UNITED STATES DEPARTMENT OF THE INTERIOR

Environmental Geology of Harrison Bay, Northern Alaska

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Open-File Report 82-35

CONTENTS

ILLUSTRATIONS

ABSTRACT

The surficial and shallow subsurface geology of Harrison Bay on the Beaufort Sea coast was mapped as part of the U.S. Geological Survey's prelease evaluation for Outer Continental Shelf (OCS) Oil and Gas Lease Sale 71. During the 1980 summer season, approximately 1600 km of mulisensored, high-resolution geophysical profile data were collected along a rectangular grid with 4.8 km line spacing. Interpretation of these data is presented on five maps showing bathymetry, sea-floor microrelief, ice-gouge characteristics, Holocene sediment thickness, and geologic structure to depths of approximately 1000 m.

On a broad scale, the seafloor is shallow and almost flat, although microrelief features produced by sediment transport and ice-gouge processes typically vary up to several meters in amplitude. Microrelief bedforms related to hydraulic processes are predominant in water depths less than 12 m. Microrelief caused by ice gouging generally increases with water depth, reaching a maximum of 2 m or more in water depths beyond the 20 m isobath. This intensely gouged area lies beneath the shear zone between the seasonal landfast ice and the mobile polar ice pack.

The thickness of recent (Holocene) sediment increases offshore, from 2 m near the Colville River delta to 30 m or more on the outer shelf. The thin Holocene layer is underlain by a complex horizon interpreted to be the upper surface of a Pleistocene deposit similar in composition to the present Arctic Coastal Plain. The base of the inferred Pleistocene section is interpreted to be a low-angle unconformity 100 m below sea level. Beneath this Tertiary-Quaternary unconformity, strata are interpreted to be alluvial fan-delta plain deposits corresponding to the Colville Group and younger formations of Late Cretaceous to Tertiary age. Numerous high-angle faults downthrown to the north trend across the survey area. With few exceptions, these faults terminate at or below the 100 m unconformity, suggesting that most tectonism occurred before Quaternary time. Acoustic anomalies suggesting gas accumulation are rare, and where identified typically occur adjacent to faults. A laterally continuous zone of poor seismic data occurs in the nearshore area and is interpreted to be caused by subsea permafrost. This report describes these geologic conditions in Harrison Bay and discusses potential hazards that they may pose for future oil and gas operations in Sale 71 and adjacent Beaufort Sea shelf areas.

INTRODUCTION

Purpose of Study

Harrison Bay is located on Alaska's Beaufort Sea coast, about 100 km west of Prudhoe Bay. Harrison Bay and adjacent offshore areas have been tentatively selected for inclusion in proposed Oil and Gas Lease Sale 71 (Figure 1). In order to identify geologic features or conditions that might prove hazardous to petroleum exploration and development, the U.S. Geological Survey (USGS) contracted with Western Geophysical Company to acquire and process high-resolution geophysical data within the proposed sale area. This survey collected tract-specific data over about 40% of the Sale 71 area. Poor weather and sea-ice conditions prevented data collection over the remaining tracts.

This study was designed to contribute to an understanding of the surficial geology of the seafloor as well as the structure and stratigraphy in the shallow geologic section. It is our hope that both the private and the public sectors will find this information useful when planning for offshore development in the Sale 71 area. Copies of the data, base maps, and digital navigation tapes can be obtained from the National Geophysical and Solar-Terrestrial Data Center (address: NOAA/NGSDG, Code D-621, Boulder, Colorado 80303). Inquiries should refer to OCS Sale 71, data set identifier AK 19181.

Data Acquisition

From July 20 to September 22, 1980, approximately 1600 km of profile data were collected from the vessel MV Arctic Sun. Marine high-resolution seismic operations require both open water and a relatively calm sea state. The ship's course and speed must be maintained along preplotted lines to allow successful common-depth-point (CDP) processing of digital seismic data. During the 1980 field season, survey operations were constrained by both poor visibility because of fog and frequent incursions of the offshore ice pack. In September, when poor visibility conditions and ice pack incursions were less frequent, seawater temperatures below 0°C caused a persistent malfunction of the water gun seismic source. High sea states, which increase background noise and cause degradation of record quality, were also more frequent later in the field season.

A suite of instruments was deployed for this high-resolution geophysical survey, each instrument had a different resolution and sea-floor penetration depth. Figure 2 is a diagram of the equipment and deployment scheme for this survey. The analog geophysical instruments

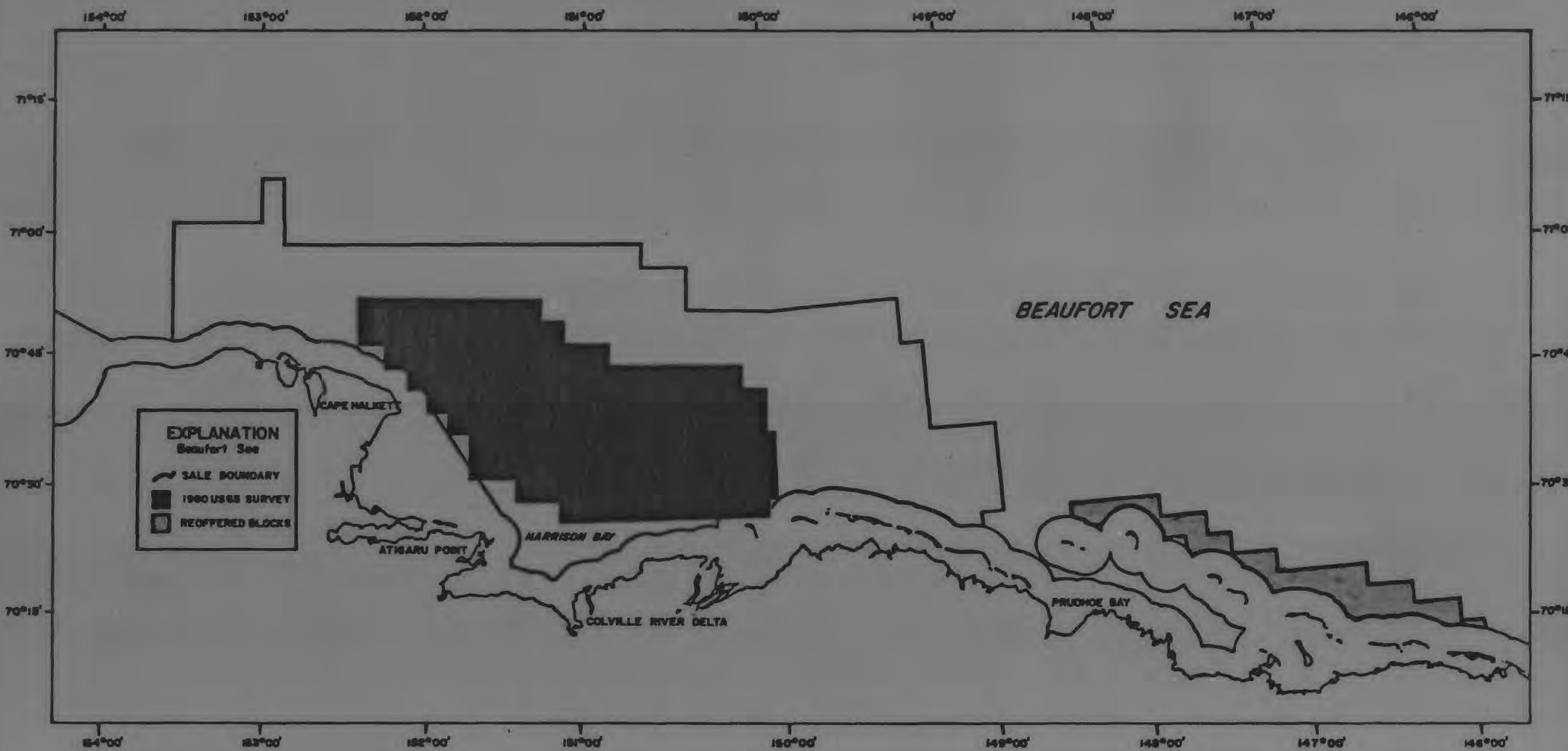


FIGURE 1.--SURVEY AREA IN RELATION TO TENTATIVE BOUNDARY OF SALE 71.

