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BULLETIN 303**

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OF THE BEAUFORT SHELF

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Preface

With exploration for hydrocarbons moving into Canadian Arctic waters, more information is needed for a better understanding of the highly sensitive Arctic marine environment where relatively small interferences with natural processes may result in pronounced disturbances. To facilitate this understanding the environment must be regarded as a dynamic system that comprises a series of biological and physical processes which have development times ranging from a single season to many years. Sediments collected from the Beaufort Shelf with piston cores provide evidence for geological processes that developed during postglacial changes in sea level, i.e. during the last 10 000 years.

This Bulletin will be of interest to the companies engaged in drilling operations on the Beaufort Shelf because it describes in detail the sediments of the upper 10 m and discusses the large scale biological and oceanographic processes associated with the sedimentation on the Shelf.

D.J. McLaren
Director General
Geological Survey of Canada

Ottawa, October 1977

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THE HOLOCENE MARINE ENVIRONMENT OF THE BEAUFORT SHELF

Abstract

The marine environment on the Canadian continental shelf of the Beaufort Sea is described on the basis of data on foraminifera, molluscs, and sediments. The fauna and sediment were studied in 659 surface samples, 49 sediment cores, and 80 plankton tows, most of which were collected from *CSS HUDSON* during the summer of 1970.

The sediments consist mainly of silt and clay from the Mackenzie River. Silt is predominant inshore to the north and east of Mackenzie Delta, sand is the predominant fraction in a few localities on the shelf east of the Delta, and gravel is present only in a small area west of Herschel Island and near Baillie Islands to the east.

In an anticlockwise transport model, the sediment is carried towards the east along the coast and west along the outer shelf. The main regions of deposition are Mackenzie Canyon and its vicinity.

Sea ice and the interaction of runoff and ocean waters are the determining factors of organic production and distribution of species. The occurrence of the planktonic foraminifer *Globorotalia pachyderma* is reduced by several orders of magnitude during winter and is absent from the waters of the inner shelf during both· seasons. Two benthonic foraminiferal species demonstrate a distinct preference for watermass properties. *Elphidium clavatum* is predominant in waters that are influenced by the runoff of Mackenzie River; *Islandiella teretis* is predominant in the offshore waters. The molluscan fauna is diverse, but few undisturbed specimens were found in waters deeper than 100 m.

Cores taken from the continental shelf contained only Early to Late Holocene sediments, but deposits of one of the glacial periods may have been recovered from the continental slope. On the basis of core recovery, ^{14}C data, and faunal discontinuities, the rate of sedimentation may be in the order of 3-30 cm/1000 y on the continental shelf, more than 100 cm/1000 y in Mackenzie Canyon, and 20-30 cm/1000 y along the continental margin – upper continental slope at depths greater than 1000 m.

The faunal evidence also indicates that along the continental margin to the north of the delta the extent of sediment slumping has increased during the last 5000 years. During the same period the influence of offshore waters in Mackenzie Canyon has also increased. Because one of the causes for the shoreward eddy in the canyon is the eastward migration of the Mackenzie runoff, it is suggested that the present anticlockwise circulation on the continental shelf has existed for at least the last 5000 years.

The thin layer of the postglacial sediments on the continental shelf to the east of the delta may contain a preserved record of ancient shorelines. Several inner shelf cores contain barren layers below the present fauna and in the lower layers of a number of outer shelf cores the diverse faunas are replaced by the inner shelf-estuarine *Elphidium clavatum*. In addition, some of the well sorted sands contain small numbers of foraminifera with an occasional barren layer. The paucity of preserved foraminiferal tests is in accordance with the view that these sediments are remnants of ancient beaches. Off Baillie Islands the sandy sediments are rich with a diverse foraminiferal and molluscan fauna and contain gravel deposited during the late Holocene. A foraminiferal species *Protelphidium nanum* n. sp. is described. It is a small species occurring at water depth between 24 and 69 m.

Résumé

Dans la présente étude, on décrit le milieu marin caractérisant la plate-forme continentale canadienne de la mer de Beaufort, d'après les données fournies par l'étude des foraminifères, des mollusques et des sédiments. On a étudié la faune et les sédiments contenus dans 659 échantillons de surface, 49 carottes de sondage du sédiment et 89 échantillons de plancton recueillis par dragage; la plupart de ces travaux ont été effectués par le *CSS HUDSON* pendant l'été 1970.

