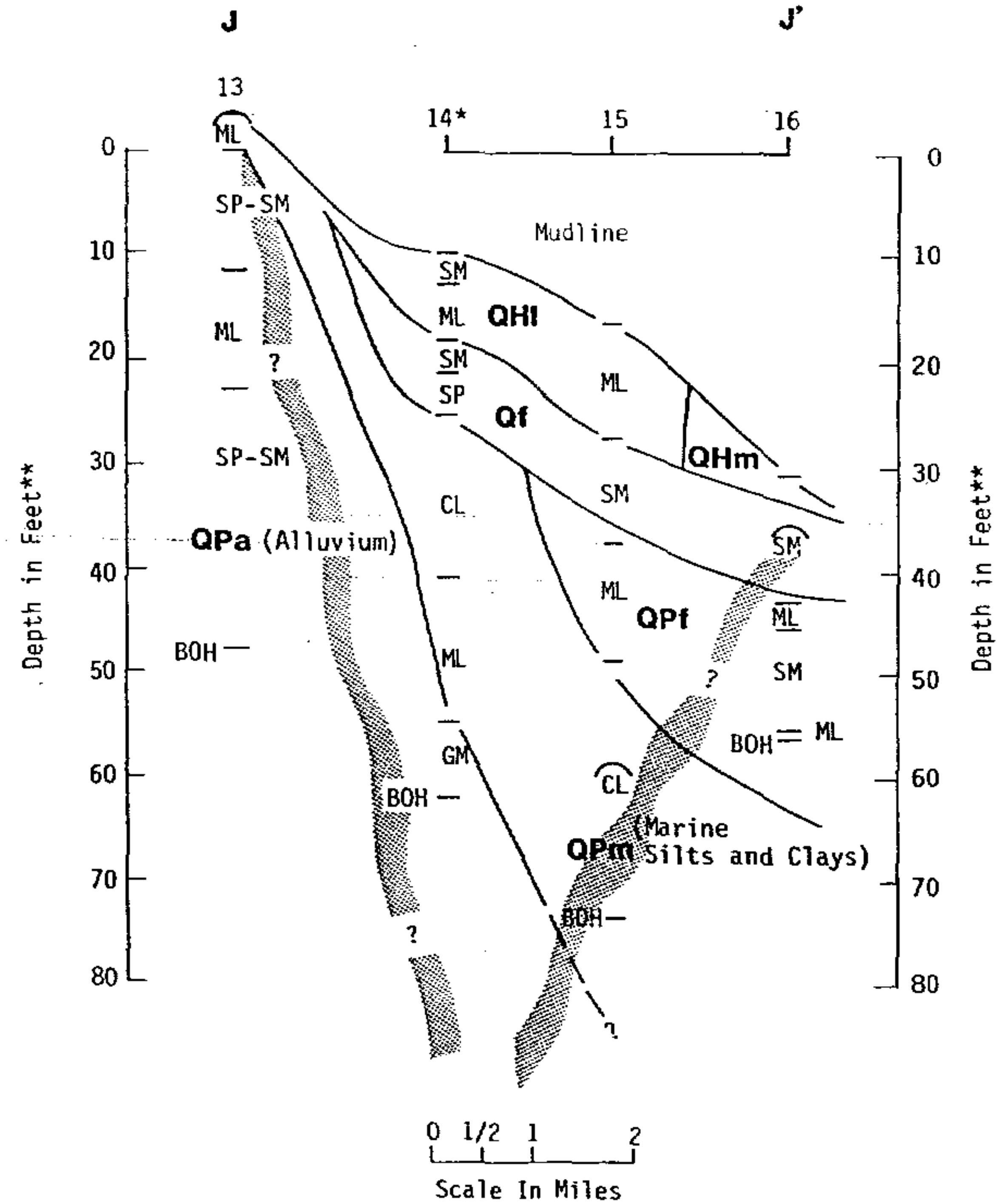
Geologic Cross-Section G–G' and H–H'

Pt. Thomson Development Project, Winter 1982
Geotechnical Study, EXXON Company, U.S.A.

PLATE **IV-8**

DRAWN	JOB NUMBER	APPROVED	DATE	REVISED	DATE
Y	9612,031.08	JRB	4/82		





LEGEND

Top of ice-bonded materials within boring

Bottom of ice-bonded materials within boring

Boring location

* No ice-bonded material encountered to depth of boring

Interpreted depth to ice-bonded materials

** Datum is local mean sea level

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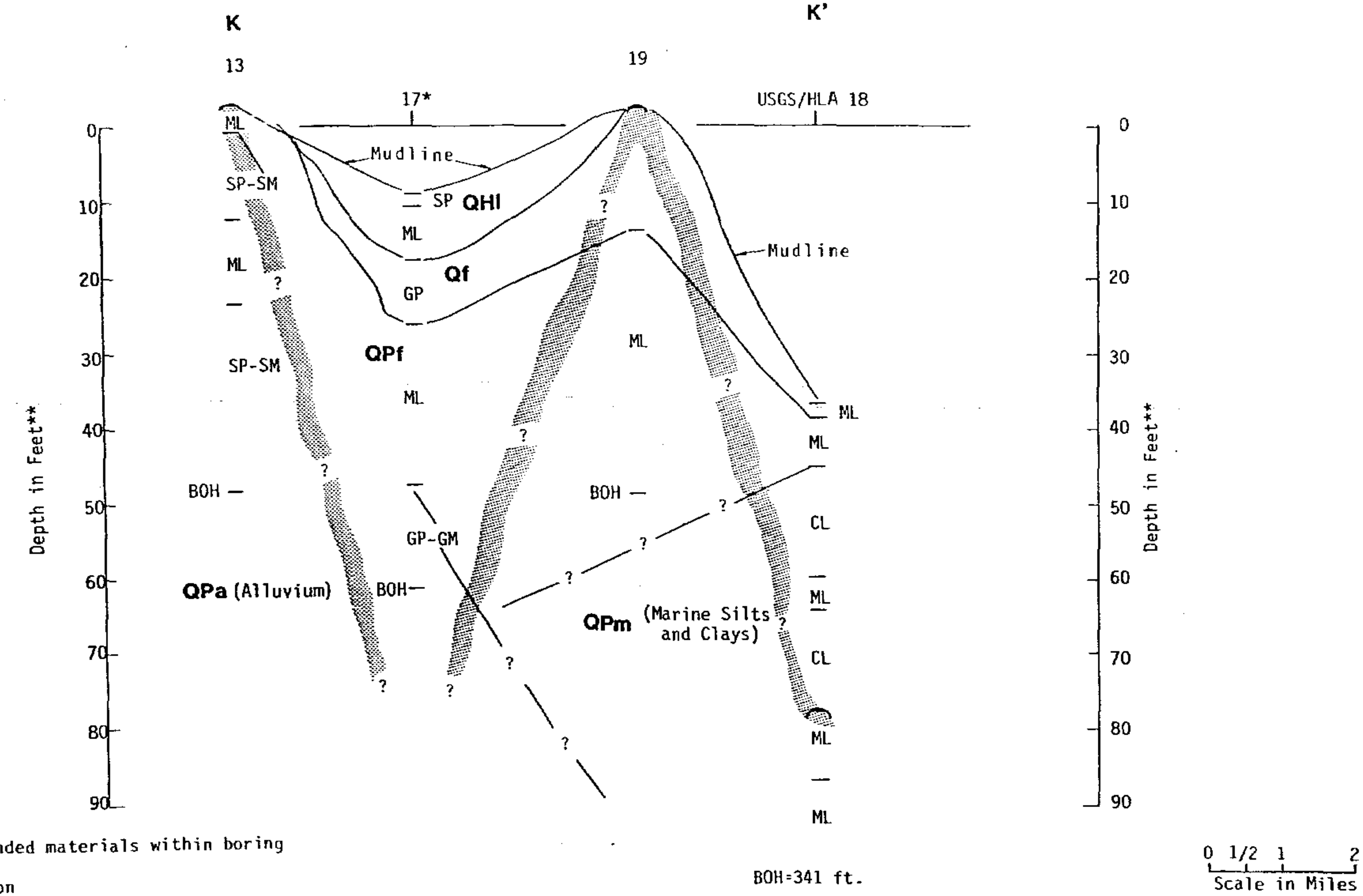
Geologic Cross-Sections I-I' and J-J'
Pt. Thomson Development Project
Winter 1982, Geotechnical Study
EXXON Company, U.S.A.

PLATE **IV-9**

DRAWN	JOB NUMBER	APPROVED	DATE	REVISED	DATE
Y	9612,031.08	JFB	4/82		



Legend

⌒ Top of ice-bonded materials within boring

⊥ Boring location

* No ice-bonded material encountered to depth of boring

Interpreted depth to ice-bonded materials

** Datum is local mean sea level

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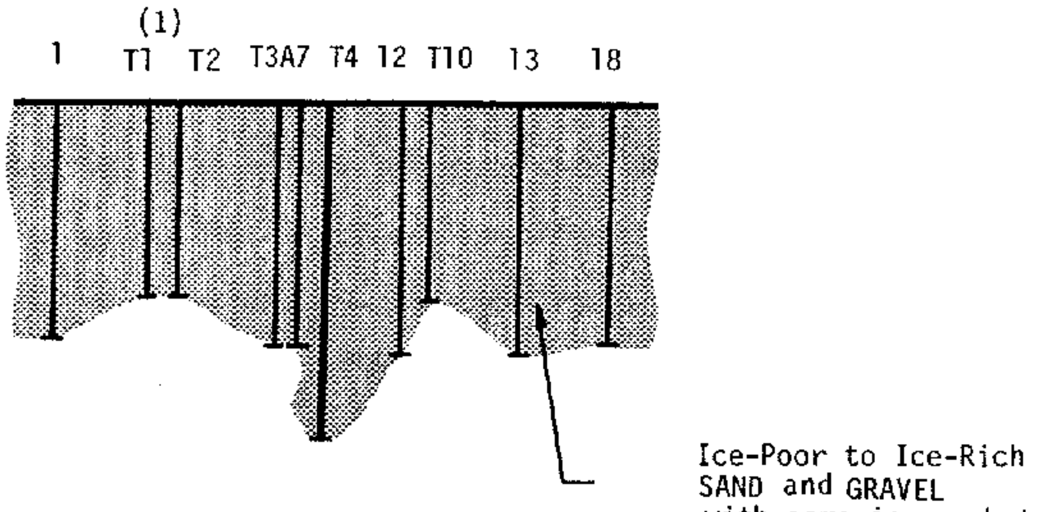
Geologic Cross-Section K-K'
Pt. Thomson Development Project
Winter 1982, Geotechnical Study
EXXON Company, U.S.A.

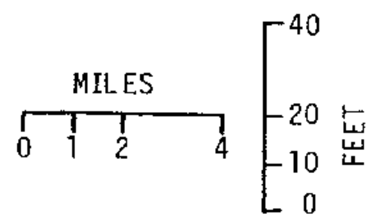
PLATE **IV-10**

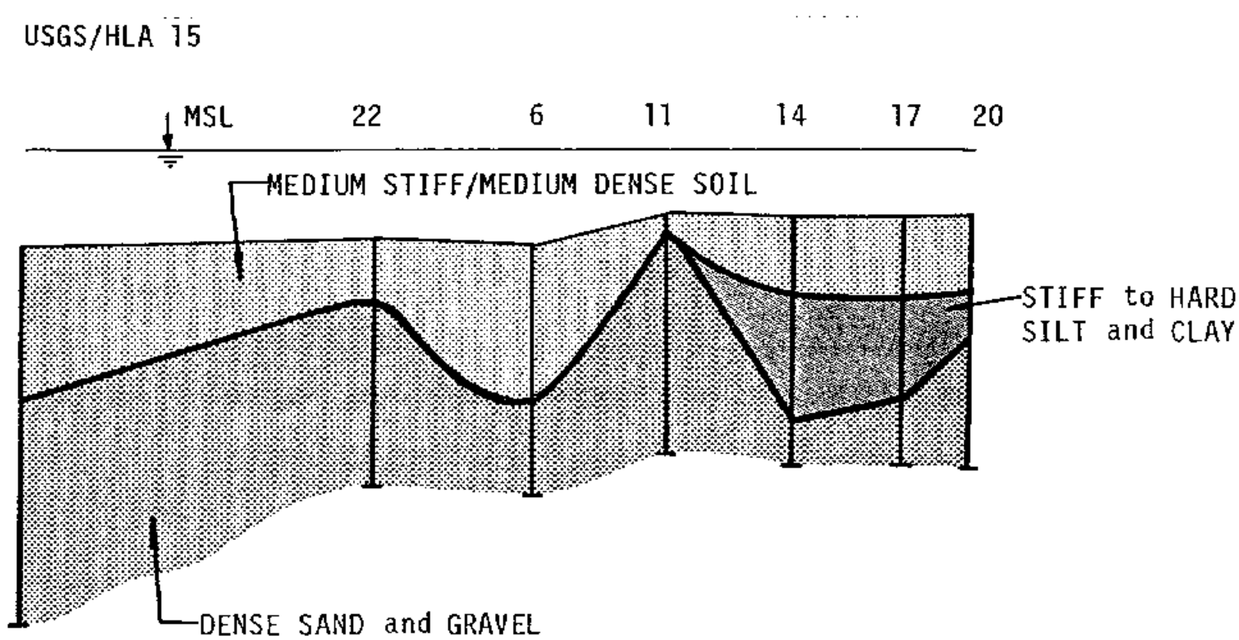
DRAWN	JOB NUMBER	APPROVED	DATE	REVISED	DATE
[illegible]	9612,031.08	[illegible]	4/82		



ONSHORE

(1) Borings denoted "T" are from Exxon Gravel Study, 1980.