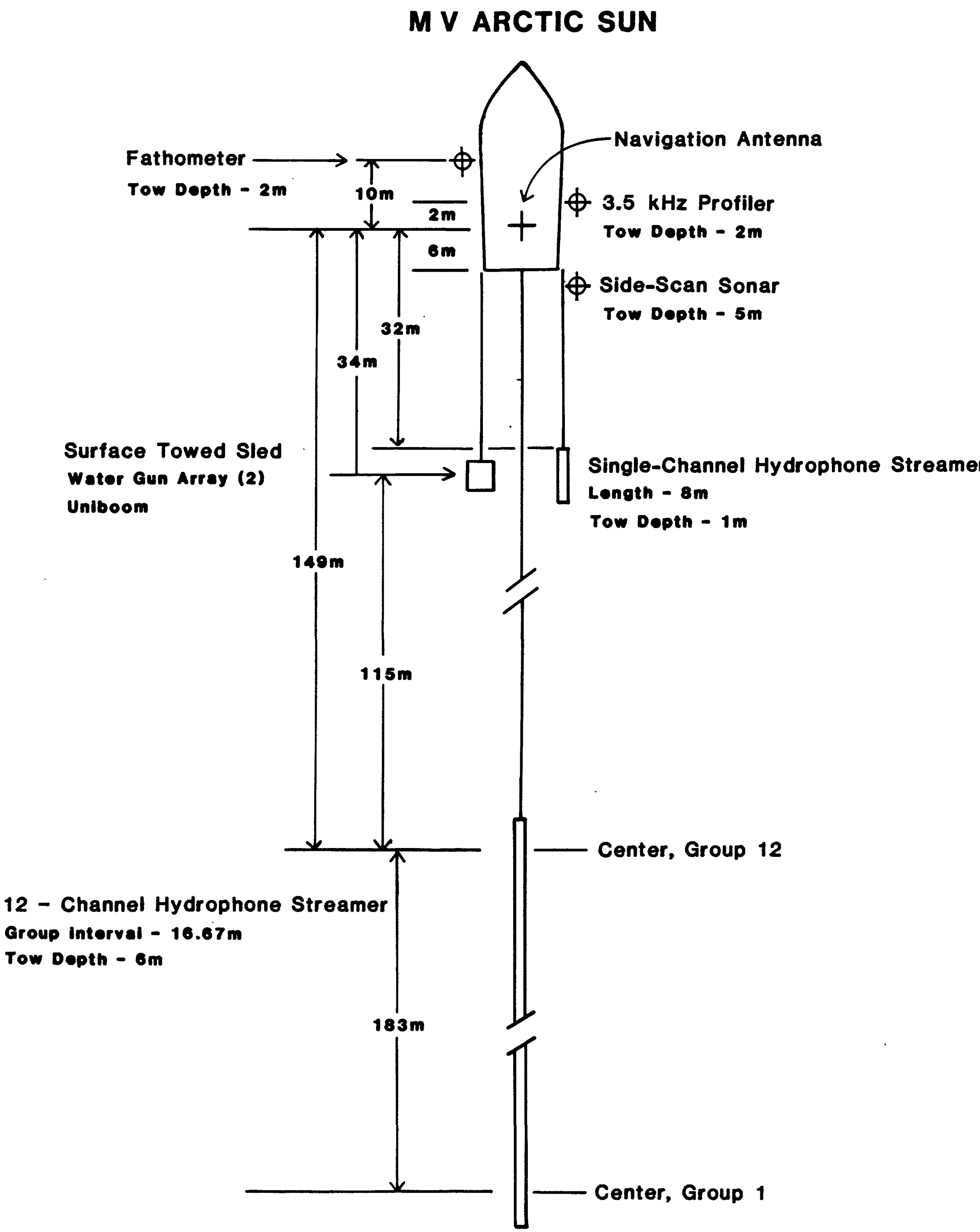


Figure 2.—Instrument Deployment

included a high-frequency (40-kHz) fathometer, a side-scan sonar, a 3.5-kHz subbottom profiler, and an electro-mechanical subbottom profiler (Uniboom). The multichannel seismic system consisted of two 15-cubic-inch water guns as the sound source, a 12-channel hydrophone streamer, and a digital recording system. The analog data were displayed on 19-inch, dry-paper recorders, with sweep scales ranging from 0.125 s (fathometer records) to 0.5 s (near-trace of seismic data). The side-scan sonar records show a planimetric view of the seafloor for about 200 m on either side of the ship's track. The vertical resolution of the analog systems, set both by instrument frequency and recorder scale, is as follows: fathometer, 0.2 m; side-scan sonar, 2 to 4 m; 3.5-kHz profiler, 1.0 m; uniboom, 2.0 m; and digital seismic system, 10 m. All instruments produced acceptable records except for the Uniboom profiler. Poor data quality from this instrument could have been caused by its towing characteristics or high power output (800 joules) for the shallow water and hard bottom of the survey area.

Navigation control was an important consideration for this tract-specific survey. The ship was required to maintain course within 30 m of preplotted fix points at 300-m intervals. The primary navigation system was an ARGO DM-54, with three shore-based transponder stations located on bench marks. A Motorola Mini-Ranger III system with four shore stations was used as the secondary navigation system to calibrate the ARGO, for lane count verification, and as a back-up. These systems have a field accuracy of about ± 5 m and worked well throughout the survey which was conducted 5 to 60 km offshore.

SURFICIAL GEOLOGY

The analysis and interpretation of fathometer and side-scan sonar records is presented on a series of maps (Plates 1, 2, and 3) illustrating surficial sea-floor features. When viewed on a regional scale, the seafloor is smooth and almost flat, with a gentle slope of only 3 m in 10 km (0.02°) to the north. On a local scale, however, the seafloor is very irregular, with microrelief commonly of a meter or more produced by sedimentary processes and the grounding of ice floes. In shallow water (less than 12 m) hydraulic bedforms are predominant, while in deeper water, ice gouges are the predominant microrelief features. The maps are used to evaluate active geologic processes which affect the seabed at present. These processes are potential hazards and could cause erosion and damage of pipelines, scour and subsequent failure of platform moorings, scour or deposition around subsea completion systems, and erosion of artificial island slopes.

Bathymetry

The bathymetric map (Plate 1) was constructed by manually digitizing and contouring profile data produced by the fathometer system. Water depths were posted at significant changes in depth or at 1.5-km intervals in featureless areas. Because most of the area is covered by irregular microrelief, water depths were picked along a hypothetically smoothed sea-floor surface, and only broad-scale features are shown on the bathymetry map. Water depths were converted from acoustic travel time using an assumed sea-water velocity of 1500 m/s. In this shallow water setting, slight variations of acoustic velocity in seawater will have an insignificant effect on the depth calculation. Tidal corrections were also considered to be insignificant because the tidal range in this area of the Beaufort Sea is usually less than 0.2 m. The vertical datum is mean sea level. A correction was applied to account for the fathometer tow depth of 2 m. The internal consistency of the data was checked by comparing the depth picks at track-line intersections. At 136 line intersections a mean precision of 0.29 m was computed, indicating that our hypothetical smoothing accurately defines broad-scale bathymetric relief. Periodic calibration of the fathometer by wireline measurements at sea indicated an instrumental inaccuracy of 1% or less throughout the survey.