Les sédiments sont surtout composés de silt et d'argile provenant du fleuve Mackenzie. Le silt est dominant près du rivage, au nord et à l'est du delta du Mackenzie, le sable est la fraction granulométrique principale en quelques endroits de la plate-forme continentale à l'est du delta, et l'on ne trouve des graviers que dans une zone très restreinte, à l'ouest de l'île Herschel, et près de l'île Baillie à l'est.

Dans un modèle de transport rotatoire en sens contraire des aiguilles d'une montre, le sédiment est transporté vers l'est le long de la côte, et vers l'ouest le long du rebord extérieur de la plate-forme. Les principales régions de sédimentation sont le canyon du Mackenzie et ses approches.

La glace de mer et l'interaction des eaux d'écoulement et des eaux océaniques jouent un rôle essentiel dans la production de matière organique et la répartition des espèces. Pendant l'hiver, la densité de population du foraminifère planctonique **Globorotalia pachyderma** diminue fortement pendant l'hiver, et celui-ci ne fréquente les eaux de la partie interne du plateau continental à aucun moment des deux saisons. Deux espèces de foraminifères benthoniques manifestent une nette préférence pour certaines conditions de température et de salinité. **Elphidium clavatum** domine dans les zones modifiées par les eaux du fleuve Mackenzie; **Inslandiella teretis** domine dans les eaux du large. La faune de mollusques est diversifiée, mais on n'a rencontré qu'un petit nombre de spécimens intacts à plus de 100 mètres de profondeur.

Les carottes d'échantillonnage prélevées sur la plate-forme continentale ne contenaient que des sédiments dont l'age s'étant du début à la fin de l'Holocène mais sur la pente continentale, certains sédiments ramenés en surface datent peut-être du l'une des périodes glaciaires. D'après le type d'échantillons recueillis, la datation au C^{14}, et les lacunes que présente la faune, on estime que le rythme de sédimentation est de 3 à 30 cm pour 1 000 ans sur la plate-forme continentale, de plus de 100 cm pour 1 000 ans dans le canyon du Mackenzie, et de 20 à 30 cm pour 1 000 ans le long de la marge continentale et du niveau supérieur de la pente continentale, à plus de 1 000 mètres de profondeur.

Les indices fournis par la faune suggèrent aussi que le long de la marge continentale, au nord du delta, le glissement des sédiments s'est accentué pendant les 5 000 dernières années. Pendant cette période, l'influence des eaux du large a augmenté dans le canyon du Mackenzie. Etant donné que l' existence de remous dirigés vers le rivage dans le canyon est en partie due au mouvement vers l'est des eaux du Mackenzie, il est possible que la circulation actuelle des eaux dans le sens contraire des aiguilles d'une montre sur la plate-forme continentale se soit établie il y a au moins 5 000 ans.

La mince couche de sédiments postglaciaires déposés sur la plate-forme continentale à l'est du delta a conservé les traces d'anciennes lignes de rivage. Plusieurs carottes d'échantillonnage prélevées dans la partie interne de la plate-forme contiennent des couches stériles au-dessous des sédiments fossilifères actuels; dans les niveaux les plus profonds d'un certain nombre d'échantillons recueillis sur le rebord externe de la plate-forme, les diverses faunes font place à l'espèce **Elphidium clavatum**, établie dans les estuaires et l'intérieur des plates-formes. En outre, certains des sables bien triés contiennent un petit nombre de foraminifères, et parfois une intercalation stérile. La rareté des coquilles de foraminifères bien conservées confirme l'opinion que les sédiments en question sont les vestiges d'anciennes plages. Au large des îles Baillie, les sédiments sableux contiennent une riche faune de foraminifères et de mollusques, et des graviers déposés à la fin de l'Holocène. Dans la présente étude, on décrit l'espèce de foraminifères **Protelphidium manum** n. sp. Il s'agit d'une espèce de petite taille, vivant entre 24 et 69 m de profonduer d'eau.