LAGOON

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Generalized Soil Strata

Pt. Thomson Development Project
Winter 1982, Geotechnical Study
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PLATE **IV-11**

DRAWN	JOB NUMBER	APPROVED	DATE	REVISED	DATE
JP	9612,031.08	DEB	4/82		

The load-bearing capacity and long-term settlement of foundations installed in ice-bonded soils are dependent on the moisture (ice) content of the soils. For this study we have treated soils with moisture contents greater than 50 percent as ice-rich in evaluating soil properties. In order to simplfy soil properties for the design of onshore foundations, we have grouped the soils in the onshore portion of the study area into three types based on their moisture (ice) content and particle size, as shown in Table IV-2.

TABLE IV-2. ONSHORE SOIL TYPES

Soil Type	Moisture (Ice) Content (Percent by Weight)	Classification
I	less than 50%	gravel and clean sand (GP), (GP-GM), (SP)
II	more than 50%	sand, silty sand, silt, organics, and massive ice (SP), (SM), (ML), (OL), (Pt), (ICE)
III	less than 50%	sand, silty sand, and and silt (SP), (SM), (ML)

The relationships between terrain units and the depth of soil types within the Point Thomson region are summarized in Table IV-3.

TABLE IV-3. TERRAIN UNITS AND DEPTH OF CHARACTERISTIC SOIL TYPES

		Soil Type[1] and Depth (ft)		
Terrain Unit	Map Symbol Abbreviation	Type I Coarse, Ice-poor	Type II Fine, Ice-rich	Type III Fine, Ice-poor
Low Centered Polygons	LCP	NE[2]	0-20	10-20
High Centered Polygons	HCP	5-40[4]	0-6	4-50
Reticulate Ground	RG[3]	--	--	--
Non-Patterned Ground	NPG	NE	0-15	3-40
Frost Boil Tundra	FBT	16-40	0-20	4-16
Thermokarst Terrain	TK[3]	--	--	--
Low Energy Beaches	LEB[3]	--	--	--
High Energy Beaches	HEB	0-50	NE	NE

Notes:

1. Refer to Table IV-2 for descriptions of soil type.
2. NE = Not encountered.
3. Terrain unit not drilled during boring program.
4. Test Boring T3A, Point Thomson Gravel Study, HLA #9612,008.08

Low centered polygonal ground (LCP) and non-patterned ground (NPG) landforms were generally underlain by ice-rich Type II soils to depths of at least 15 to 20 feet. Massive ice was encountered in the upper 20 feet in 6 of the 10 borings drilled in these areas (Exxon, 1980). Where encountered, ice-poor Type I and III soils were generally found approximately 10 feet below the ground surface.

Ice-rich Type II soils were found to a depth of about 6 feet in the high centered polygon (HCP) units. Massive ice was found in two of the five borings drilled in this terrain unit. Ice-poor Type I or III soils were encountered below the upper ice-rich material in all five borings. The gravel content of the Type I and III soils generally increased with depth. Ice contents of the Type I and III soils decreased with depth.

The frost boil tundra (FBT) units generally occurred in areas of mixed LCP and HCP landforms. This type of unit exhibited the greatest variability in soil type of all the terrain units mapped in the study area. Ice-rich Type II soils were found to depths ranging from 2 to 20 feet. Massive ice was encountered in the upper 20 feet in 4 of the 10 borings. Ice-poor Type I or III soils were encountered below the upper ice-rich material in all 11 borings. Type I materials were found in the upper 20 feet in 8 of the 10 borings (Exxon, 1980).

No test borings were drilled in thermokarst (TK) areas. Soil conditions in TK areas should be similar to those found in the FBT areas with the exception that higher massive ice contents are expected in TK areas.

Test Boring 3 was drilled in a high energy beach (HEB) unit on Point Gordon. Unbonded Type I materials were encountered just below the surface and were present throughout the test boring to a total depth of 38 feet. Ice-bonded Type I materials were present from 38 to 50 feet.

No test borings were drilled in low energy beaches (LEB). Unbonded Type II and III soils with high organic contents and occasional gravel seams should be expected.

b. Ground Temperatures

Ground temperatures were measured in two of the onshore borings on March 13 and April 17, 1982. Boring 7 was drilled in a high centered polygon terrain approximately two miles south of Point Hopson. Boring 13 was drilled in a terrain unit containing high and low centered polygons approximately one mile south of Point Thomson. The equipment and procedures to measure the ground temperatures are described in Appendix C, Volume II.

Temperature versus depth profiles from Borings 7 and 13 are presented on Plate IV-12. Temperature data from Test Borings 7 and 13 are virtually identical. Temperature variations between borings in the upper 30 feet are a maximum of 1.0°C. Below a depth of 30 feet the maximum variation is ±0.1°C. The temperature versus depth curve has a negative slope indicating that colder temperatures exist at depths below that reached by the test borings.

The low ground temperatures measured in the upper 30 feet of Test Borings 7 and 13 are the result of cooling of the surface during the winter months. Ground temperatures below a depth of 30 feet in Test Borings 7 and 13 compare very well to data obtained in Test Boring 1 drilled in August, 1981 along the coast (on the beach) in the DID area (Exxon, 1981c). Comparison of the data indicates that the most significant seasonal variations in temperature occur within the upper 30 feet of the ground surface in both areas.

Ground temperatures in the DID area were found to be warmer inland from the coast. Based on the comparison of the Point Thomson and Duck Island data, we conclude that ground temperatures in the Point Thomson region will also be warmer inland. Warmer inland ground temperatures result from warmer air temperatures inland during the summer as indicated by the estimated thaw indices of 375°C days for coastal areas versus 550°C days for inland areas.

3. Offshore Soils

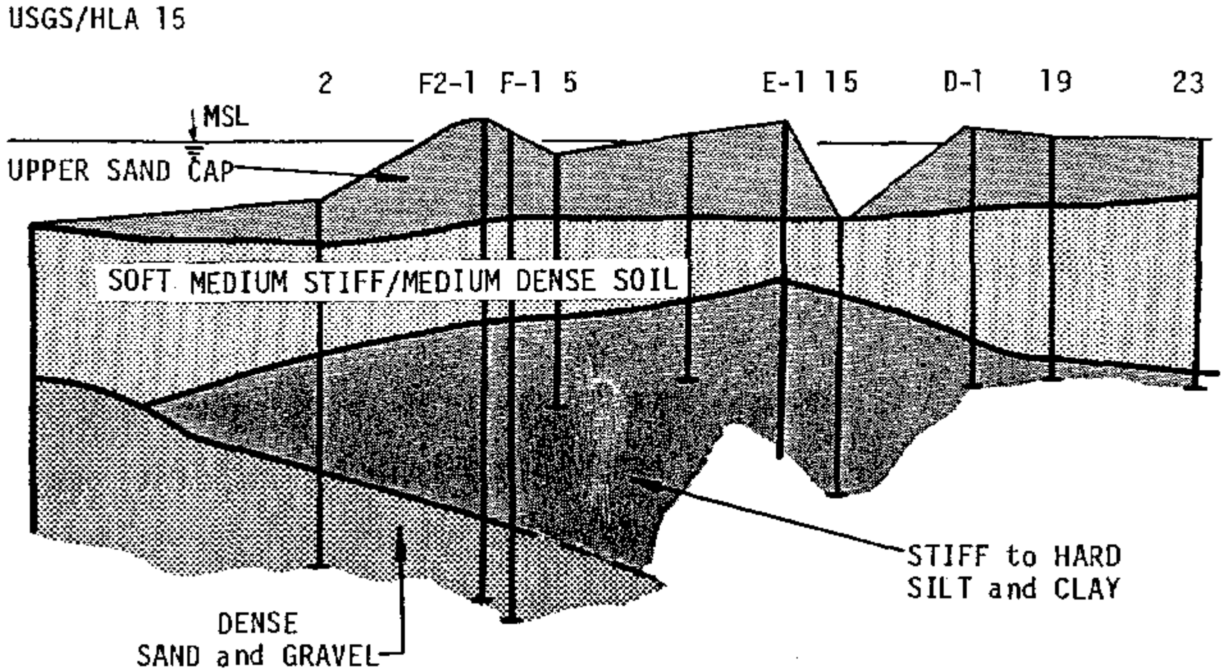
a. Soil Groups

The offshore sediments in the project area consist of a complex sequence of Holocene and Pleistocene marine units that overlay Pleistocene fluvial and glaciofluvial sands and gravels. For the purpose of engineering analysis, it is possible to group soils with similar properties into three idealized cross-sections. These three cross-sections are shown on Plates IV-11 and IV-12 for typical lagoon, barrier island, and deep water areas.

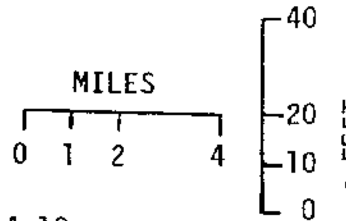
The offshore soils profiles presented on Plates IV-11 and IV-12 have been divided into four general groups based on their moisture content and dry density as shown in Table IV-4. Related geologic classifications are also shown in Table IV-4. Detailed descriptions of the geologic units were presented in Table III-3.

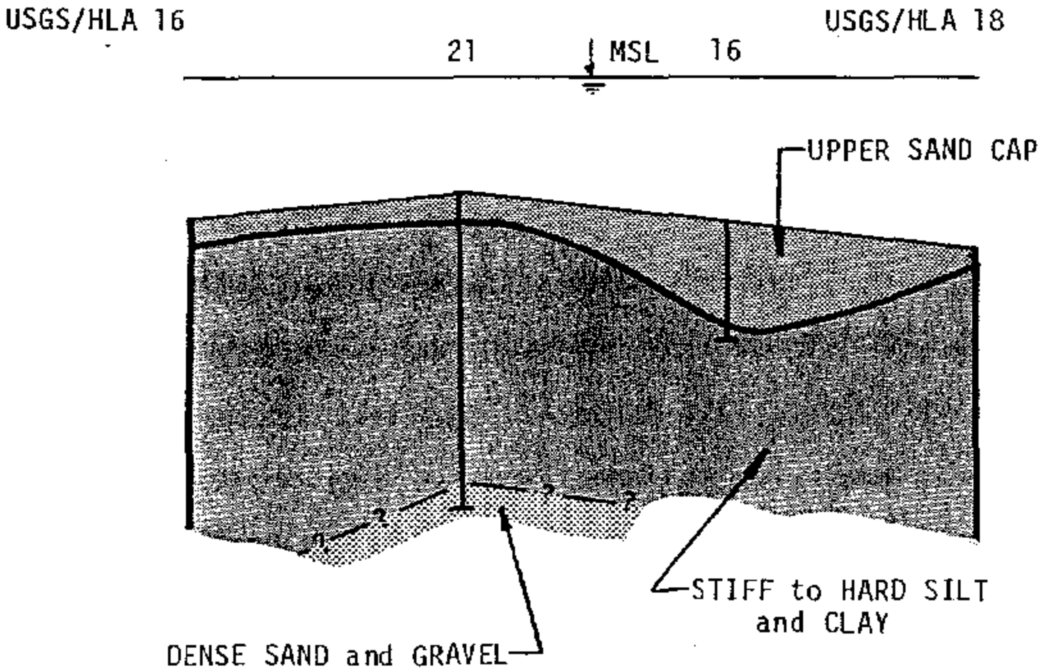
TABLE IV-4. OFFSHORE SOIL GROUPS

Group	Unified Soil Classification	Geologic Map Symbol	Description
1	SP - SM	QHs	medium to very dense poorly sorted fine sands
2	SM - ML	QHl, QNd, QHnm, Qf	soft to medium stiff silts and loose to medium dense sands
3	CL - ML	QPf, QPm	stiff to hard clays and silts
4	GP - SP	QPb, QPo, QPa	medium dense to dense sands and gravels



BARRIER ISLANDS





DEEP WATER

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Generalized Soil Strata
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Winter 1982, Geotechnical Study
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PLATE
IV-12

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Group 1 is most clearly depicted on Plate IV-12. This layer is the sand cap that forms the barrier islands. It is also present as a thin veneer of sand and silty sand, up to five feet thick, north of the barrier islands (HLA/USGS, 1979). Geologically, it is composed of Holocene beach and Flaxman lag deposits.

Group 2 is composed of a mixture of soft to medium stiff Holocene lagoon and lag deposits. This soil type is found in the lagoon area, up to about 30 feet below mudline and is present beneath the barrier islands. The soil types found in this layer range from silt to sand, along with sporadically occurring gravel, cobbles, and boulders.

Group 3 is a sequence of stiff to hard silts and clays which commonly overlies the dense sand and gravel deposits in the lagoon, barrier islands, and deep water areas. This soil is composed primarily of Pleistocene marine sediments that were deposited when sea levels were considerably higher than they are today. Although the stratum pinches out before it reaches the coastline, it thickens offshore and is in excess of 300 feet thick at USGS/HLA Boring 18.