Several bathymetric features are anomalous to the gently sloping shelf in Harrison Bay. A distinctive shoal rises from depths of about 20 m in the northern part of the survey area. This feature, and other similar "stamukhi shoals," have been mapped previously by Reimnitz and others (1978). Their studies indicate that these shoals may be formed by intense plowing of the seafloor by deep-keeled ice ridges at the shoreward margin of the shear zone. The shear zone forms each winter between the seasonal landfast ice sheet and the mobile polar ice pack.

Another curious feature, also previously recognized by Barnes and Reimnitz (1974), is a broad terrace between 17- and 19-m depths in central Harrison Bay. The origin of this feature is uncertain, although its location in the lee of the stamukhi shoal suggests these features may be related.

Sea-floor Microrelief and Processes

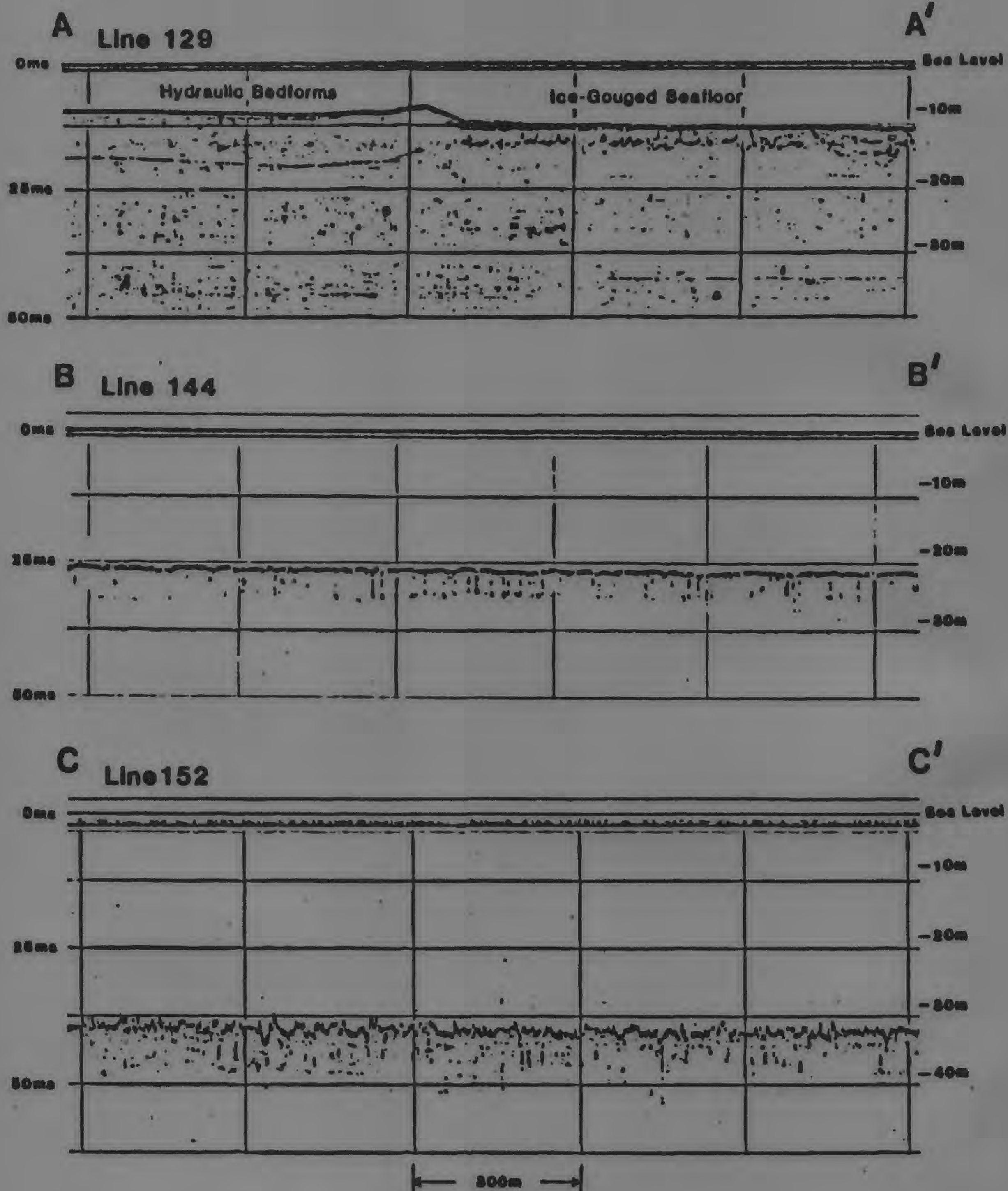
The distribution of microrelief features, shown on Plate 2, is an indication of the intensity of recent geologic processes that shape the seafloor in Harrison Bay. By analyzing both fathometer and side-scan sonar records, we were able to differentiate microrelief into two basic types: bedforms produced by the hydraulic action of oceanic currents, and gouges produced by the action of grounding ice. These microrelief features cannot be mapped individually at the map scale of 1:250,000 or traced between survey lines spaced at 4.8 km. To construct this map, the maximum amplitude (crest to trough) of the largest microrelief feature in a 1.5-km interval was plotted and equal microrelief areas were contoured. Because wide variation in microrelief amplitude may occur in this distance, we selected contour intervals of <0.5-m, 0.5- to 1-m, 1- to 2-m, and >2-m. This map is a general interpretation of very irregular, localized, and probably transient sea-floor features, and we expect some change in the map contours during the next few years.

The microrelief map indicates the precision of the bathymetric contours shown on Plate 1. As previously stated, bathymetric data were picked on a hypothetically smoothed seafloor, thereby eliminating the effects of microrelief variability and illustrating only broad scale features. This means that in central Harrison Bay where the seafloor has microrelief up to 1 m, the bathymetric contours are strictly accurate to ±0.5 m. This is an important consideration for true water depths in northeastern Harrison Bay where the variability produced by microrelief (± 1 m) may be greater than the bathymetric contour interval.

The seafloor in Harrison Bay can generally be divided into areas dominated by two types of active geologic processes. These are: hydraulic processes involving the transport, deposition, or redistribution of sediment by bottom currents, and ice gouging by deep-keeled ice floes pushed into shallow water by wind and sea currents. Over most of the survey area, hydraulic and ice grounding processes together actively rework the seafloor, although ice gouges are the predominant microrelief form in water depths greater than about 12 m.

Along the shoreward margin of the survey area and generally in water depths less than 12 m, the sea-bed microrelief is dominated by hydraulic bedforms (Figure 3, A). Linear shoals, sand waves, and scour channels are evidence of active sediment movement. The microrelief in this area may reach 1 to 2 m, and the seabed is typically devoid of ice gouges. Two other areas containing hydraulic bedforms were mapped

Figure 3.--Sea-floor Profiles
(Fathometer Records)



on shoals further offshore. Although these shoals were probably created by the shoreward push of grounding ice, the bedforms present on their surfaces indicates active hydraulic reworking of these areas (Reimnitz and others, 1978).