THE HOLOCENE MARINE ENVIRONMENT OF THE BEAUFORT SHELF

INTRODUCTION

During 1969-70, **CSS HUDSON** circumnavigated South and North America to conduct an extensive scientific survey and sampling program. The ship entered the Beaufort Sea from the west and continued her voyage to the east through the Northwest Passage (Fig. 1). From August 24 to September 22, 1970. the ship remained in the waters of southeastern Beaufort Sea, spending much of the time in the Mackenzie delta area. Station work consisted of taking plankton tows, water samples, sediment cores, and bottom grab samples and while the ship was underway, detailed hydrographic, magnetic, gravity, side-scan sonar, and shallow seismic surveys were carried out.

This paper describes the marine environment of the southern Beaufort Sea (Fig. 1). Sea floor morphology, water mass properties, ice cover, and sediments are discussed and related to the distribution of certain species of foraminifera and molluscs. A model of sediment transport on the continental shelf is proposed on the basis of textural relationships of surficial sediments. Holocene sedimentation and paleoecology are described from the evidence in sediment cores according to the relationships that govern the existing ecology and sediment dynamics of the area.

This is an initial attempt to describe the Holocene marine environment on the Canadian portion of the Beaufort continental shelf. Surficial sediments have been described by Carsola (1952) and Pelletier (1975) and suspended sediments were examined by Bornhold (1975). Bartlett (1971) described the foraminiferal content of cores 76 m deep along a line facing the Mackenzie River delta. The assemblages he described as marginal marine and inner shelf shallow water foraminifera are dominated by **Elphidium incertum, Protelphidium orbiculare, Islandiella islandica,** and **I. teretis.** Faunal changes in the cores suggest a more favourable marine environment at present. A subsurface layer barren of recent foraminifera but containing reworked Cretaceous foraminifera was found in several cores.

G. Vilks is responsible for the identification and interpretation of foraminifera and physical and biological oceanography, F.J.E. Wagner for the molluscs, and B.R. Pelletier for sediment analyses and geomorphology.