Group 4 is a layer of dense sand and gravel that is composed primarily of Pleistocene alluvium and underlies the entire project area. As shown on Plates IV-11 and 12, this material comprises the majority of the onshore sediments. Although it is found close to the surface onshore, it generally dips steeply to the north offshore, and was not encountered in any of the deep water test borings. However, in the lagoon area at Test Boring 11, Pleistocene sands and gravels were encountered less than five feet below the mudline and extended to a depth of at least 50 feet.

b. Ground Temperatures

Ice-bonded permafrost was encountered in the barrier islands test borings and in Test Borings 3, 8, 15, and 16. Although no ice-bonded soil was observed in the other offshore test borings, it is probably present at greater depths than were explored.

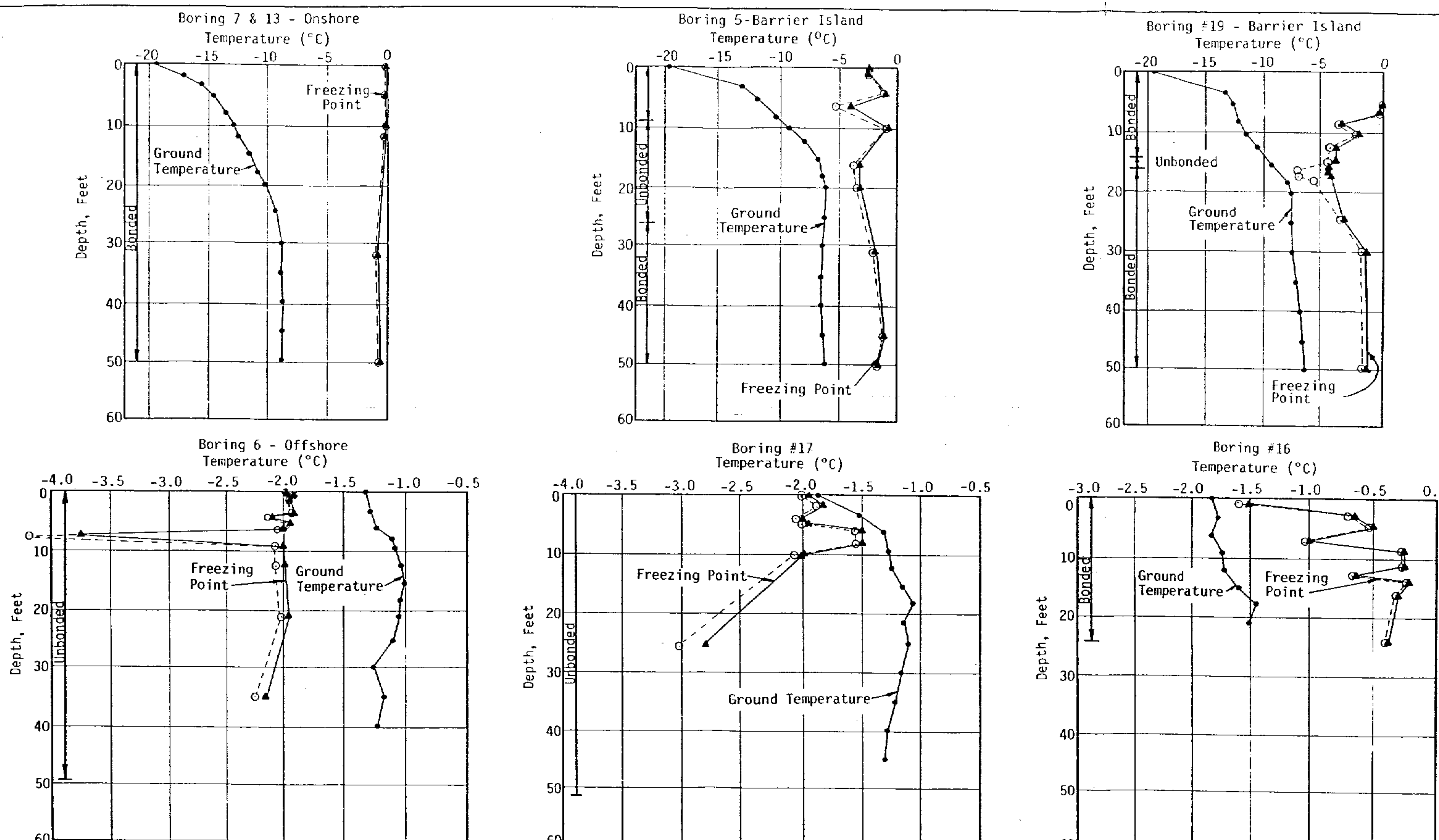
Ice bonding was confirmed by the presence of visible ice in the borings or estimated to be present on the basis of secondary information such as the temperature and salinity relationships and sampling resistance of the materials. The visible ice generally consisted of thin layers and laminations, individual crystals and ice coatings. The ice layers and laminations were predominantly 1/8 to 1/2 inch in thickness and were present in fine-grained deposits only. The laminations and layers of ice, although occasionally horizontal, frequently had an orientation that was steeply inclined or even vertical. In the sand and gravel deposits, the ice was predominantly in the form of small ice crystals and/or grain coatings and was frequently only visible with a hand glass.

The presence of ice-bonded subsea permafrost was expected since conservative estimates of coastline retreat indicate that much of the Point Thomson offshore area could have been above sea level and exposed to winter air temperatures as recently as 3000 years ago. Furthermore, some of the subsea soils have also been exposed to a colder thermal regime as the barrier islands migrate to the southwest. Therefore, since the present offshore permafrost is actually a relict onshore permafrost, variations in ice content should be similar to those observed in deeper onshore permafrost.

Ground temperatures were measured in the offshore borings, and have been correlated with the estimated freezing point based on soil salinity as shown on Plate IV-13. These data show that the offshore ground temperatures are considerably warmer than those found either onshore or on the barrier islands. By extrapolating the data, as discussed in Appendix C, the average sea floor temperature is about $-0.8^{o}C$, while the average ground surface temperature, both onshore and on the barrier islands, is about $-9^{o}C$. The average surface temperature of Test Boring 5 is slightly warmer at about $-6^{o}C$ because it is located on the shoreline of the island. There will be large seasonal variations from these average surface temperatures.

Measured ground temperatures and calculated freezing points (FP) typically correlate well with the zone of ice-bonded permafrost. Exceptions to this relationship are observed in the unbonded, coarse-grained soil on the barrier islands. There is good correlation between the unbonded soil and high salinity in the barrier islands test borings. The FP values shown were calculated using freezing point-salinity relationships for seawater (57th Edition, Chemistry Handbook). The compound sodium cloride (NaCl) comprises 68 percent of the salts in seawater. If NaCl relationships are used, the freezing point approaches the actual measured ground temperatures in zones of high salinity. Since the pore fluids tested are composed of 90 percent Na and Cl salts, the NaCl assumed relationships might be more appropriate for determining the freezing point. The FP based on the NaCl relationship is presented on Plate IV-13 for comparison.

The surface of offshore permafrost is quite variable and complex. The area around Test Boring 16 has the greatest variation in the permafrost surface. In Test Boring 16, permafrost was encountered three feet



Note:

▲——▲ Denotes freezing point determined using sea water/salinity relationship

○---○ Denotes freezing point determined using NaCl/salinity relationship

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Summary of Ground Temperature

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PLATE **IV-13**

DRAWN	JOB NUMBER	APPROVED	DATE	REVISED	DATE
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below mudline. It does not occur until 39 and 41 feet below mudline in Test Boring 15 and HLA/USGS Boring 18, respectively. Differences in the permafrost table of as much as 40 vertical feet in a 350-foot horizontal distance have been reported in the DID area.

These large variations in the surface of the permafrost are similar in appearance to those found in marginal, discontinuous permafrost zones, such as in the interior of Alaska. Variations in vegetation, soil type, moisture, and solar exposure are the principal causes of discontinuities on land. Offshore, the fairly uniform seawater temperatures and soil conditions appear to preclude thermal factors as causes of the variations. For example, subsurface temperature measurements from other Beaufort Sea studies indicate a range of average sea floor temperatures of about $\pm 0.5^{o}C$. Additionally, thermal conductivity tests of the offshore unfrozen silts and sands also indicate only slight differences between materials.

We believe that the large vertical variations in the surface of the subsea permafrost could be due to downward permafrost decay caused by salt advection, i.e., the diffusion of salt into the sediments. Salt advection is strongly indicated as the cause of permafrost thawing along the shoreline and outside the barrier islands where the salinity ranges from 30 to 50 parts-per-thousand (ppt).

The lagoon is characterized by fine grained Holocene deposits which have never frozen overlying Pleistocene deposits which were probably frozen prior to deposition of the Holocene soils. As with the permafrost outside the barrier islands, we believe that salt advection is the cause of the Pleistocene sediments thawing with this thawing process ongoing duing deposition of the Holocene sediments.

As mentioned previously, large vertical variations in the permafrost surface could also be due to the migration of the barrier islands. As the islands move across an area, the permafrost surface is raised in that region.

B. Soil Properties

1. Unfrozen/Unbonded

The soil properties that are discussed in the following section are representative of the conditions that are encountered in the unfrozen/unbonded sediments in the lagoon, deep water, and barrier islands areas. In several cases where there is little overall difference in behavior between strata, only a single generalized parameter with a discussion of local exceptions is presented.

a. Specific Gravity

The average specific gravity that was measured on typical soil types is presented in Table IV-5. These results are within the range of values that are considered normal for each type of soil.

TABLE IV-5. SPECIFIC GRAVITY

Upper Sand Cap SP, SM	Medium Stiff Silt Medium Dense Sand SM, ML	Stiff to Hard Silt and Clay CL, ML	Dense Sand and Gravel SP, GP
2.69	2.70	2.75	2.69

b. Moisture Content and Dry Density

There is a wide variation of natural moisture contents over the depth of the test borings in the lagoon and deep water areas. Furthermore, there is often significant local variation of these values due to numerous, thin interbeds of increased sand, silt, clay or organic content. Sandy or gravelly soils typically have the lowest moisture contents and organic soils have the highest.

TABLE IV-6. AVERAGE WATER CONTENT AND DRY DENSITY IN OFFSHORE SEDIMENTS

Upper Sand Cap		Medium Stiff Sand Medium Dense Sand(1)		Stiff to Hard Silt and Clay		Dense Sand and Gravel	
w (%)	γ (pcf)	w (%)	γ (pcf)	w (%)	γ (pcf)	w (%)	γ (pcf)
15-25	90-110	25-35	70-90	15-25	90-110	5-15	115-130

(1) For unfrozen barrier islands sediments, w avg = 10-20% and γavg = 110-115pcf.

The high and low values of moisture content and dry density fall within a relatively narrow band in all of the soil types except for the medium stiff/medium dense layer. In this material, there are significant local variations in the maximum and minimum values. Additionally, the stiff Pleistocene silts and clays in the eastern portion of the lagoon have natural moisture contents approximately 5 percent lower than the average for that strata. A similar decrease in moisture content is also evident in the dense sands and gravels in this area.

c. Salinity

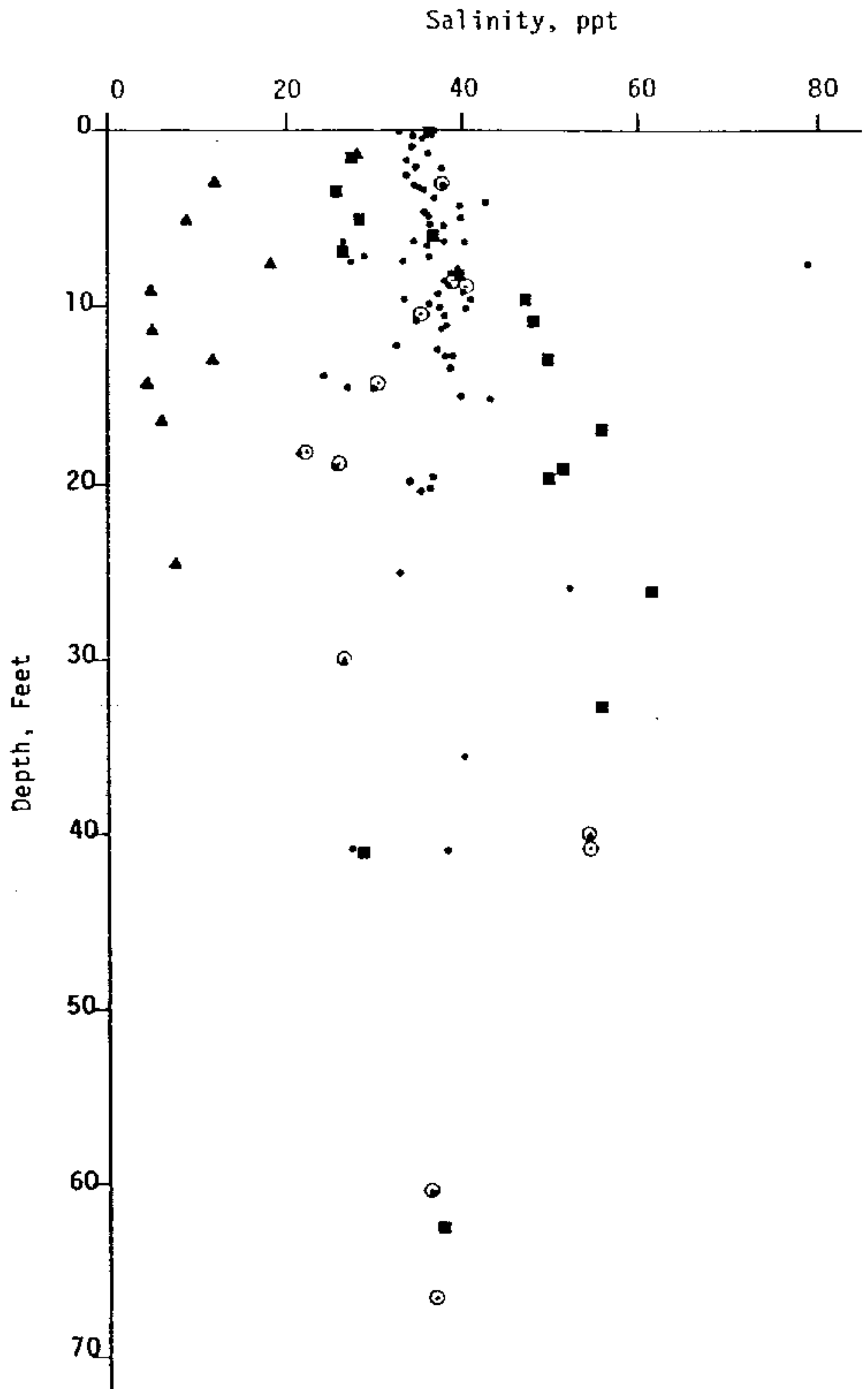
A number of salinity measurements were made throughout the area. The results of these tests are summarized on Plates IV-14 and IV-15; salinity profiles for individual test borings are presented in Appendix D on Plates D-55 through D-59. Additionally, the relationship between salinity, ground temperature and freezing point depression is discussed in Section A of this chapter.