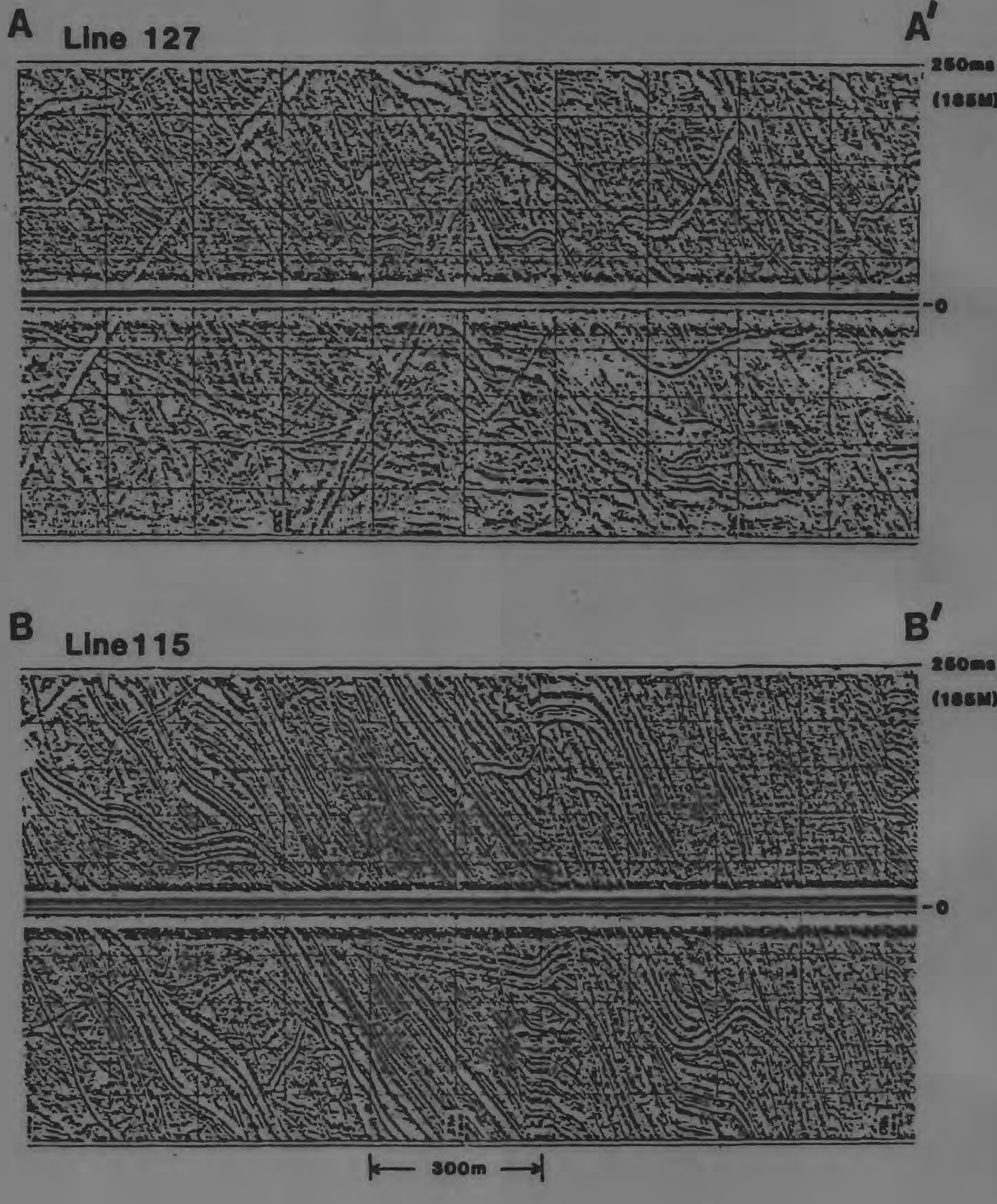
Between approximately 12- and 20-m water depths, the ice gouges are typically shallow and smooth in appearance (Figure 3, B). Low flanking ridges and flat troughs of the gouges suggest that they have been reshaped by bottom currents and partially filled with sediment. Microrelief in this central area is typically 0.5 to 1 m. Patches of smooth sediment are rare in this area saturated by ice gouges. In water depths greater than 20 to 22 m, the microrelief produced by ice gouges is >2 m and the gouges have sharp-crested ridges and V-shaped troughs (Figure 3, C). These characteristics suggest that ice gouging is very active and intense, and hydraulic processes play a limited role in reshaping the seabed.

Ice-Gouge Trends and Sea-floor Coverage

Side-scan sonar records (Figure 4) were analyzed to define the sea-floor coverage and general orientation of ice gouges in Harrison Bay (Plate 3). These microrelief features, unique to shallow arctic shelf areas, have received considerable attention (Reimnitz and Barnes, 1974; Reimnitz and others, 1978) and their origin is well established. When deep-keeled floes are driven into shallow water by wind and sea currents, a large groove (gouge or scour) is plowed into the seabed. The deep-keeled floes are remnants of pressure ridges formed in the shear zone between the seasonal landfast ice and the mobile polar ice pack. Ice gouges may be several tens of meters wide and several meters deep. The ice-gouge map (Plate 3) can be used with the microrelief map (Plate 2) to indicate the distribution and relative activity of present geologic processes in Harrison Bay.

Ice-gouge coverage (percent of the seafloor covered by ice gouges) was estimated by visually comparing the sonograph records to schematic charts. Because of the high local variability of gouge densities, gouge widths, and the problem of overlapping gouges, we divided the survey area into these broad categories: gouge-free; low density (<10% coverage); medium density (10% to 50% coverage); and high density (>50% coverage). The high density area is considered as saturated gouging; that is, the entire seafloor is covered by cross-cutting gouges and no new gouges can be formed without affecting the existing gouges. The orientation or trend of ice gouges was measured by means of graphs constructed to correct for width exaggeration on the sonograph records. Dominant ice-gouge trends were measured in 15° increments from the ship's heading and plotted at 10 fix-point intervals (3 km) along the survey tracks.

Figure 4.—Side-Scan Sonographs



The interpretations of microrelief based on fathometer data (Plate 2) and ice-gouge coverage on the basis of side-scan sonographs (Plate 3) are consistent. The hydraulic bedform area closely matches the low-coverage area for ice gouges, suggesting that while ice gouging may occur in shallow water, the hydraulic processes quickly erode and fill the gouges. The ice gouge coverage map also indicates the abrupt transition from low- to saturation-gouged conditions. This narrow transition could indicate the overlap of sediment deposition on an ice gouged seafloor. Seaward of the 12- to 15-m isobaths, high density or saturated ice gouging is typical of Harrison Bay.

The orientation of individual ice gouges is variable in localities throughout Harrison Bay, although several general patterns or trends can be identified. The dominant trend is NW, parallel to the bathymetric contours, and suggests that movement of grounded ice is largely controlled by sea-floor relief. A secondary trend of NE presumably indicates onshore ice movement directed by prevailing wind or sea currents. Two contrasting ice gouge trend areas are delineated on Plate 3. In western Harrison Bay, ice gouges trend uniformly in a NW direction (area 2). In central and eastern Harrison Bay, ice gouges vary widely in orientation and frequently meander without a consistent trend (area 1). Examples of these contrasting areas are shown in Figure 4, and the rose diagram on Plate 3 characterizes the irregular trends found in eastern Harrison Bay. A possible explanation for this contrast in ice-gouge trend is that gouges in eastern Harrison Bay are produced during ice incursions in the summer open-water season when variable wind and sea currents move ice around the bay. The regular trend in western Harrison Bay suggests the influence of the outer stamukhi shoal. This feature could shelter western Harrison Bay from the incursions of deep-keeled ice and focus ice moving from eastern Harrison Bay along bathymetric contours.

Sea-floor evidence for an early winter shear zone along the 10-m isobath and the midwinter shear zone seaward of the 20-m isobath, as reported by Reimnitz and others (1978) and Stringer (1978), is not recognized in our sonograph data. The data sets are not strictly comparable because these investigators mapped surface ice features from satellite and aerial images whereas our interpretation is based on sea-floor features produced by the underside of the ice. We do, however, recognize a major change in seabed microrelief and gouge appearance seaward of the 20- to 22-m isobaths and believe that this intensely gouged area is produced beneath the midwinter shear zone.

STRATIGRAPHY

Three distinct stratigraphic units are present in the subsurface of Harrison Bay. Each unit is separated by an unconformity and can be mapped according to its unique seismic character. From the seafloor downward, these units are designated by their inferred age as Holocene, Pleistocene, and Upper Cretaceous to Tertiary deposits. Our interpretation of subsurface lithology, depositional environment, and age are speculative because core data is limited in this area. However, our conclusions are based on recognized onshore stratigraphy and well data, as well as previous seismic surveys and shallow boreholes in adjacent offshore areas.