Methods

Cores were taken with an Alpine piston corer using a 700-kg core head and a core barrel of 6 cm inner diameter. Shortly after the recovery, most of the cores were extruded, halved, sectioned in 1.5-m lengths, and wrapped in 2-mm plastic film. The storage facility was kept at 4°C under controlled humidity. As a result, after over four years of storage the sediment remained in a semi-moist state with reasonably unchanged water content. Surface samples used for sediment textural analyses were collected with a Van Veen bottom sampler during the following cruises: CSS **HUDSON** – 1970; **CSS RICHARDSON** – 1970; **CSS BAFFIN** – 1970; **CSS PARIZEAU** – 1970, 1971, 1972, and 1975; and from charter helicopter (Polar Continental Shelf Project) – 1970, 1971, 1972, and 1975. The present study is based on mechanical and faunal analyses of 659 geographically representative surface samples and 49 cores.
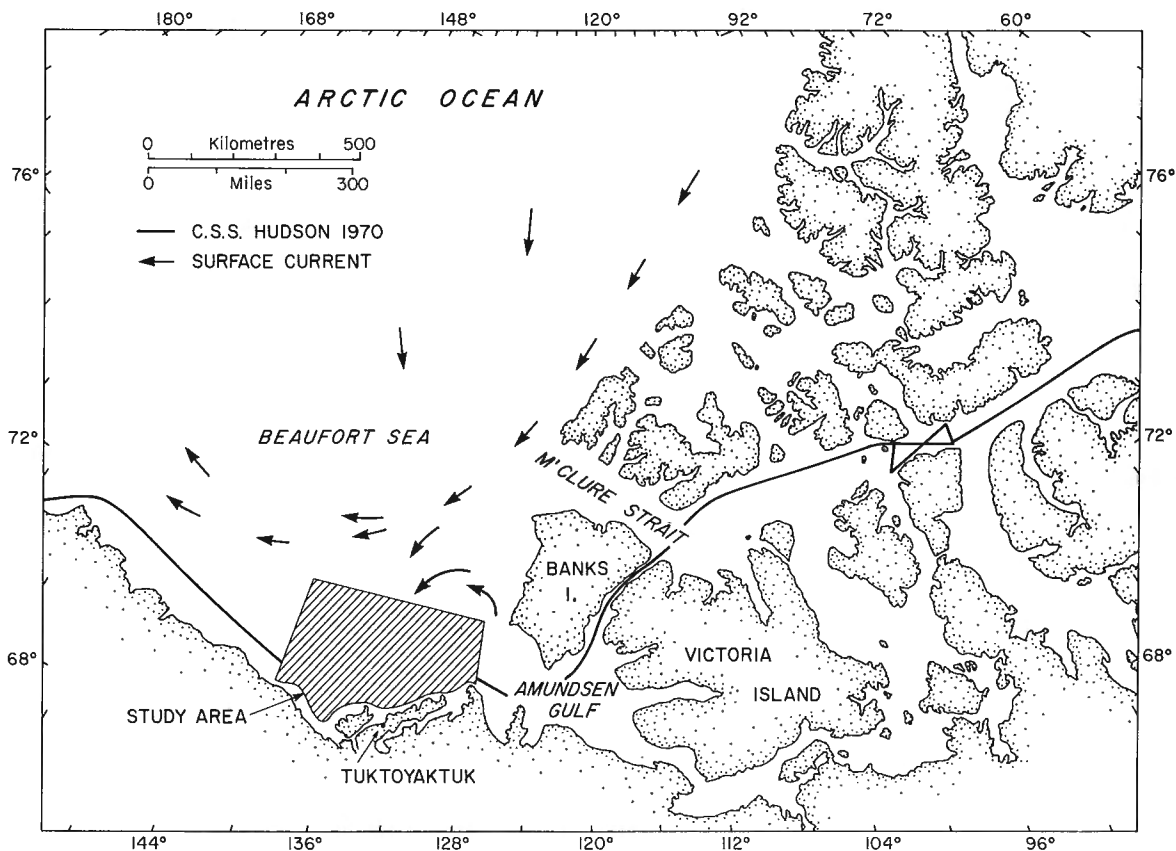
Figure 1. Index map.
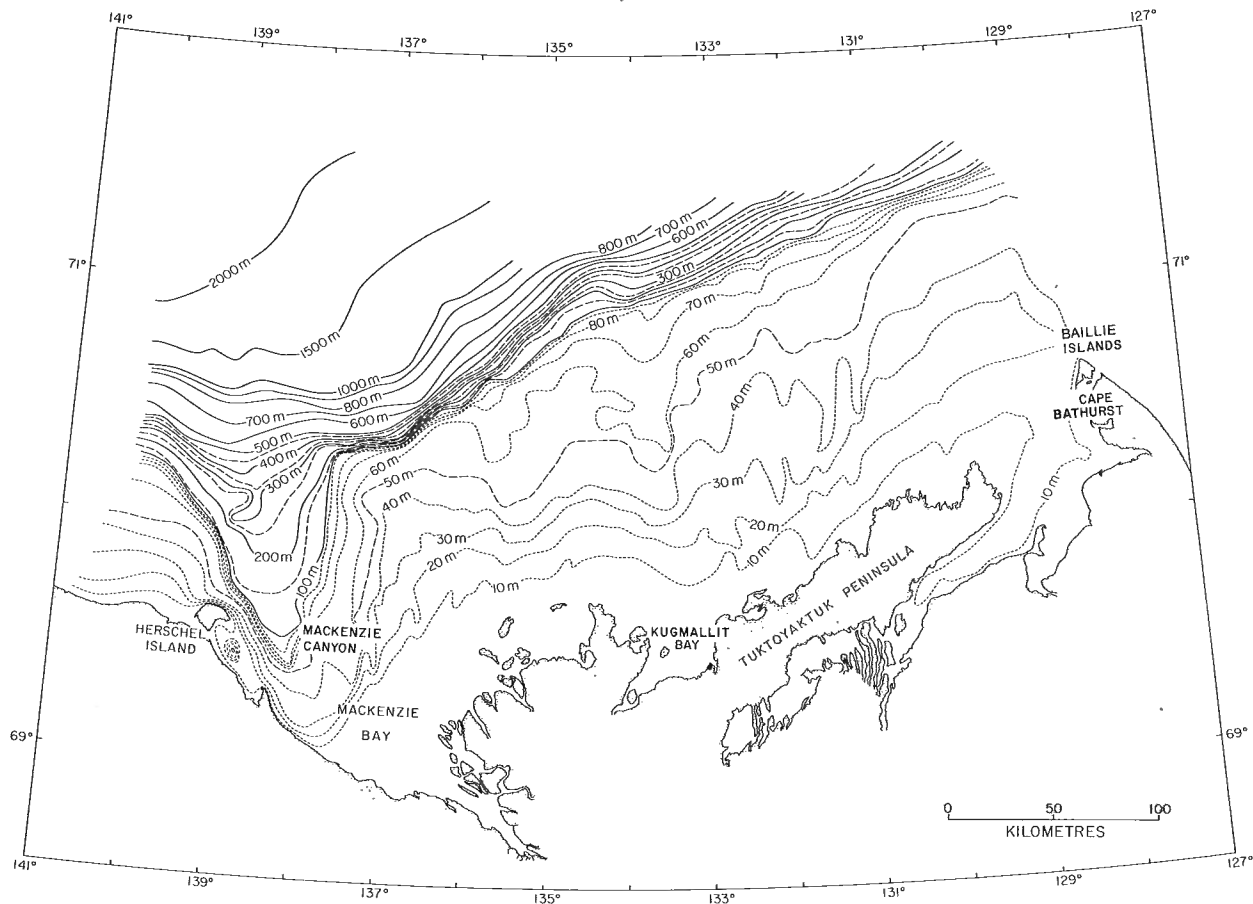
Figure 2. Bathymetry of the continental shelf and slope of the southeastern Beaufort Sea.