In all of the test borings, highest salinities correlate well with zones of unbonded soil. This relationship is especially evident in data obtained from the barrier islands, where salinity in the unbonded zones was greater than 100 ppt. The high salinity concentration is suspected to be a result of brine rejection as the upper soil freezes. In the lagoon area where no permafrost was encountered and in the beach test borings the salnities are generally greater than 30 ppt and tend to range between 35 ppt and 42 ppt. Onshore salinities were significantly lower than those measured in any other area and tended to increase slightly with increasing depth.

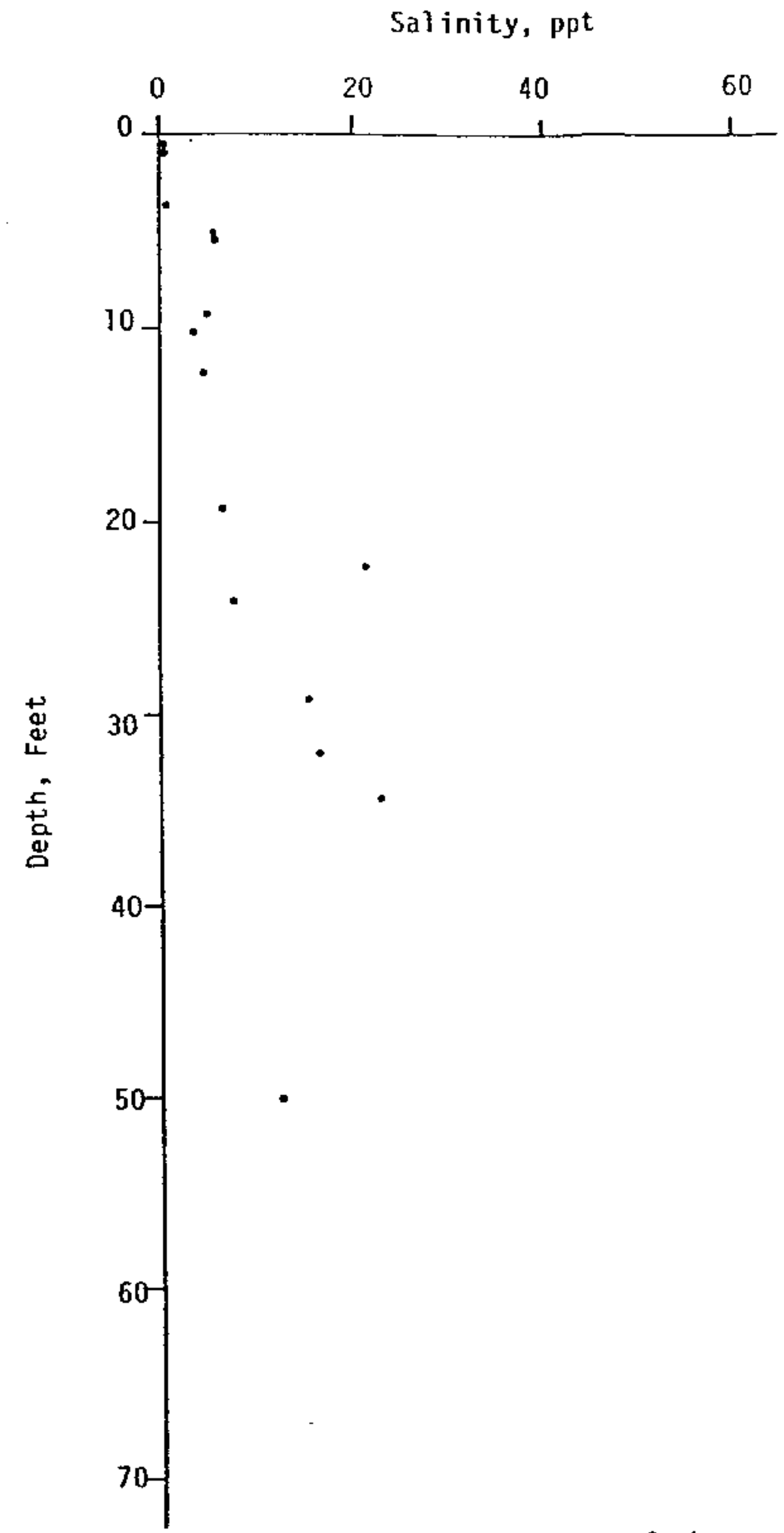
d. Organic Content

The offshore samples that were tested contained less than 16 percent organic matter by weight. The majority of the soils within this area contain only trace amounts of organic matter. Those samples with high organic contents were typically found as thin seams of material.

In general, the presence of organics tends to decrease the dry density and increase the moisture content of a soil. Also, with the exception of peat or highly fibrous sediment, Beaufort Sea organic silts typically do not exhibit either a noticeable reduction in the shear strength nor an increase in compressibility as compared to non-organic soils. This finding is



Offshore



Onshore

Notes:

- • Denotes data from Lagoon borings
- ⊙ Denotes data from Boring 2
- ▲ Denotes data from Boring 16
- ■ Denotes data from Boring 21

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Summary of Salinities,
Lagoon and Onshore Borings
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PLATE **IV-14**

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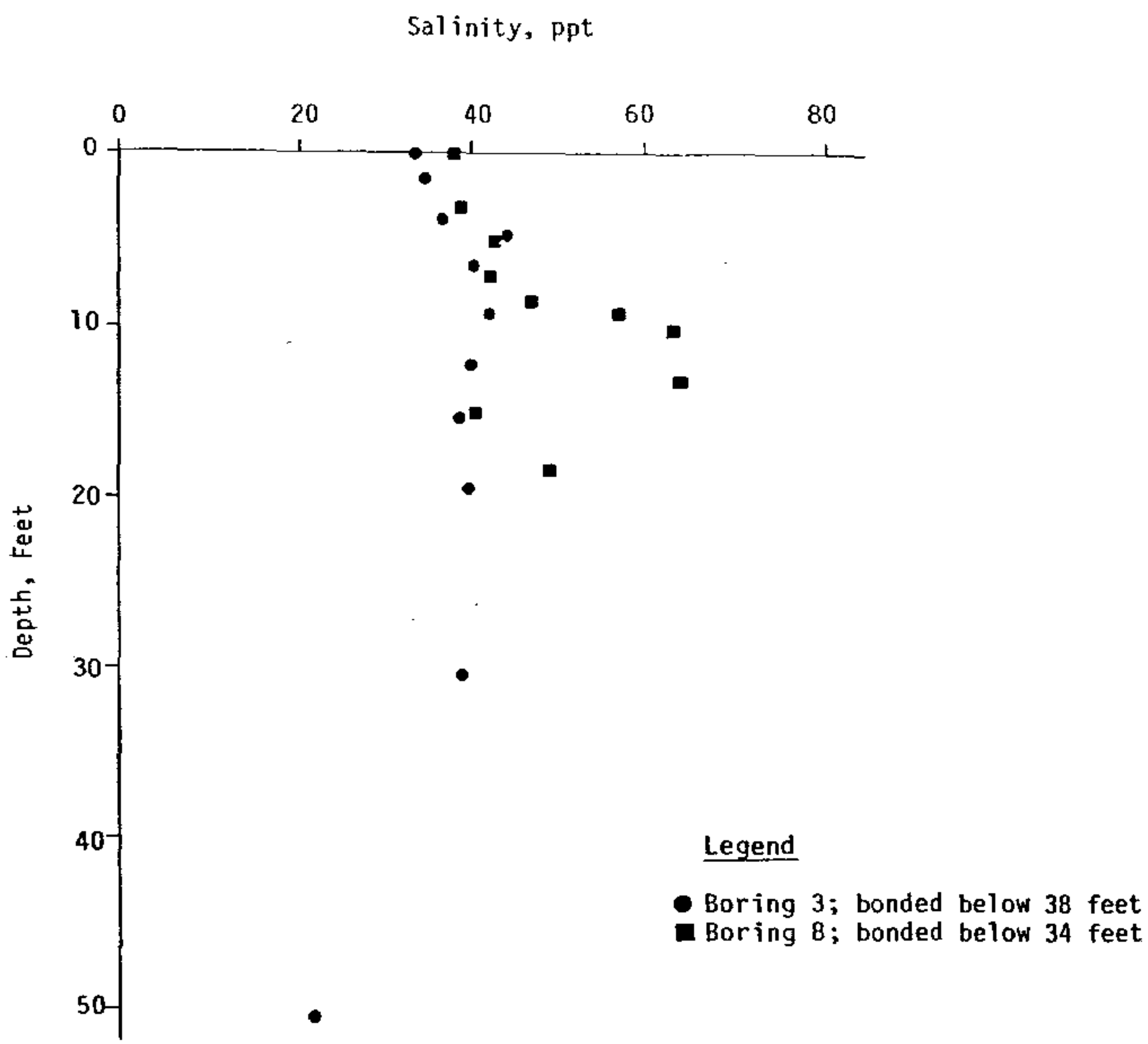
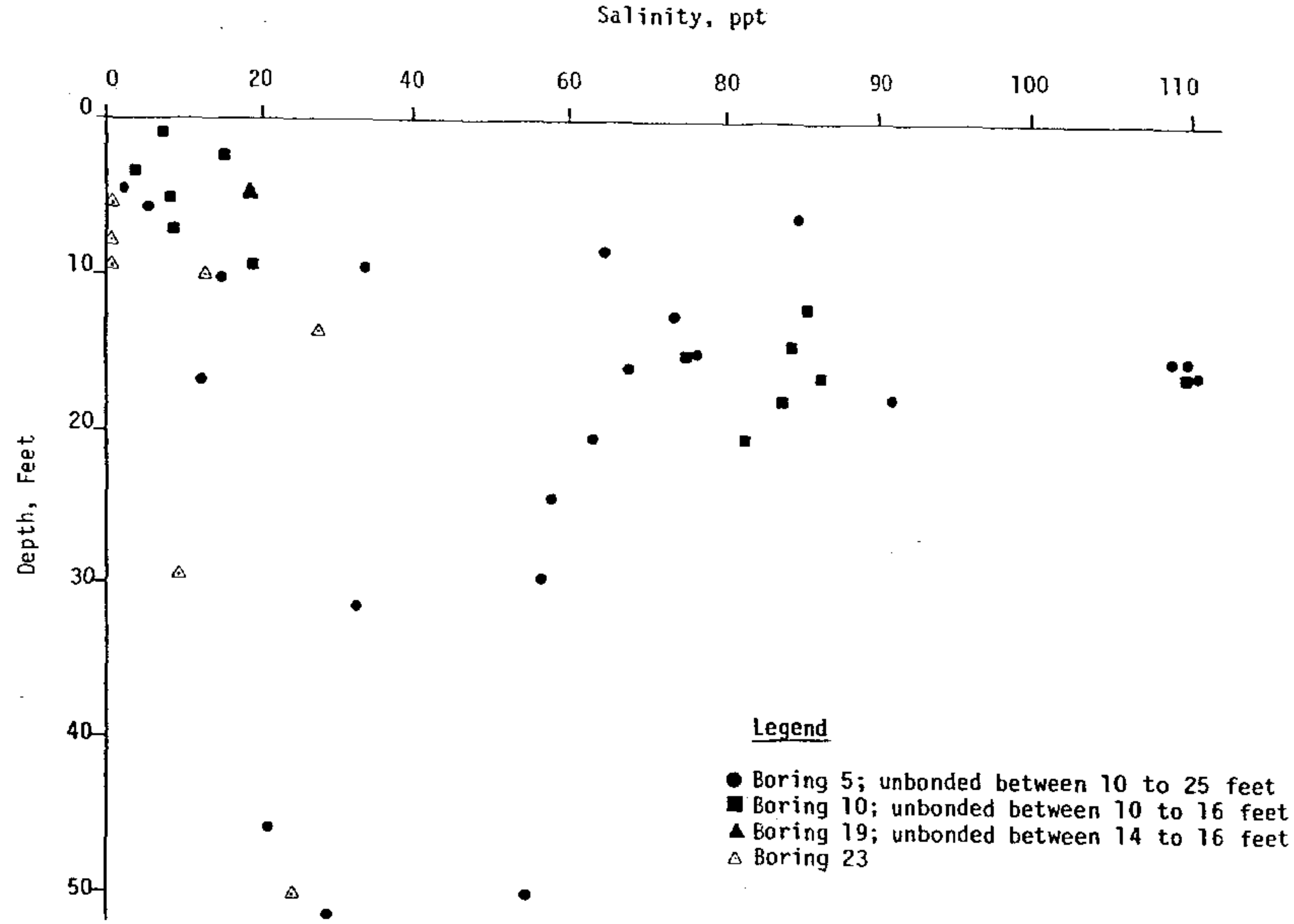


Beach



Barrier Islands

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Summary of Salinities,
Beach and Barrier Islands Borings
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PLATE **IV-15**

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in agreement with Franklin et al. (1973), where it was reported that when the organic content is less than about 20 percent, its effect is less important than that of minor mineralogical or structural differences. Therefore, it may be concluded that differences in the mineral constituents of the soils have a greater influence on their mechanical properties than does a small percentage of organics.