Holocene Deposits

An acoustically transparent sediment layer beneath the sea-floor surface was delineated by the 3.5-kHz subbottom profiler. The thickness of this layer was measured from the seafloor to a Pleistocene reflective surface (inferred age) and contoured at 2-m intervals on Plate 4. Seismic travel time was converted to subbottom depth using an assumed acoustic velocity of 1.6 km/s. Acoustic penetration of several tens of meters by this low-energy acoustic system suggests that this surficial layer is unconsolidated. Its upper stratigraphic position indicates that these sediments probably accumulated since the postglacial marine transgression, and on this basis we infer the age of this deposit to be Holocene. The Holocene deposit generally thickens away from the Colville River, indicating that strong ocean currents have actively redistributed sediment away from this source. Surficial sampling (Barnes and Reimnitz, 1974; Barnes and others, 1980) and shallow coring (Barnes and others, 1979; Harding and Lawson, 1979; Osterkamp and Harrison, 1980) of this deposit indicate that sediment lithology varies greatly over short distances, probably in response to active ice gouging and hydraulic processes. The typical sediment lithology is poorly sorted, sandy silt with occasional gravel components. Occasional internal reflecting horizons in our subbottom profile data are interpreted to be sand, or perhaps gravel, interbeds.

Pleistocene Deposits

A strong and continuous reflector is tenatively identified as the Holocene-Pleistocene boundary (Figure 5). The highly reflective character of this horizon, eliminating penetration by the 3.5-kHz acoustic signal, could be caused by a change in lithology, consolidation state, or interstitial gas. The lack of available borehole data in Harrison Bay makes our interpretation of the nature of this acoustic horizon speculative. Because the acoustic character of the reflecting

Figure 5.--Subbottom Profiles

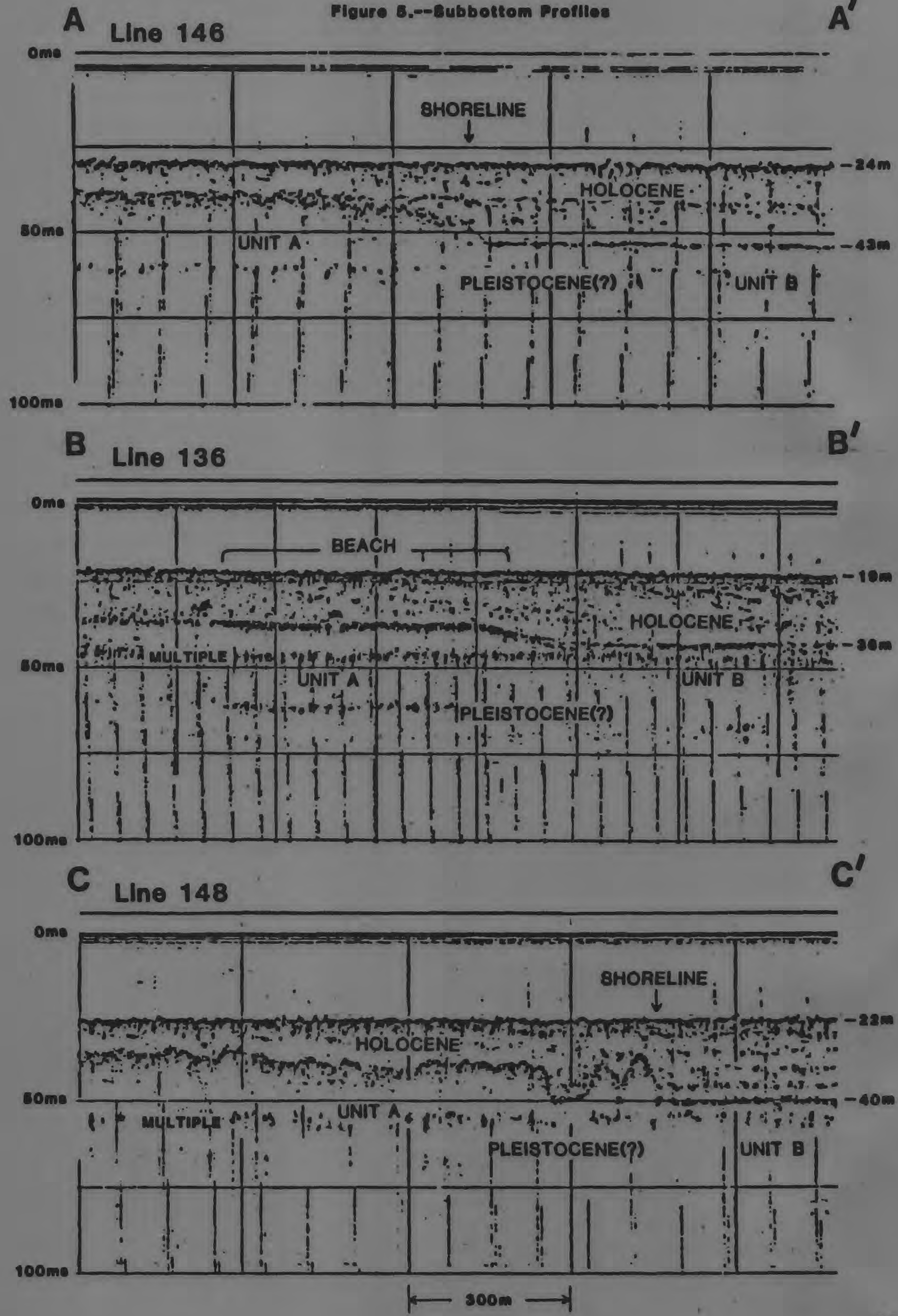
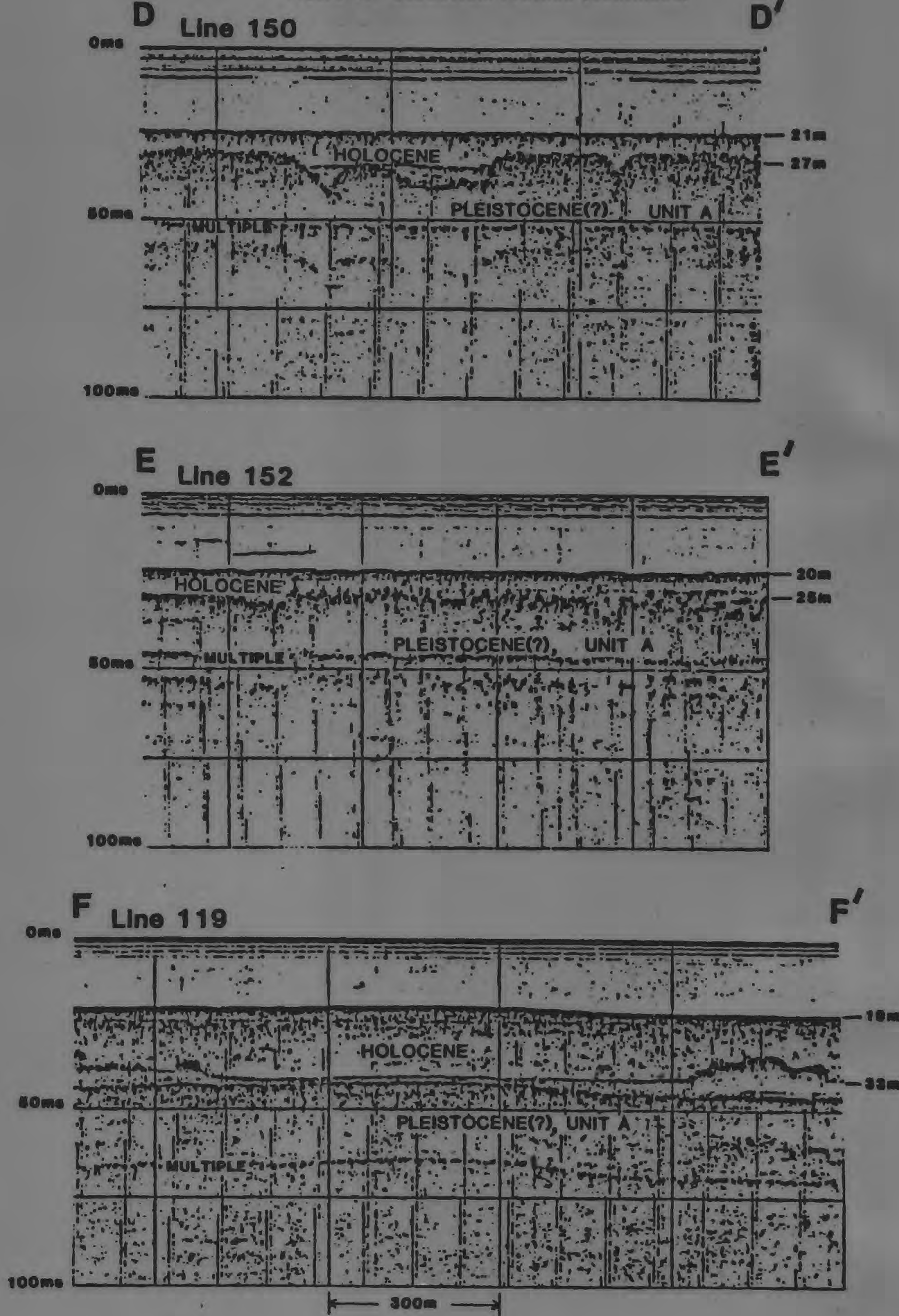