In the laboratory one half of each core was subsampled at 25-cm intervals, each subsample consisting of a vertical section 5 cm long and containing one quarter of the core by volume. The sediment volume of each subsample was therefore kept constant at 35 cm³ and in rare instances where 3-cm sections were taken, a foraminiferal number was converted to the standard volume.

The two identical subsamples of each interval were analyzed; one for fossil content and the other for sediment size. The relative percentages of sediment grain sizes were determined at one phi intervals using the pipette method for the finer fractions. Samples for paleontological analyses were wet-sieved through a 0.063 mm sieve and the fauna collected from the coarse fraction. To avoid destruction of the fragile foraminiferal tests, the sediment was not dried before washing.

ENVIRONMENT

Seafloor Morphology

Three major physiographic features are present on the floor of the Beaufort Sea (Fig. 2): 1) the moderately wide gently sloping continental shelf, which extends approximately 100 km off the Yukon coast to a depth of 100 m; 2) the continental slope, which falls steeply at the 100-m isobath to a depth of 2000 m in the Canada Basin approximately 500 km offshore; and 3) the Mackenzie Canyon, which transects the continental shelf and upper slope in a pronounced V-shaped pattern, with the headward portion lying immediately adjacent to the Mackenzie River delta. From the mouth of the delta Mackenzie Canyon extends about 120 km along a northwest axis to a depth of some 500 m, and thence to the upper slopes of the Canada Basin.

From bathymetric maps of the area (Canadian Hydrographic Service Charts 23092A, 23096A, 26508A, 26602A, and 26606A), the possible routes of old drainage systems may be inferred, particularly in areas lying off Kugmallit Bay and regions to the east. At least one of these has been confirmed by seismic reflection profiling (Shearer 1970). One submarine feature lying at the edge of the continental shelf directly northeast of Mackenzie Bay (Fig. 2) may represent an area where mass wastage of the subsoil occurred.