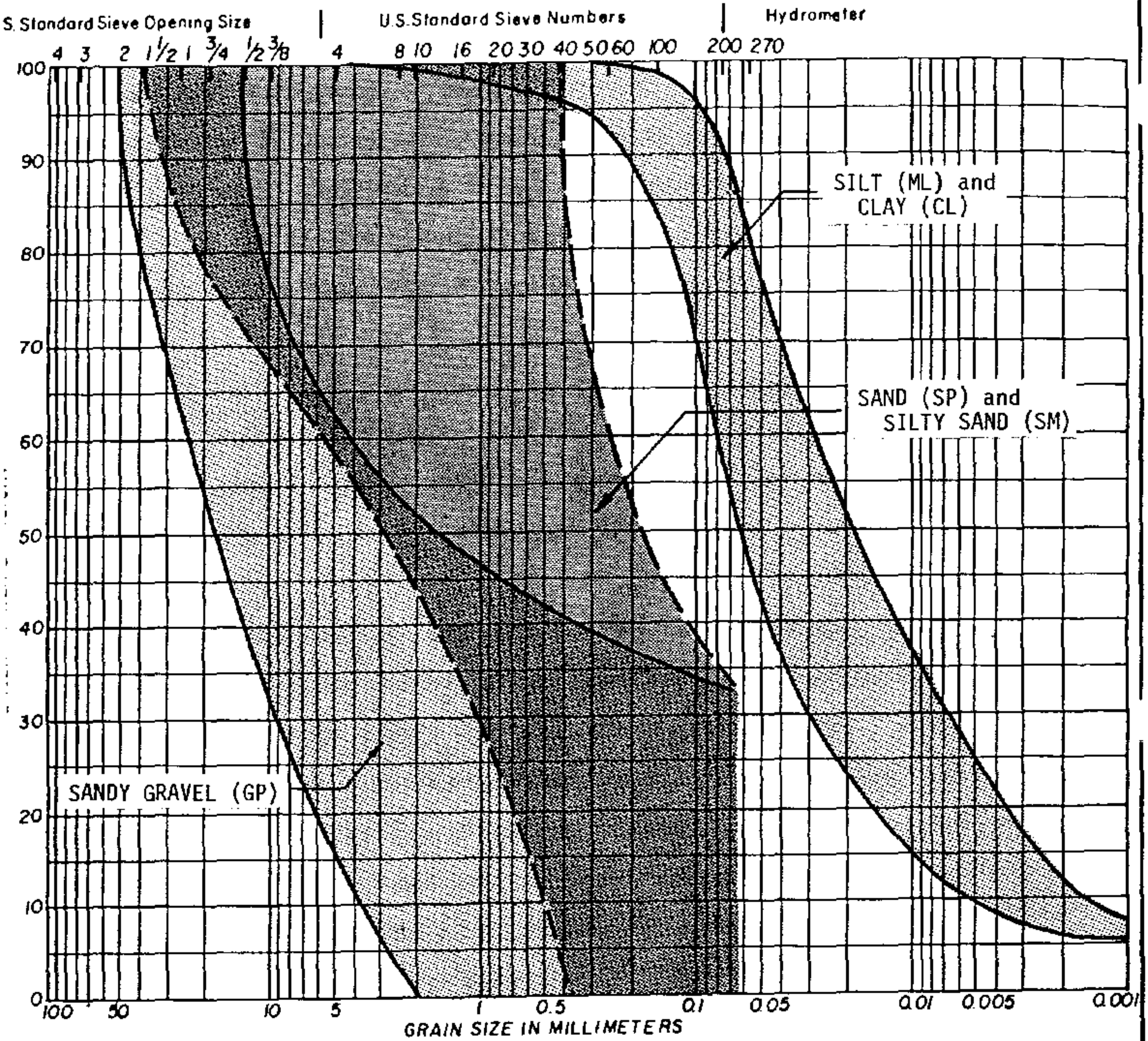
e. Particle Size Analysis

The quantitative distribution of particle sizes was determined by performing sieve and hydrometer tests on representative samples. Individual tests results are summarized on Plates D-44 through D-47 and graphically on Plate IV-16.

The gravels in the project area are generally less than 2 inches in diameter, and contain more than 15 percent sand and less than 37 percent silt. The sands that were tested have mostly coarse to medium size particles. Furthermore, these sands typically contain up to 40 percent gravel finer than 1-1/2 inches in diameter, and less than 35 percent silt. The silts and clays in the area exhibit a much narrower band of particle sizes than either the sands or gravels. All of the silts and clays that were tested contain between 6 to 40 percent fine sand particles.

f. Atterberg Limits

The Atterberg limits of the samples that were tested are summarized on Plate IV-17. The fine grained soils range from non-plastic to moderately plastic. The non-plastic specimens are sandy silts that were sampled at various depths throughout the lagoon area. The remaining samples are either silts or clays that are clustered around the A-Line. This clustering of silts and clays around the A-Line is also a common feature of the soils in this region.



BBLES	GRAVEL		SAND			SILT OR CLAY
	COARSE	FINE	COARSE	MEDIUM	FINE	

ymbol	Sample Source	Classification

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Summary of Particle Size Analyses

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PLATE **IV-16**

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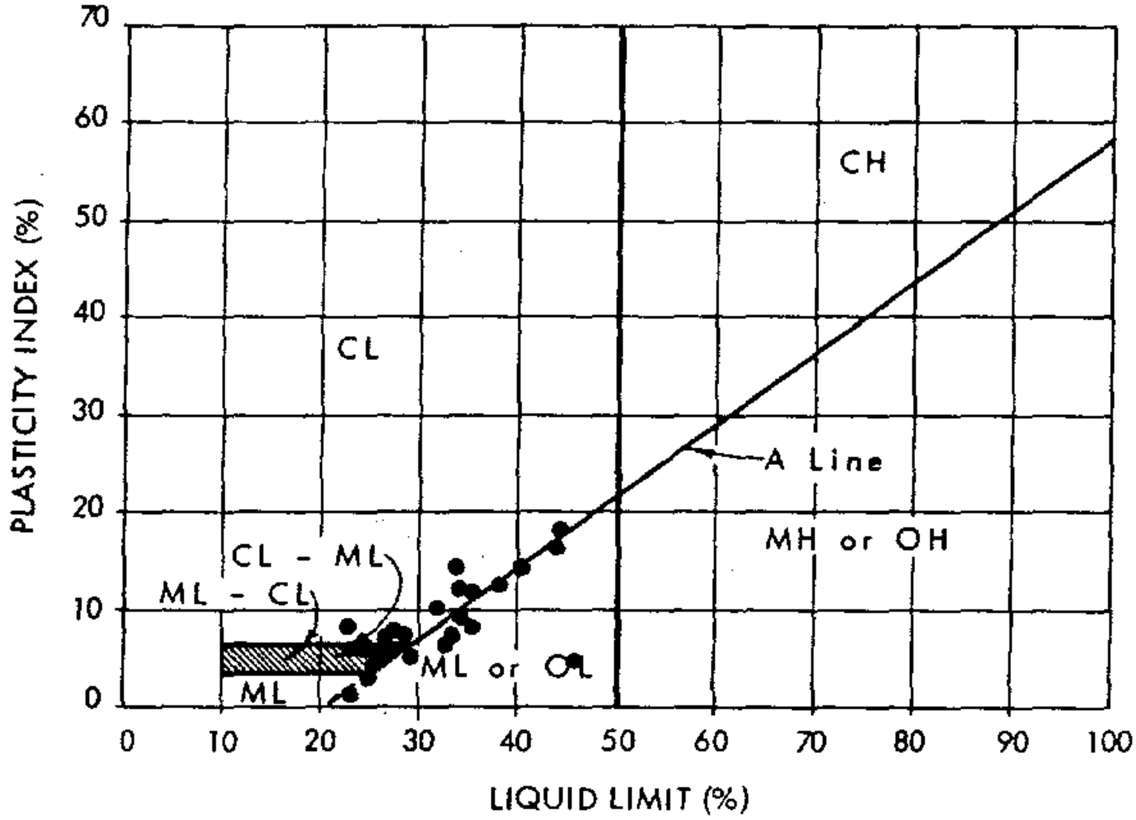

Classification	Number of Samples	Liquid Limit (%)		Plastic Limit (%)		Plasticity Index (%)	
		Average	Deviation	Average	Deviation	Average	Deviation
ML-OL	11	32	8	24	5	7	4
CL	10	33	6	22	3	11	4
CL-ML	5	25	2	20	2	6	1/2

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Summary of Plasticity Indices

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PLATE **IV-17**

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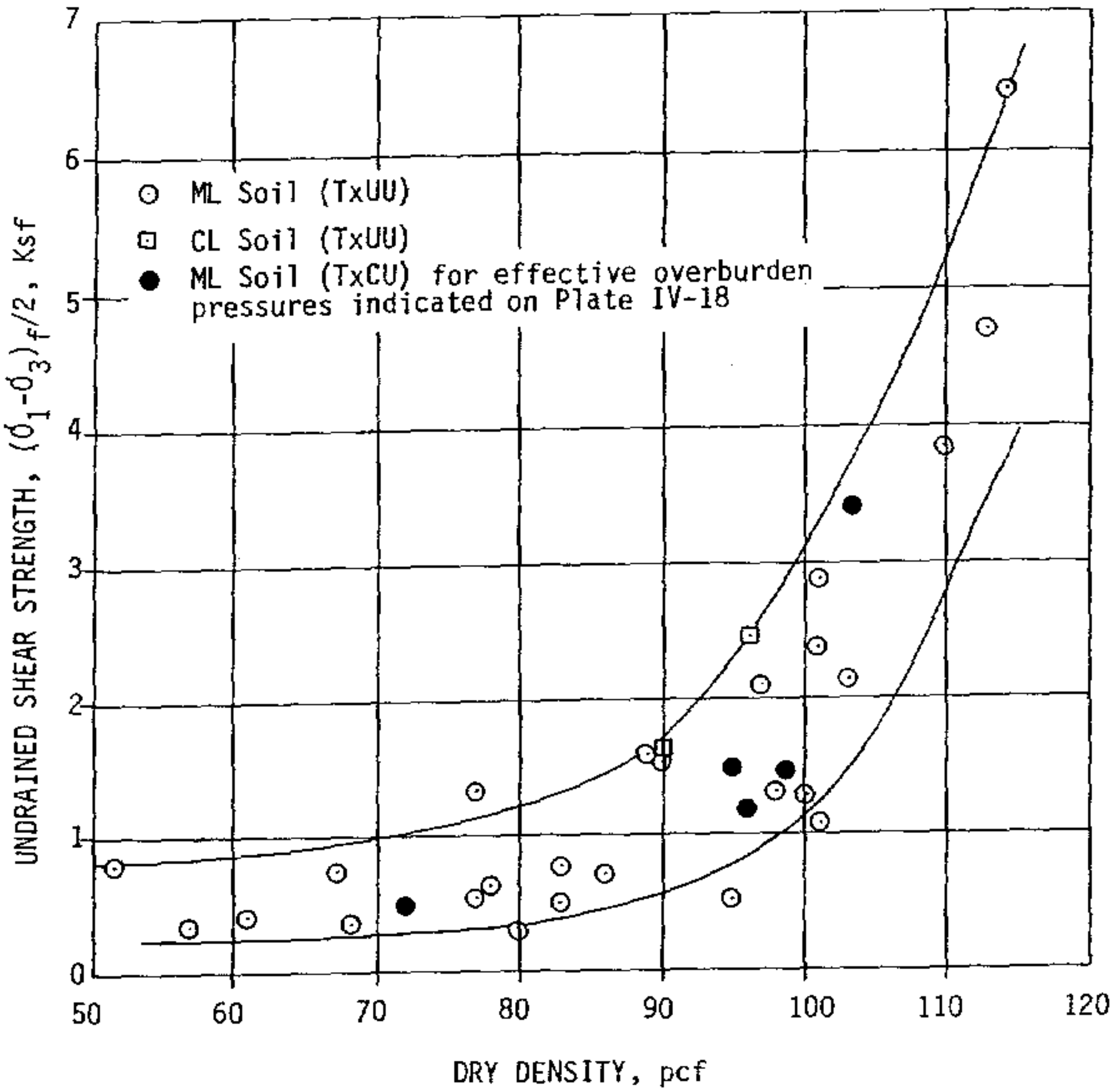
g. Shear Strength

The shear strength of unfrozen fine-grained soils is greatly dependent upon the pore water drainage conditions during loading. If drainage cannot occur, excess pore pressures develop and the undrained condition exists. This condition occurs where there has been a sudden change in the stress state of the soil, such as is common in short-term or end-of-construction situations. Conversely, when a load is applied sufficiently slowly so that the pore pressures can dissipate, drained tests can be used to evaluate the effective stresses. Pore pressures dissipate most rapidly in sand, followed by silt and clay, respectively.