Figure 5.--Subbottom Profiles (continued)



horizon is similar in appearance to many natural relief features on the Arctic Coastal Plain, and it lies unconformably beneath the Holocene deposit, we interpret this reflector to represent the upper surface of a Pleistocene deposit. The relief of the pretransgressive Pleistocene surface can be inferred from the Holocene isopach map (Plate 4).

The acoustic character of the Pleistocene surface varies in Harrison Bay from a heterogeneous, high-relief horizon to a uniform, low-relief horizon. We differentiated these laterally continuous and distinct reflector types and infer that they represent the surface of a nonmarine coastal plain deposit (Unit A) and a marine deposit of equivalent age (Unit B). The internal stratigraphy of the Pleistocene deposit cannot be resolved by our suite of geophysical instruments. A prominent low-angle unconformity, recognized only in the near-trace seismic records, was identified at approximately 100 m below sea level and inferred to be the base of the Pleistocene section (Figure 6). If the Pleistocene deposit found offshore corresponds to the Gubic Formation in adjacent onshore area (Black, 1964), we expect this section to include a diverse assortment of lithologies deposited during several transgressive-regressive cycles on the Arctic Coastal Plain.

The distinction between highly variable, coastal plain sediment (Unit A), and uniform marine sediment (Unit B) may be useful foundation information because these deposits lie beneath a relatively thin Holocene layer.

Unit A is easily recognized by its diverse acoustic appearance, varying from a diffuse to a sharp reflecting surface. It often has a "jumpy" appearance (Figure 5, E), where energy bounces from reflectors spaced several meters vertically and tens of meters laterally. The reflective surface of Unit A has relief similar in appearance and size to features of the present coastal plain, including thermokarst topography, V-shaped stream channels (Figure 5, D), thaw lakes (Figure 5, F), and beach ridges. These features, now covered by Holocene sediment, were probably modified by the Holocene transgression. Although 2 to 10 m of relief are present on the surface of Unit A, most of the features are not shown on Plate 4 because of the map scale and wide survey grid.

Unit B has a sharp, strongly reflective surface with uniformly low relief. Its acoustic character contrasts greatly with the heterogeneous appearance of Unit A's surface. Several features on the surface of Unit B are interpreted to represent sedimentary bedforms, such as beaches (Figure 5, B) and offshore bars, and they suggest that this deposit is marine in origin.

The contact between Unit A and Unit B generally follows the 12-m isopach contour, and the distribution of Unit B is shaded on Plate 4. The contact between these Pleistocene units is of interest because it may represent an ancient shoreline now buried in the subsurface. Commonly, the contact is abrupt and a shoreline bluff several meters high is recognized (Figure 5; A, B, C). There is no sea-floor expression of the bluff. Small stream channels, which could be extensions of drainage of the Colville or other rivers, frequently cut the shoreline bluff to the level of Unit B. The age of this shoreline at approximately -32 ± 2 m is uncertain, although we believe that it is a Pleistocene feature. The Holocene terraces and submarine valleys recognized in other Alaskan areas by Barnes and Hopkins (1978) have sea-floor expression. It is also possible that this shoreline was formed by a large lake on the Arctic Coastal Plain in Pleistocene time.

Late Cretaceous to Tertiary Deposits

The interpretation of deep geologic structure and stratigraphy in Harrison Bay (Plate 5) is based on seismic reflection data, including near-trace analog profiles and twelve-channel digital seismic sections. Digital seismic data were recorded in the field for two-way travel time of 1 second at a sample rate of 1/2 ms. These data are considered to be "high resolution" because of the high frequency seismic source and the short group interval on the hydrophone streamer. The field tapes were processed at 1 ms as a 12-fold CDP stack and displayed in relative true amplitude and automatic gain control sections. Velocity analyses were made of the sections at five fix-point intervals (1.5 km) along each survey track. An example CDP section with its corresponding velocity analysis and a more complete listing of recording and processing parameters is given in Plate 6.

The seismic section (to approximately 1000-m depth) consists of parallel to slightly divergent reflectors with high amplitude and good continuity. The reflectors tend to offlap to the North and occasionally vary in amplitude. This seismic character suggests the widespread deposition of interbedded sand and shale lithologies. The lower part of the seismic section generally consists of hummocky, discontinuous reflectors of variable amplitude. This character suggests the deposition of laterally discontinuous sand bodies in a dominantly shale setting. We interpret the seismic section to represent a prograding sequence, consisting largely of alluvial fan-delta plain deposits. On the basis of an examination of well logs from onshore wells (see Plate 5 for location) and a regional synthesis by Brosgé and Tailleur (1971), we infer that this section corresponds to the Colville Group, a thick regressive sequence deposited on the Arctic platform in Late Cretaceous to Tertiary time. This broad age definition is caused by difficulties in defining stratigraphic boundaries in a predominantly nonmarine sequence. Most workers usually refer to this regressive sequence as "Colville Group and younger." We also do not attempt to divide the section into Upper Cretaceous (Schrader Bluff and Prince Creek) or Tertiary (Sagavanirktok) formations because there is no available offshore well control.

We selected a prominent marker horizon in the upper part of this fan-delta sequence to indicate the geologic structure (Plate 5). Depths to the marker horizon are contoured in meters below sea level using an assumed seismic velocity of 1.8 km/s. Our velocity analyses are in agreement with refraction velocities reported for the Beaufort Shelf by Houtz and others (1981). "Shallow" faults that displace the marker horizon are shown as solid lines, and "deep" faults which terminate below it are shown as dashed lines.

In general, the structure of the inferred Late Cretaceous to Tertiary section is subdued, with strata dipping gently to the northeast (0.5° to 1.0°) and small displacements by faults (less than 50 m). The Barrow Arch, thought to trend through this offshore area, is not visible in the 1 s seismic sections. High-angle normal faults with down-to-basin displacement (to the North) are most common. The occasional high-angle reverse faults are closely associated with the normal faults and produce narrow horst blocks. With rare exception, all faults terminate at or below the unconformity between Pleistocene and Late Cretaceous to Tertiary deposits at 100 m below sea level (Figure 6). The normal and reverse faults may be listric (growth) faults and associated antithetic faults, but their lower curved portions are not visible on the 1-second sections. Growth faults are typical of prograding sequences. The dominant trend of the faults is NW, with a secondary trend E. Monoclines are occasionally recognized above "deep" fault traces, and splay faults are common. A long NW-trending fault system bisects the survey area, and in some locations displaces horizons above the -100 m unconformity. Although seismic resolution in the upper 200 ms is generally poor, owing to strong reverberations, evidence of fault displacement to 60 m below sea level was recognized in the near-trace profiles (Figure 6). The upper extent of these shallow faults is uncertain. The highly irregular surface of the inferred Pleistocene deposit and the ice gouged nature of the seafloor would tend to obscure any fault displacement of these deposits. Because most faults were found to terminate at or below the -100-m unconformity, we conclude that tectonic activity has been infrequent in Quaternary time. Seismicity studies by Biswas and Gedney (1979) support this conclusion.