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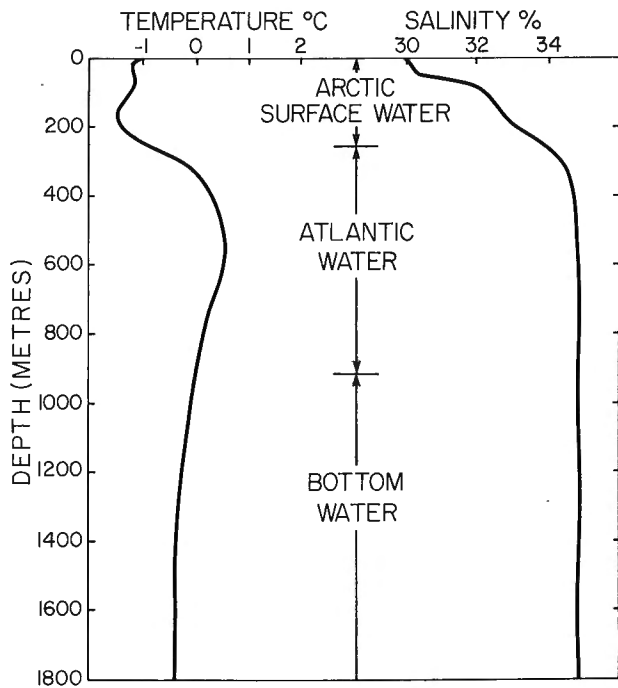
Figure 3. *A typical profile of temperature and salinity from the Beaufort Sea. (modified after Coachman and Aagard, 1974).*

Other morphological features shown on the Canadian Hydrographic charts are submarine hills that resemble the pingos described by Mackay (1976) on the Tuktoyaktuk Peninsula. The so-called submarine pingos (Shearer, et al., 1971) have summits that reach to within 11 m of sea level. These pingos are ice cored conical mounds up to 300 m in diameter at their base and rise to 20 to 50 m peaks which commonly have been breached by expansion within the pingo. Generally the submarine pingos occur on the outer shelf east of Mackenzie Canyon; those found in the inshore areas may have formed on land and subsequently may have been partly eroded and drowned recently by a rising sea (Shearer et. al., 1971). As on land, the submarine pingos occur singly and in clusters. Some conical mounds resembling pingos lie along the eastern edge of Mackenzie Canyon, but these appear to have been formed by the localized thixotropic movement of fine sediments. An accoustical cross-section of one such feature revealed a body of sediment that originated from an adjacent layer and was extruded through a vent in the core. These features also occur singly and in clusters, and are shallow in origin.

Grooves, or furrows, are abundant on the sea floor. They are generally steep walled linear features approximately 0.5 to 10 m deep, up to several tens of metres wide, and several hundred metres long. These features are produced by keels of drifting ice dragging along the sea floor. Although their orientation varies, the general direction of the grooving is southeasterly (Pelletier and Shearer, 1972) in response to the prevailing wind direction which drives the ice from the west and northwest. Most of the scours occur at depths between 10 and 50 m. At the shallower depths the scouring is more frequent and the scours shallower; in deeper waters the scours are fewer but deeper. Grooves at depths exceeding 50 m are thought to be mainly relics (Lewis, 1975).

Along the low-lying coast of the mainland, spits and bars are present and are associated with numerous headlands and offshore islands. These features are growing eastward in the direction of sediment transport, except where local gyres create counter currents along the shore that transport the
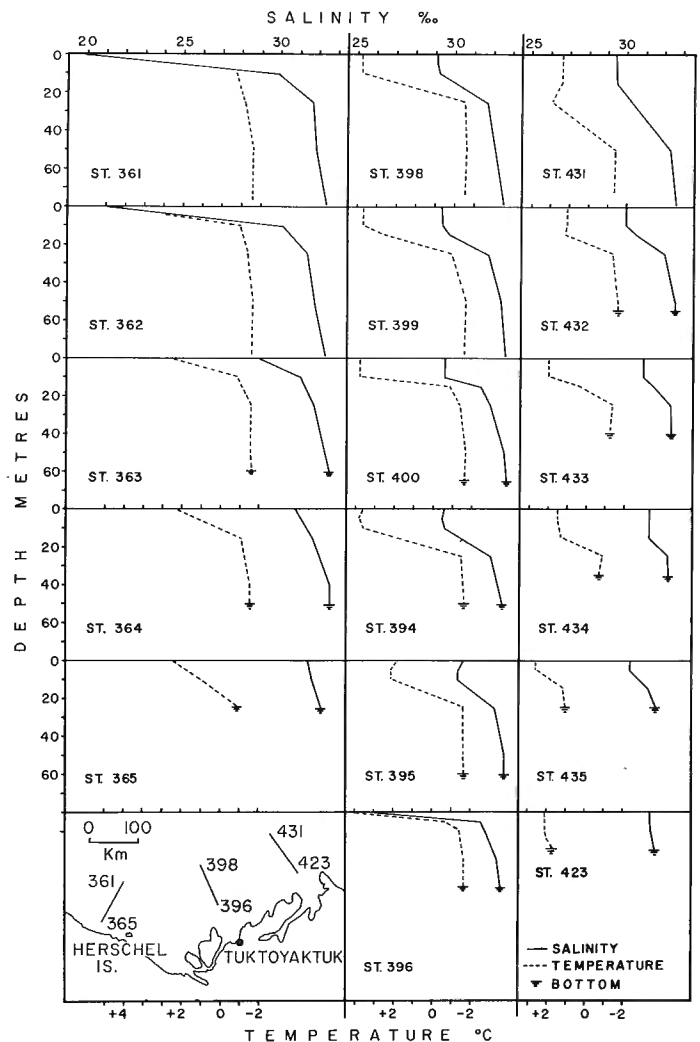
Figure 4. *Relation of summer salinity and temperature with depths in the Beaufort Sea (After Vilks, 1972).*