Typically, the undrained shear strength of fine-grained, homogeneous soil correlates well with depth. However, during this investigation a meaningful correlation between the undrained shear strength versus depth could not be established due to the heterogeneous nature of the soil. Rather, the shear strength correlates very well with dry density, as is shown on Plate IV-18.(1) The undrained shear strength is also related to the effective consolidation pressure, σ'_{3c}. This relationship is shown on Plate IV-19. In general, the ratio of increase in shear strength to increase in σ'_{3c} is approximately 0.5 for the silts and clays. In addition, the soil is generally overconsolidated having an overconsolidation ratio (OCR) between 1 and 3.

(1) The dry density can be related to other soil properties such as the void ratio by applying standard soil mechanic fundamental definitions.



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Undrained Shear Strength vs Dry Density
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PLATE **IV-18**

DRAWN	JOB NUMBER	APPROVED	DATE	REVISED	DATE
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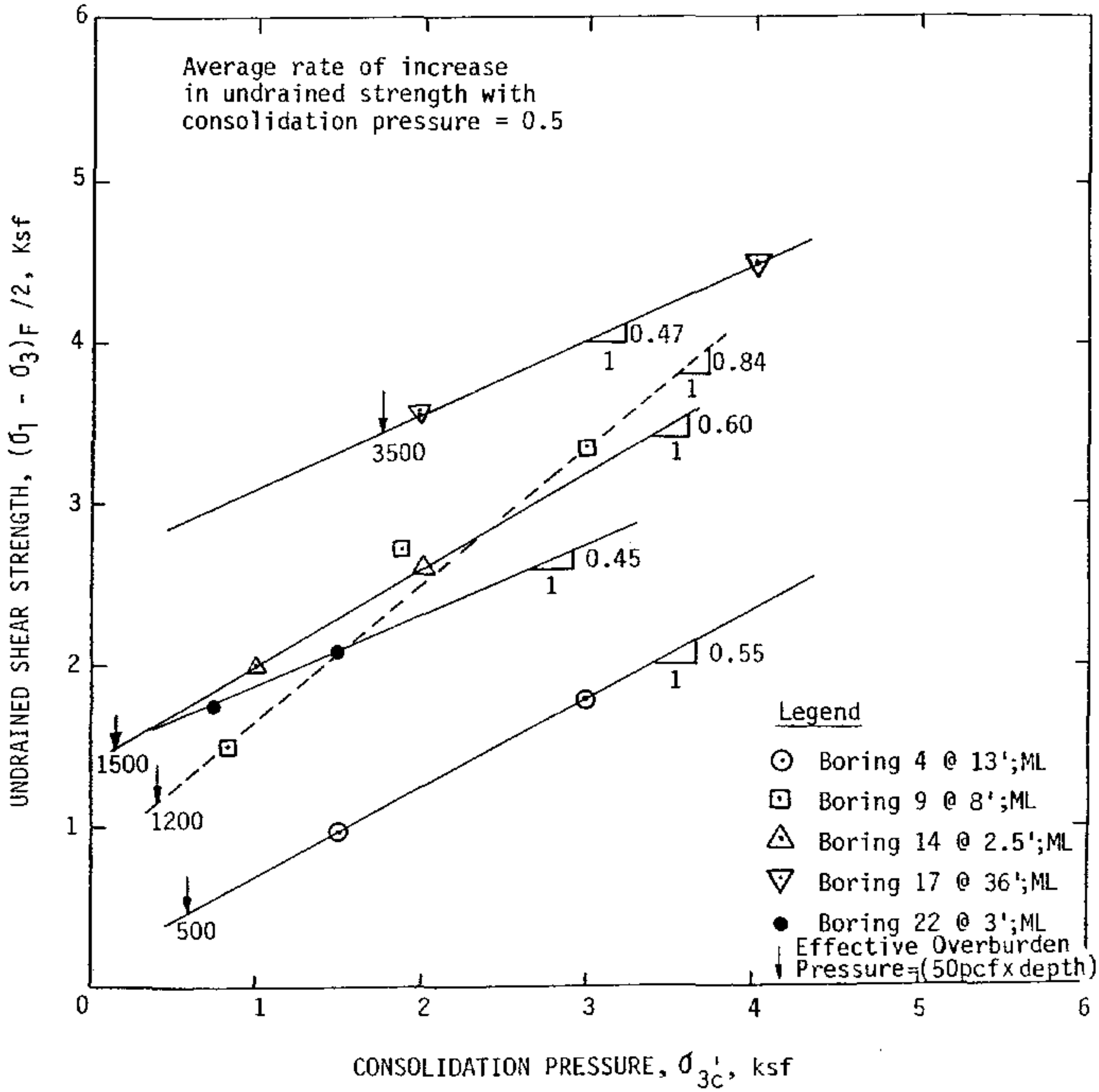

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Undrained Shear Strength vs Effective Consolidation Pressure

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PLATE **IV-19**

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Plate IV-20 shows the peak effective shear strengths that were measured for samples of sands, silts, and clays throughout the project area. Under effective stress conditions, all of these soil types behave as cohesionless soils with an effective angle of internal friction of 40^{o}, which is consistent with the values that have been reported for similar Beaufort Sea soils. (Exxon, 1981; Exxon, 1980).

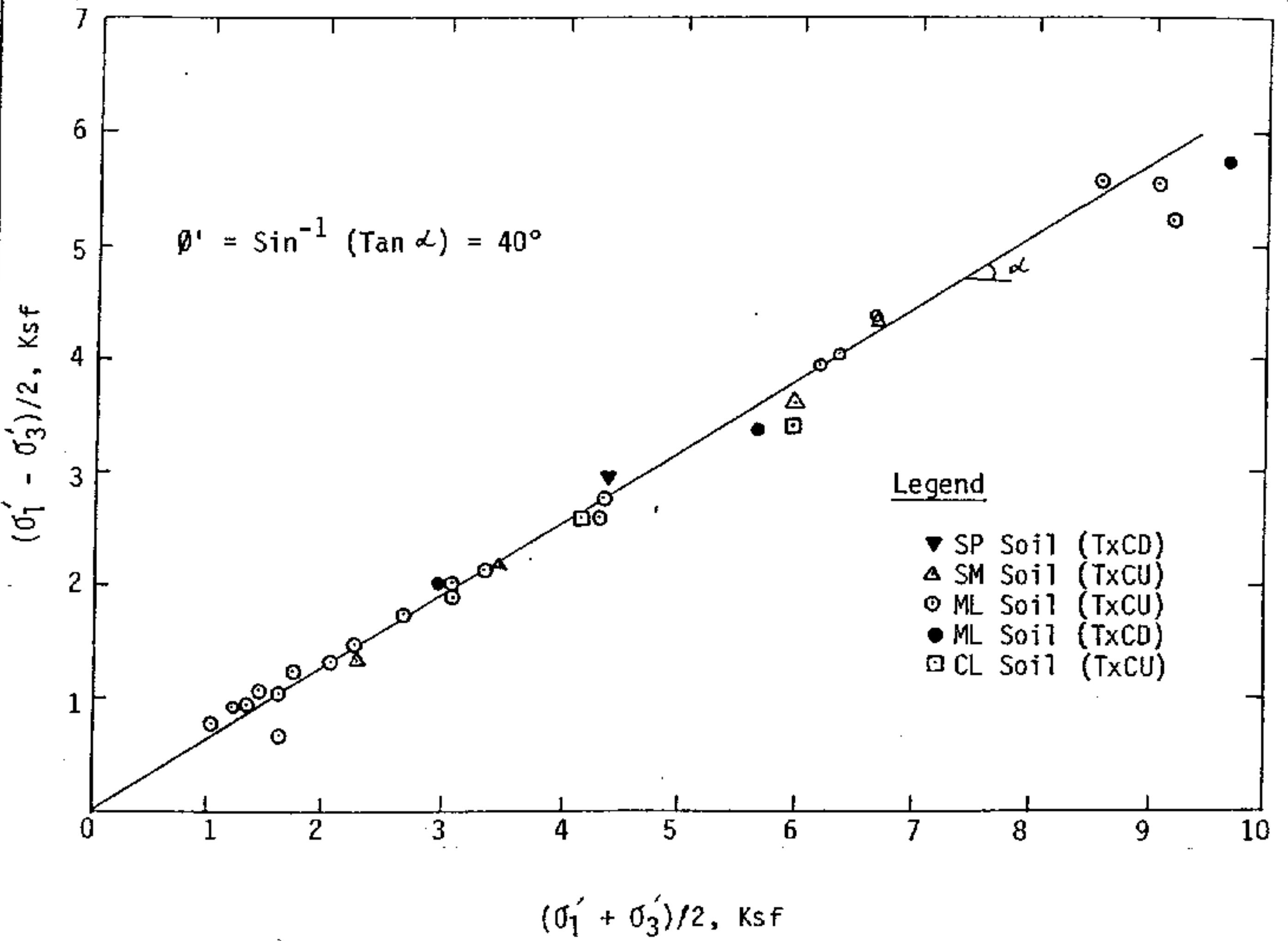
h. Compressibility

Consolidation tests were conducted on selected representative specimens. For each test, an average compression ratio was calculated, as described in Appendix D, for the range of expected design loads. Furthermore, recompression ratios were also calculated. These ratios are plotted versus dry density on Plate IV-21. From this plot, it is seen that the average compression ratio approaches the recompression ratio as dry density increases.

Plate IV-22 shows the relationship between the coefficient of consolidation and dry density for silts and clays. The two points that are typically shown for each dry density correspond to coefficients that were calculated for different consolidation pressures. In general, the soils in the Point Thomson area consolidate relatively quickly compared to similar Beaufort Sea sediments (Exxon, 1981; Exxon 1980).

2. Frozen

Ice-bonded permafrost was observed in all soil strata. The fine-grained soil contains visible ice that ranges in size from small crystals to layers of massive ice. The presence of ice has the effect of lowering the dry density of the frozen soils and increasing the distribution of moisture contents.



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Effective Shear Strength

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PLATE **IV-20**

DRAWN	JOB NUMBER	APPROVED	DATE	REVISED	DATE
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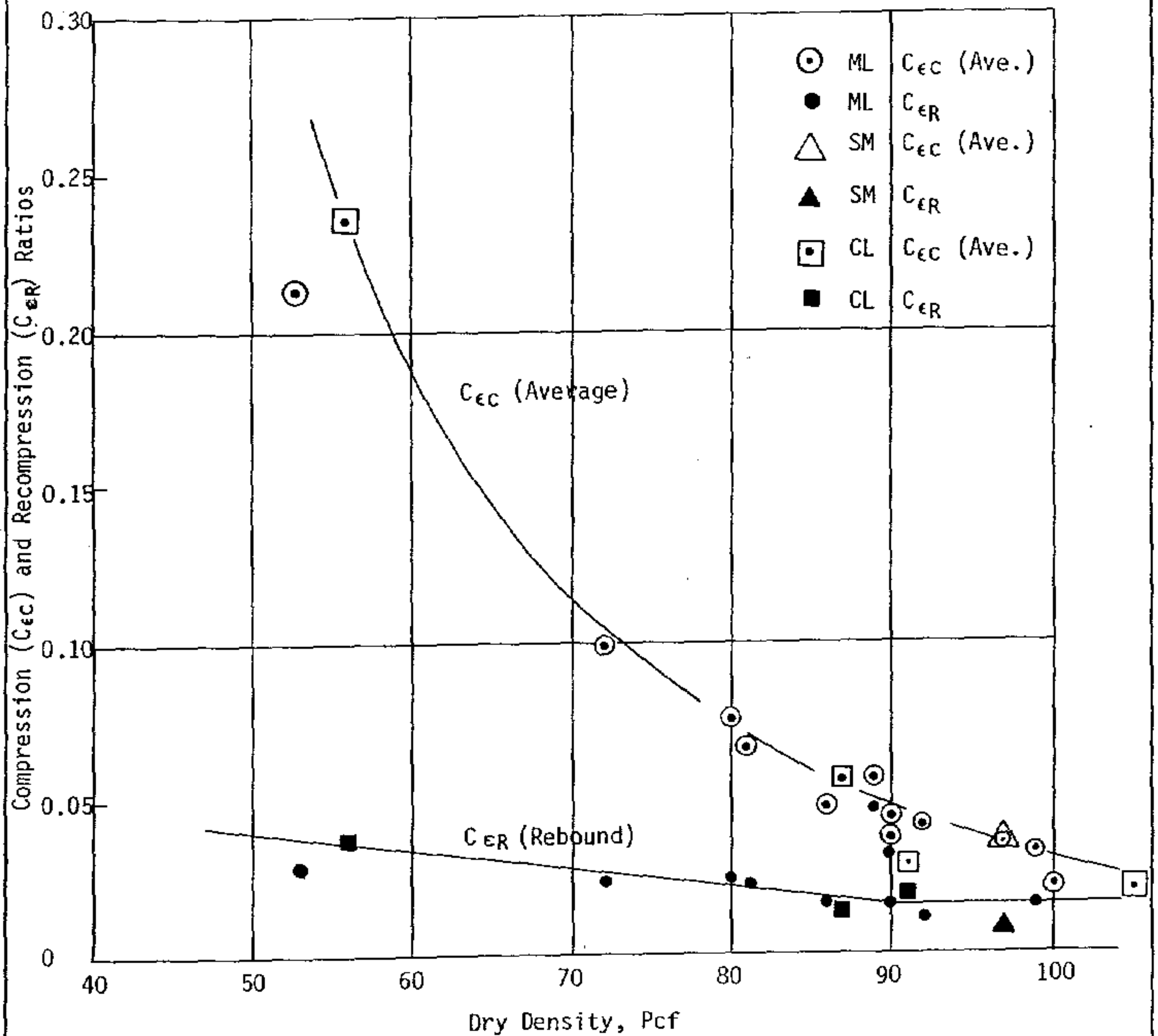