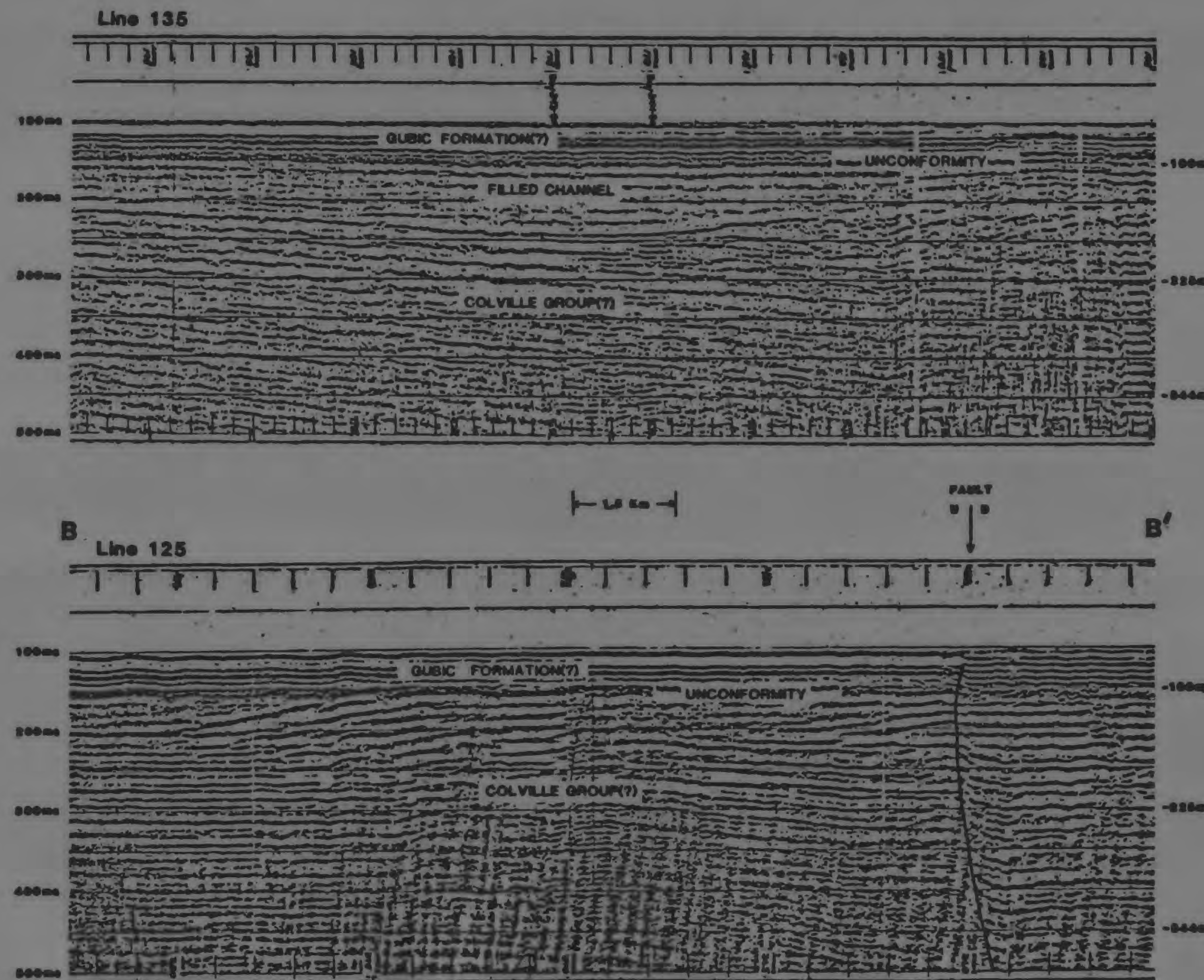


Figure 6.—Near Trace Seismic Profiles
(Top profile located east of map area, Plate 5)

Another observation from these seismic data is that a continuous zone of poor quality data is found along the shoreward margin of the survey area (Plate 5). The nature of this rather abrupt degradation of seismic data is uncertain. One explanation is that it is caused by problems of seismic data recording in a shallow-water, hard-bottom area. Another explanation is that it is related to the occurrence of high velocity, bonded permafrost in the upper geologic section. Sellmann and others (1981) mapped a high velocity layer that they interpreted to be permafrost in Harrison Bay. The distribution of this permafrost layer and associated acoustic anomalies coincides closely with the area of poor quality seismic data in our records. Because permafrost occurrence has been confirmed by drilling programs in nearshore areas of the Beaufort Sea (Sellmann and others, 1980; and Harding and Lawson, 1979), the area of poor seismic data was mapped and we speculate that it may be related to a bonded permafrost layer in the upper geologic section. It is also possible that discontinuous, ice-bonded sediment may be encountered elsewhere in this area because the entire shelf was exposed subaerially in Pleistocene time. However, thin or discontinuous ice lenses would probably not be resolved by low-frequency seismic systems.

Shallow gas accumulations are often identified by acoustic anomalies. We mapped several acoustic anomalies that typically occur in structures adjacent to faults (Plate 5). These anomalies have bright spot (amplitude increase), reflector pull-down, and attenuation of high-frequency signal characteristics. In some areas away from fault traces, increased amplitude of reflectors (brightening) is visible although typically not accompanied by seismic characteristics indicative of low-velocity (gas-containing) strata, such as reflector wipe-out, pull-down, or phase reversal. Consequently, we did not map these local anomalies as possible shallow gas accumulations. On the basis of the onshore well evidence, we do suspect that small stratigraphic traps contain minor accumulations of gas throughout the Late Cretaceous to Tertiary section. Brosgé and Tailleur (1971) state, "the numerous strong gas shows in the nonmarine beds indicate that the Colville is likely to be an important gas reservoir." These authors point to the relationship between abundant coal deposits and excellent reservoir properties of the nonmarine beds and speculate that, "the upper Colville and possibly the Tertiary are probable sources and reservoirs for gas" in offshore areas. The occurrence of gas hydrates in permafrost or interstitial gas in strata formerly frozen was discussed by Sellmann and others (1981). We also expect permafrost and associated gas hydrates to be more common in the nearshore areas of Harrison Bay, especially in the poor-data areas shown on the map. We acknowledge that these interpretations of stratigraphy, shallow gas occurrence, and subsea permafrost distribution in Harrison Bay area highly speculative because there is no available offshore well data.

ENVIRONMENTAL CONSIDERATIONS

In this section, we will present an overview of geological conditions in the survey area and briefly describe potential hazards to future petroleum exploration and production activities. This study is not a comprehensive geologic evaluation, rather it is a preliminary interpretation constrained by areal limits and geophysical resolution. For example, the active process of coastal erosion, considered to be a potential hazard to shoreline development (Hopkins and Hartz; 1978), is beyond the scope of this survey. We do believe, however, that many of our interpretations can be extrapolated into adjacent offshore areas that, at present, have very limited data coverage. This report describes geological conditions typical of the inner Beaufort Sea shelf and points out important gaps in knowledge of this setting.