sediments to the west. Further aspects of the deltas and coasts, including their geography, erosion, aggradation, and sediments, are discussed by Lewis and Forbes (1975).

Oceanography

The Beaufort Sea is the southernmost extremity of the Arctic Ocean where the 1000-m isobath extends south of latitude 71°N (Fig. 2). The waters of the Canadian continental shelf of the Beaufort Sea have not been studied extensively. Early hydrographic observations were made by Inspector H.A. Larsen from the Royal Canadian Mounted Police vessel **ST. ROCH** while on patrol duties during 1935-37 (Tully, 1952). The first systematic survey of the water column and bottom features was carried out by Cameron (1952, 1953), from the **CGMV CANCOLIN**. Although the survey suffered from insufficient navigation facilities, important soundings were carried out in the nearshore areas. The effect of discharge from the Mackenzie River on the oceanic waters of the southeastern Beaufort Sea was determined under various meteorological conditions during the summer. The information on the offshore water mass structure has been gathered by Worthington (1959), Bailey (1957), Coachman and Barnes (1961, 1963), and Vilks (1972). Vilks (1973) reported temperature and salinity relationships with depth over the continental shelf and slope during the winter.

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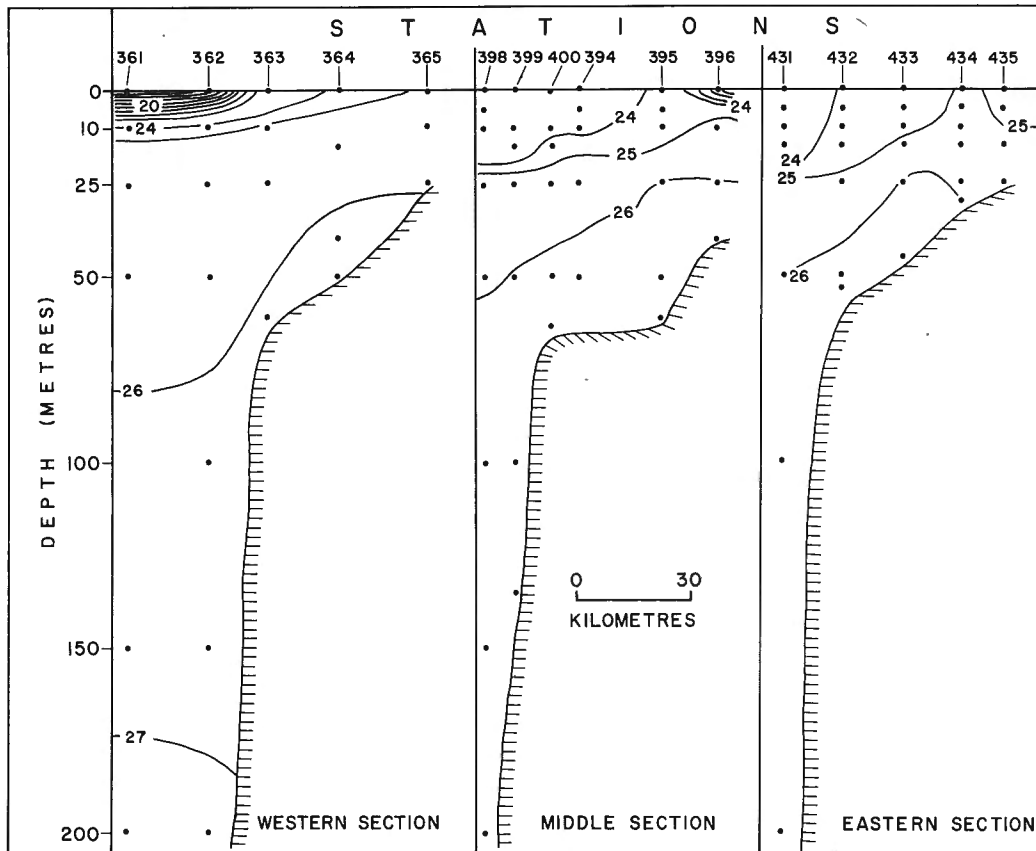
Figure 5. *Relation of summer density with depth in the Beaufort Sea (after Vilks, 1972). (Expressed as sigma-t which is defined as*
$$\sigma_t = (p-1)\ 1000 \text{ where } p \text{ is density of water}$$