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Compression and Recompression Ratios vs Dry Density

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PLATE **IV-21**

DRAWN	JOB NUMBER	APPROVED	DATE	REVISED	DATE
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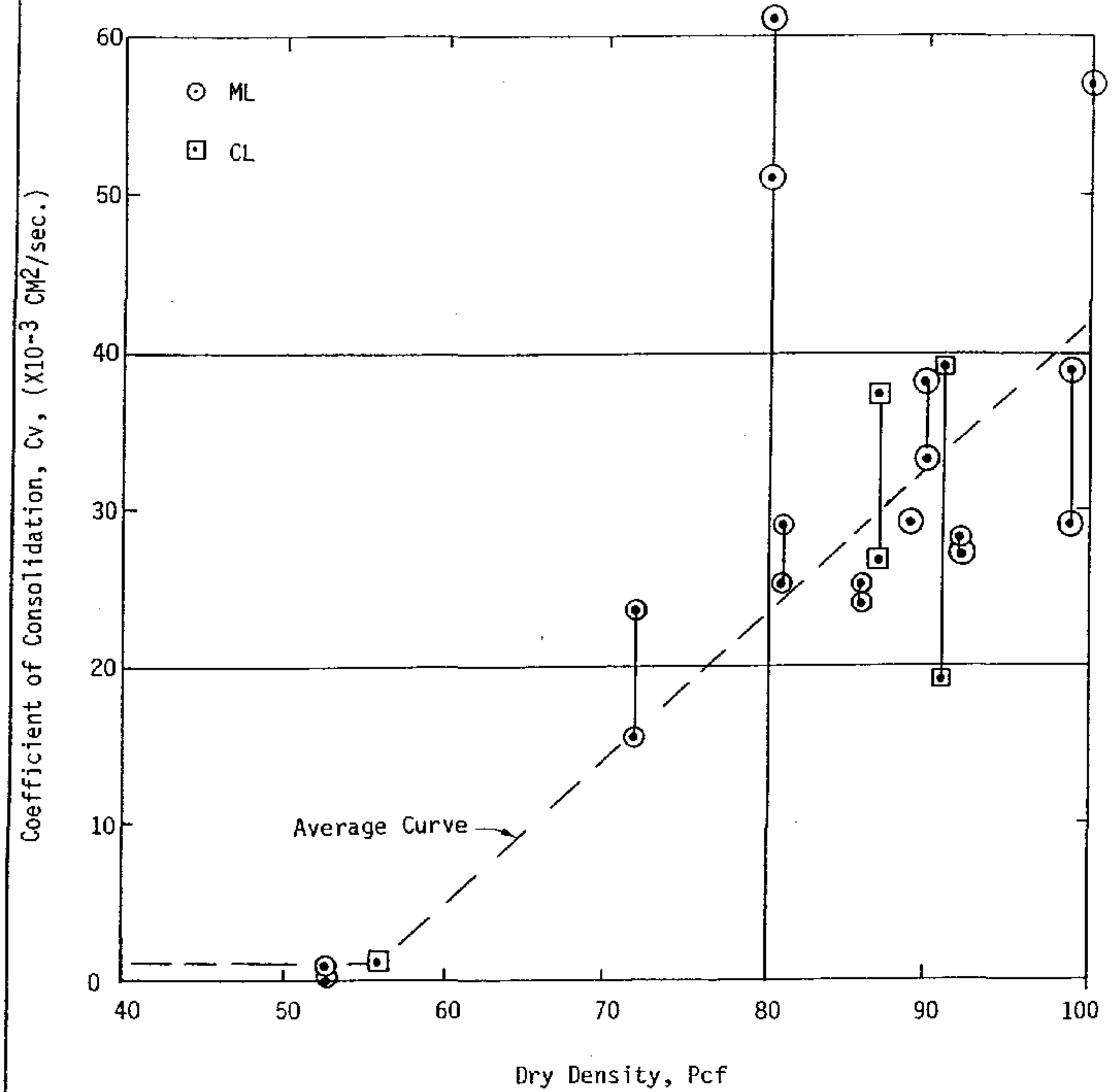

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Coefficient of Consolidation vs Dry Density

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PLATE **IV-22**

DRAWN	JOB NUMBER	APPROVED	DATE	REVISED	DATE
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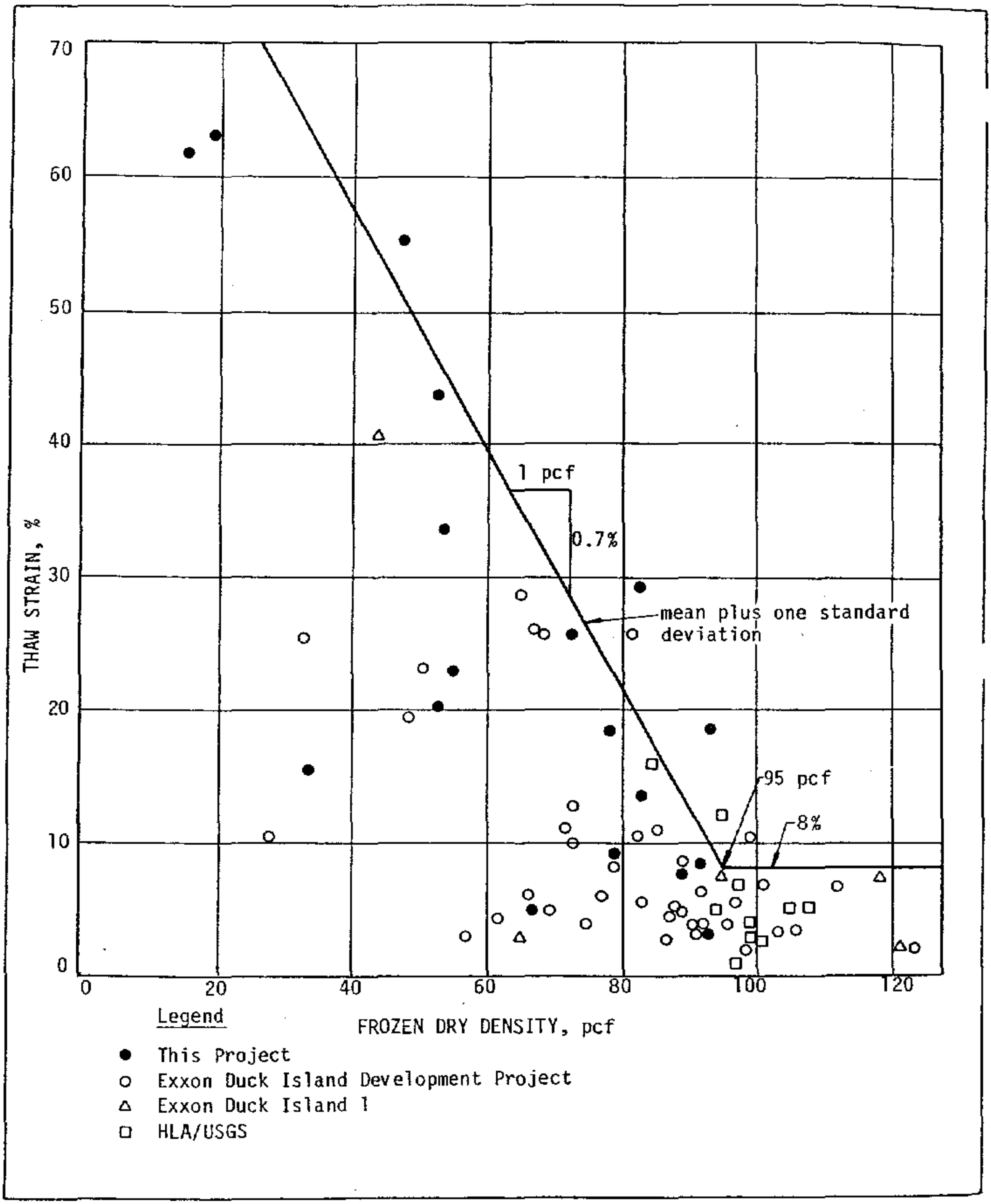
a. Thaw-Strain

Ice-bonded, fine-grained samples were tested for thaw consolidation in our laboratory. Test procedures are described and data presented in Appendix D. A summary plot of the results is presented on Plate IV-23 along with data from previous studies (Exxon, 1981a, c; HLA, 1979). The data from other studies, because of the similarity of soil types, are included to allow the development of a relationship between dry density and thaw-strain over the full range of dry densities anticipated. Despite the broad scatter on the plot, an envelope of points computed as the mean of strain values plus one standard deviation is considered a reasonable curve for design. This curve is consistent with other published data (Luscher and Afifi, 1973). Considering the average density of frozen, fine-grained soils as 85 pcf, an average thaw-strain of 15 percent should be expected. Variations in thaw-strain from 3 to 30 percent are indicated by the data. Based on experience with onshore permafrost, the variation in ice content and resulting thaw-strain can occur in the permafrost within distances as short as 10 to 50 feet.

When the frozen dry density is greater than approximately 95 pcf, the thaw-strain is generally less than 8 percent, with an average value of approximately 4.5 percent. As the frozen dry density decreases, the scatter becomes greater. The increase in thaw-strain is approximately 0.7 percent per pcf of decrease in dry density.

Suitable gravel samples were not obtained for thaw-strain tests for this study. The results of thaw-strain tests on gravel from previous studies are presented in Chapter V.



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Thaw Strain vs Frozen Dry Density

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PLATE **IV-23**

DRAWN	JOB NUMBER	APPROVED	DATE	REVISED	DATE
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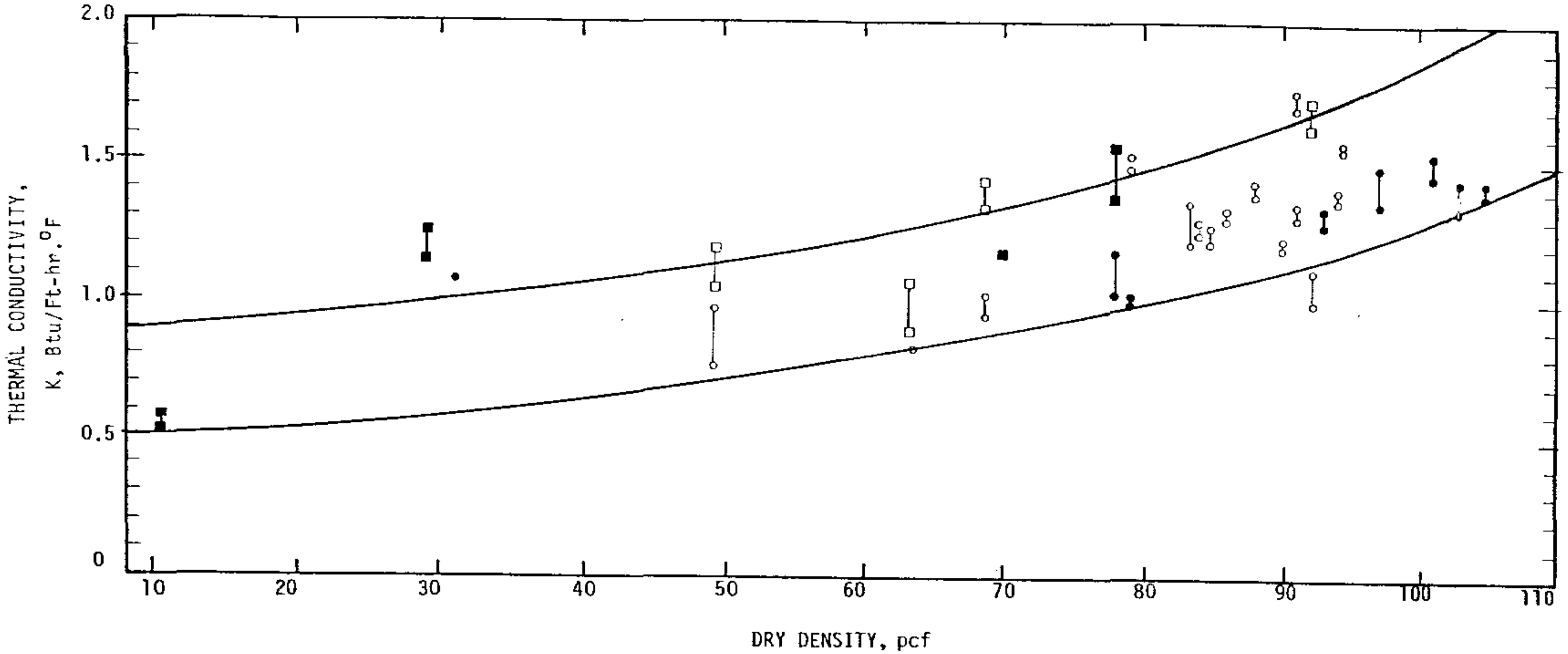
Since the offshore gravels are the same geologic unit as the onshore gravels (see Chapter III), they are expected to have similar properties. Luscher and Afifi show that gravels with dry densities in excess of 115 pcf will experience thaw-strains of two percent or less. As noted in Chapter V, information from onshore gravel studies shows that in-place ice contents are generally in the 5 to 15 percent range, with the exception of the C-1 material site, which had an average ice content of 25 percent. Moisture contents of 5 and 15 percent correspond to an in place dry density of 130 and 115 pcf, respectively. A thaw-strain value of two percent for in place sandy gravel is thus considered a conservative basis for design. For gravel material such as that encountered in the C-1 material site, a thaw-strain value of 15 percent for in place gravel is recommended for design.