The bathymetry of Harrison Bay is characterized as shallow and almost flat. Because of its gentle seaward slope (<0.5°) and thin layer of recent marine sediment, we believe that the potential for mass movement in Harrison Bay is negligible. The active processes of ice gouging and sediment redistribution do have a major effect on the stability of the seafloor, and the scour potential of these processes should be considered in the design of seabed installations. Hydraulic processes are most active in water depths less than 12 m and on offshore shoals. Bedforms such as sand waves indicate that scour and redistribution of sediment may affect up to 1 m of sediment (Barnes and Reimnitz, 1979). Hydraulic processes are especially pronounced during the late-summer open-water storms.

Ice gouging may occur in all water depths, and gouges are the predominant microrelief feature in water depths greater than 12 m. The microrelief produced by ice gouges in most of Harrison Bay is less than 1 m, although in water depths greater than 20 m, ice-gouge microrelief is 2 m or more. Pipeline installations in all parts of the bay should allow for the maximum incision depth of expected gouging as well as for the temporary overpressuring effect during gouging. In the intensely gouged area beneath the shear zone, a reasonable safety factor might require burial of pipelines or subsea completions 5 m below mudline. Our data indicate the increasing intensity of ice gouging with water depth. The meandering trends and shallow microrelief produced by ice gouges shoreward of the 20-m isobath in Harrison Bay suggest that sea-floor gouging probably occurs during the summer open-water season and is generally less intense than beneath the shear zone. Protection from ice ridges grounding in western Harrison Bay is probably provided by the outer shoals (Reimnitz and others, 1978). Reimnitz and others (1977) report that a complete disruption of the shallow seabed by ice gouging may occur in 50 to 100 years, with hydraulic processes active at a seasonal time scale. Ice grounding in the open-water season would impose infrequent and probably lower stresses on artificial structures than would large ice ridges driven by the polar ice pack.

From our examination of the available evidence, we conclude that current scour or deposition are potential environmental hazards in water depths less than about 12 m. Between 12 m and 20 m (the landfast ice zone), potential hazards will be ice override during early winter and spring breakup periods and the disruption of the seafloor by ice gouging. In water depths greater than about 20 m, the major hazard will be pressure ridging and intense ice gouging forces related to the movement of the polar ice pack. We presume that the technology for development in the landfast ice zone shoreward of the 20-m isobath in Harrison Bay will differ from that designed for the shear zone further seaward. Valuable information will be gained from the performance of exploration islands (Issungnak and Tarsuit) in the Canadian Beaufort Sea.

The thickness and inferred consolidation state of sediments in the shallow subbottom section is defined by the 3.5-kHz subbottom profiler. These data are also used to identify gas-charged sediments and gas plumes in the water column. The shallow subbottom conditions are important in the evaluation of foundation stability. We found that a relatively thin layer (2 to 25 m) of unconsolidated (Holocene) sediment overlies a complex subbottom horizon inferred to be a Pleistocene coastal plain deposit. We recognize no unusual characteristics in the Holocene layer, such as gas-charged sediment, that might create unstable foundation conditions.

The major uncertainty is the composition of the material underlying the Holocene layer. Of the two inferred Pleistocene units, one is highly variable in relief and acoustic appearance (Unit A). High-resolution data from Norton Sound (Steffy and others, 1981) contains areas of similar acoustic appearance. A study by Nelson and others (1979) correlated these Norton Sound areas to shallow biogenic gas accumulations in Quaternary peat deposits also capped by the thin Holocene layer. Because Norton Sound and Harrison Bay have many similarities, including location as shallow bays off major Arctic rivers and emergence as tundra areas in Pleistocene time, it is possible that the subsurface coastal plain deposit (Unit A) contains interstitial gas. The variety of subbottom features, such as filled channels, thaw-lake deposits, and a buried shoreline, could create variable foundation conditions beneath a thin Holocene layer. The lateral change from peaty beds with associated gas-charged sediments to alluvial gravel deposits in buried stream channels is possible over distances of 10 km. Because this coastal plain deposit was exposed to Arctic conditions during Pleistocene time, it is possible that areas of permafrost exist in this material.

In contrast to this complex, nonmarine deposit, the second Pleistocene deposit (Unit B) is inferred to be marine in origin. Foundation conditions in the outer portion of the survey area may therefore be more stable, with a thick layer of Holocene marine sediment overlying an older marine deposit. The composition and geotechnical properties of the subsurface units should be investigated by shallow boreholes, as at present, the lack of ground-truth data is a major gap in our evaluation of foundation conditions and the occurrence of gravel in Harrison Bay.

On the basis of previous work (Brosgé and Tailleur, 1971) and onshore well data, we infer that strata in the upper 1000 m correspond to the Colville Group. This Late Cretaceous to Tertiary deposit represents a major regressive sequence consisting of nonmarine (alluvial fan-delta plain) and marine (prodelta) deposits. The probable association of organic-rich beds (shale and coal) with clastic reservoir beds creates good conditions for gas generation and accumulation. Small quantities of gas have been reported in many onshore wells and are likewise expected to be present in the offshore area (Brosgé and Tailleur, 1971). Acoustic anomalies indicating gas-charged sediment are rare, however, in our seismic data. Where present, acoustic anomalies tend to occur in structures related to faults.

Several fault trends are recognized in the survey area. The high-angle normal and reverse faults usually terminate at or below a low-angle unconformity at 100 m below sea level, however occasionally faults do offset shallower horizons. If we assume that this unconformity indicates the Tertiary-Quaternary boundary, then tectonic activity in Quaternary time was rare. This conclusion is supported by seismicity studies of Biswas and Gedney (1979), who plotted recent earthquake epicenters in northern Alaska. In some cases the long NW-trending faults offset horizons in the inferred Pleistocene section. The upper extent of these faults should be defined by additional high-resolution seismic data focusing on the interval above -200 m.

The distribution of subsea permafrost is another uncertainty. If Harrison Bay was exposed to subaerial Arctic conditions during Pleistocene time, remnant permafrost may exist locally throughout the survey area. We recognize a continuous zone of poor quality data that generally parallels the shoreline of Harrison Bay (Plate 5). This seismic anomaly closely follows the area defined as subsea permafrost by Sellmann and others (1981) on the basis of seismic evidence. We were unable, however, to extract conclusive evidence (by refraction methods) from our reflection data. Because seismic techniques have usually been ambiguous in their definition of permafrost, especially the lower surface of ice-bounded material, we suggest that drilling operations are needed to define the distribution and properties of permafrost in Harrison Bay.

SUMMARY

This study has produced a series of maps and a description of shallow geologic conditions in Harrison Bay that will be used in a tract-specific hazards evaluation for OCS Lease Sale 71. This information may also be applied to adjacent unsurveyed areas of the western Beaufort Sea shelf tentatively scheduled for future OCS sales. Many of our interpretations are based on previous synthesis reports produced in support of OCS activities (Barnes and Reimnitz, 1974; Grantz and others, 1976; Barnes and Hopkins, 1978; Grantz and others, 1980), although our evaluation of subsurface stratigraphy and structure of Harrison Bay is a new contribution to available knowledge concerning the Beaufort Sea. With regard to the shallow geology, there is still a lack of data concerning the composition, age, and geotechnical properties of the seismic units identified. This data gap limits the evaluation of foundation stability and the availability of gravel resources in the offshore area. The distribution and properties of subsea permafrost is another gap in our knowledge that could affect downhole casing programs and well control. In the deeper geologic section, the location and upper extent of faults and possible gas-containing structures associated with faults is important for safe exploration and development drilling operations. To fill these known data gaps, there is an obvious need for both borehole drilling and additional high-resolution geophysical surveys. With regard to active environmental processes, ice movement and seabed interaction is the dominant force affecting all offshore activities, particularly seaward of the 20-m isobath. Additional study of ice zonation and dynamic ice processes is needed to insure the safety of offshore operations in the hostile Arctic marine environment.

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