b. Thermal Conductivity

The variation of thermal conductivity with dry density, as determined in our laboratory investigation is summarized on Plate D-48 and plotted on Plate IV-24 along with data from the DID study (Exxon, 1981). The data from the DID Study were included because of the similarity of soil types and to assess the development of a relationship between dry density and thermal conductivity. Furthermore, it is seen that thermal conductivity increases with increasing dry density for both frozen and thawed soil.

In general, the thermal conductivity of a soil is a function of its soil texture. At a given dry density and moisture content, the thermal conductivity of coarse-grained soils, such as sands and gravels, tends to be higher than that for fine-grained soils, such as silts and clays. This is in agreement with our test results. Samples of sandy soils tended to have higher



Legend

This Project:

Thawed Test
Frozen Test

Duck Island Development Project:

Thawed Test
Frozen Test

Note: The two dots represent the two runs that were performed for each test.

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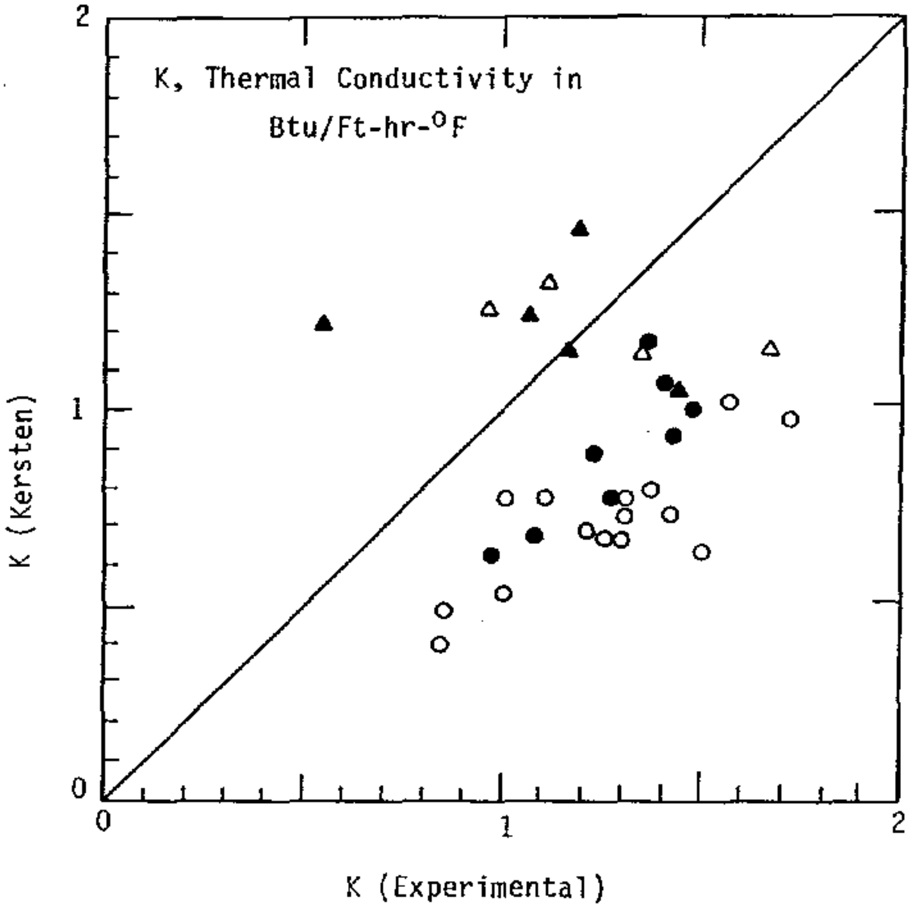
Variation of Thermal Conductivity and Dry Density
Pt. Thomson Development Project, Winter 1982, Geotechnical Study, EXXON Company, U.S.A.

PLATE IV-24

DRAWN	JOB NUMBER	APPROVED	DATE	REVISED	DATE
	9612,031.08		4/82		



Legend

This Project:

- ● Thawed Samples
- ▲ Frozen Samples

Duck Island Development:

- ○ Thawed Samples
- △ Frozen Samples

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Comparison of Thermal Conductivity Values

Pt. Thomson Development Project, Winter 1982
Geotechnical Study, EXXON Company, U.S.A.

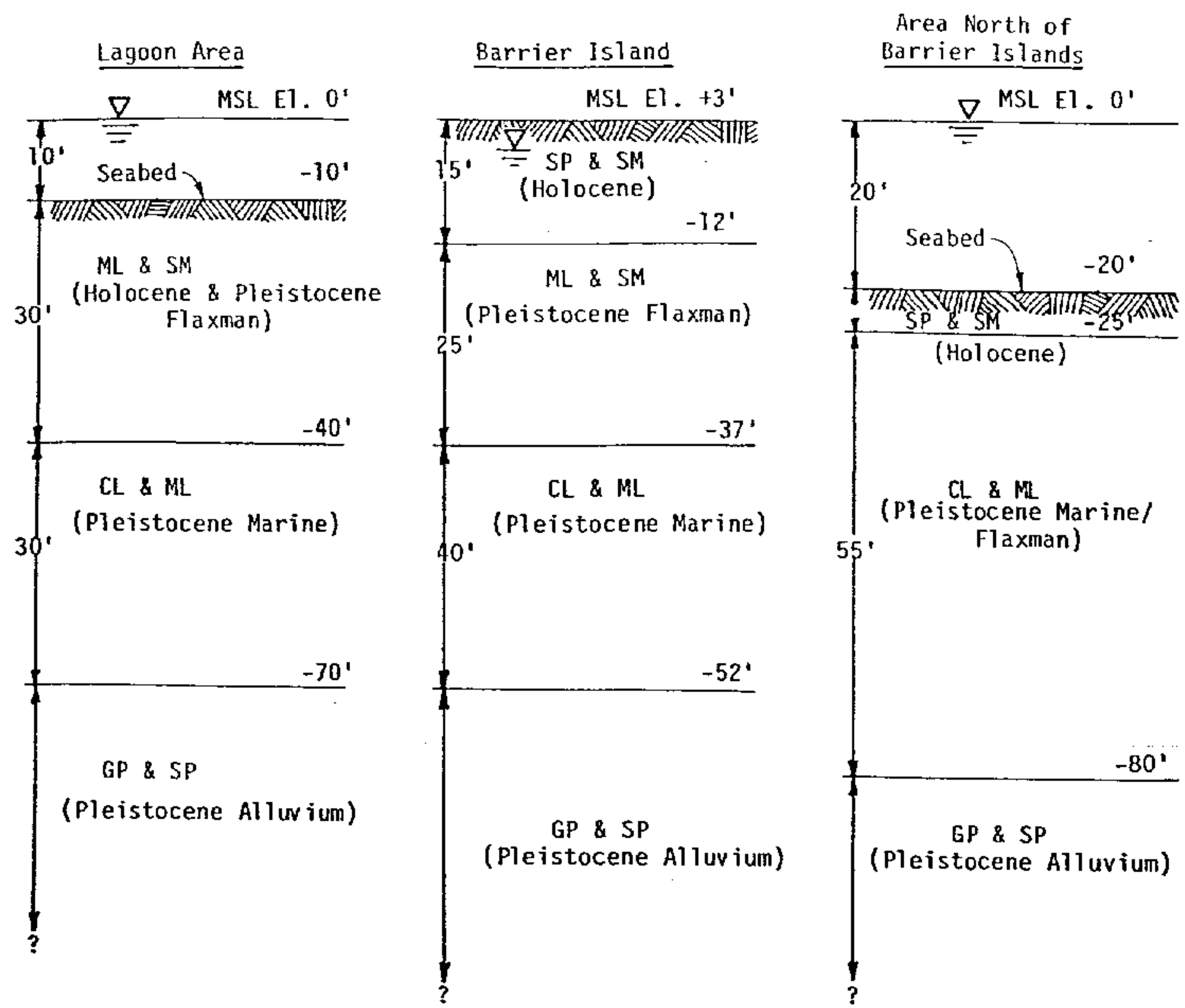
PLATE IV-25

DRAWN	JOB NUMBER	APPROVED	DATE	REVISED	DATE
DCR	9612,031.08	DEB	4/82		

thermal conductivities than those of fine-grained soils, while highly organic material had the lowest values. Without specific thermal conductivity test data, the thermal conductivity of soil is generally determined using dry density or moisture content-thermal conductivity relationships developed from Kersten's work (Kersten, 1949). On Plate IV-25, thermal conductivity data from this and the DID study are plotted against the data reported by Kersten (1949). It is seen that the thermal conductivities of thawed soils in the Point Thomson area are greater than those predicted by Kersten. These results also agree well with those presented for the DID project.

3. Recommended Design Parameters

The recommended typical geotechnical parameters for offshore soils are summarized on Plate IV-26 along with the three generalized soil profiles that were used in our design analysis. Onshore soil conditions have been defined in Section A of this chapter. Frozen soil design parameters are presented in those sections which discuss the design of structures using onshore materials. Where indicated, data from this study were supplemented with test data from other studies to develop the recommended design parameters for soil properties where tests were not conducted or where it was determined that data from other studies were suitable for this project and would allow development of more representative design parameters.



TYPICAL SOIL PROFILES AND LAYER THICKNESSES

Typical Soil Properties / Soil Type	SP & SM Soil	ML & SM Soil	CL & ML Soil	GP & SP Soil
Index Properties				
Specific Gravity	2.69(0.01)[1]	2.70(0.02)	2.75(0.03)	2.69(0.03)
Moisture Content, %	24(9.1)	32(12.3)	25(6.2)	10(8.8)
Void Ratio	0.70(0.11)	1.07[2]	0.65(0.09)	0.30***
Dry Density, pcf	100(10)	80(13)	100(6)	130***
Buoyant Unit Weight, pcf	60	50	60	80
Atterberg Limits				
Liquid Limit, %	--	31(10)	32(7)	--
Plastic Limit, %	--	23(3)	22(8)	--
Shear Strength Parameters				
S_u, Ksf	NA	$0.5+0.5\Delta\bar{P}$[3]	$2.0+0.5\Delta\bar{P}$	NA
$\emptyset'$, degrees	40	40	35	40
C', Ksf	0	0	0	0
Consolidation Parameters[4]				
Average Compression Ratio	0.03	0.075	0.03	0.015
Coefficient of Consolidation (cm^2/sec)	NA	0.023	0.042	NA
Coefficient of Secondary Consolidation	NA	0.009	0.009	NA
Thermal Conductivity				
Frozen (BTU/ft-hr-°F)	1.8*	1.5**	1.4**	2.4*
Thawed (BTU/ft-hr-°F)	1.1*	1.3**	1.4**	1.8*
Thawed Settlement Parameters				
Frozen Dry Density, pcf	81(14)	93(13)	97(8)	120***
Thaw Strain, %	15(10)	13(10)	7(4)	2***

1. Parenthesis denotes standard deviation
2. Maximum = 1.933; Minimum = 0.382
3. $\Delta\bar{P}$ = External load at surface expressed in pounds per square foot (psf)
4. Parameters determined using Plates IV-20 and IV-21 for thawed dry density values listed above.

* Kersten Values
** Average of data from this study and Duck Island Development Project, 1981
*** As reported in Duck Island Development Project, 1981

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Recommended Geotechnical Design Parameters
Pt. Thomson Development Project, Winter 1982
Geotechnical Study, EXXON Company, U.S.A.

PLATE **IV-26**

DRAWN	JOB NUMBER	APPROVED	DATE	REVISED	DATE
JP.	9612,031.08		4/82		