O'Rourke (1974) provided a summary of available oceano-graphic information on the continental shelf of southeastern Beaufort Sea.

In the Arctic Ocean the water column consists typically of three layers (see Worthington, 1953 and Coachman and Aagaard, 1974): (1) Cold and relatively diluted Arctic surface water; (2) Warmer and more saline water of Atlantic origin below 200 m to a depth of about 400 m, and (3) Arctic bottom water. A vertical profile of temperature and salinity through the three layers in the Beaufort Sea is shown in Figure 3. The upper two layers of Beaufort Sea water are slightly different than the upper layers of water of the Arctic Ocean. The surface layer is less saline and warmer due to runoff from large Siberian rivers and the Mackenzie River, and the influx of Bering Sea water. The water of the Atlantic layer is colder in the Beaufort Sea than in the Greenland Sea through which it enters the Arctic Basin. As a result of heat loss to the surface, the temperature maximum in the Beaufort Sea is at much greater depths than in other parts of the Arctic Ocean.

The circulation of the surface water in the Beaufort Sea is clockwise, with the centre of the gyre at about 80°N, 140°W (Coachman and Aagaard, 1974). The circulation of the Atlantic layer in the Arctic Ocean is anticlockwise according to Coachman and Barnes (1963). As a result, Atlantic water enters the Beaufort Sea on a broad front across a line from Prince Patrick Island to Point Barrow. At the continental rise off the Mackenzie River delta, the flow separates; some of the water is deflected towards the west and follows the

continental slope of Alaska, but the largest part of the flow is deflected toward the east along the continental margin off the Queen Elizabeth Islands.

Generalized circulation patterns on the continental shelf of southeastern Beaufort Sea have been inferred on the basis of salinity and temperature relationships in the water column. Cameron (1953) noted that in the absence of winds the outflow from Mackenzie River moves eastward along the coast but strong easterly winds can reverse the circulation. Under these conditions the saline subsurface water can reach the surface along a zone between the coast and continental shelf to the east of the delta. Vilks (1972, 1973) also reported an upward migration of the denser subsurface waters on the continental shelf during late summer and late winter under a cover of ice. Salinity and temperature profiles obtained during the summer of 1970 are shown in Figure 4 and density-depth profiles of the same stations in Figure 5.

Density-depth profiles of the three sections show that the surface waters west of the delta are influenced more by melting pack ice than by land runoff. This is indicated by the landward surfacing of the isopycnals in the western section of Figure 5. The other two sections show evidence of the dilution of surface waters by Mackenzie River, but only at the shoremost stations. It is apparent that during the time of sampling Mackenzie River waters were following the coast to the east of the delta within a zone not wider than approximately 50 km. The summer density-depth profiles also show an upward migration of subsurface waters along all three sections.
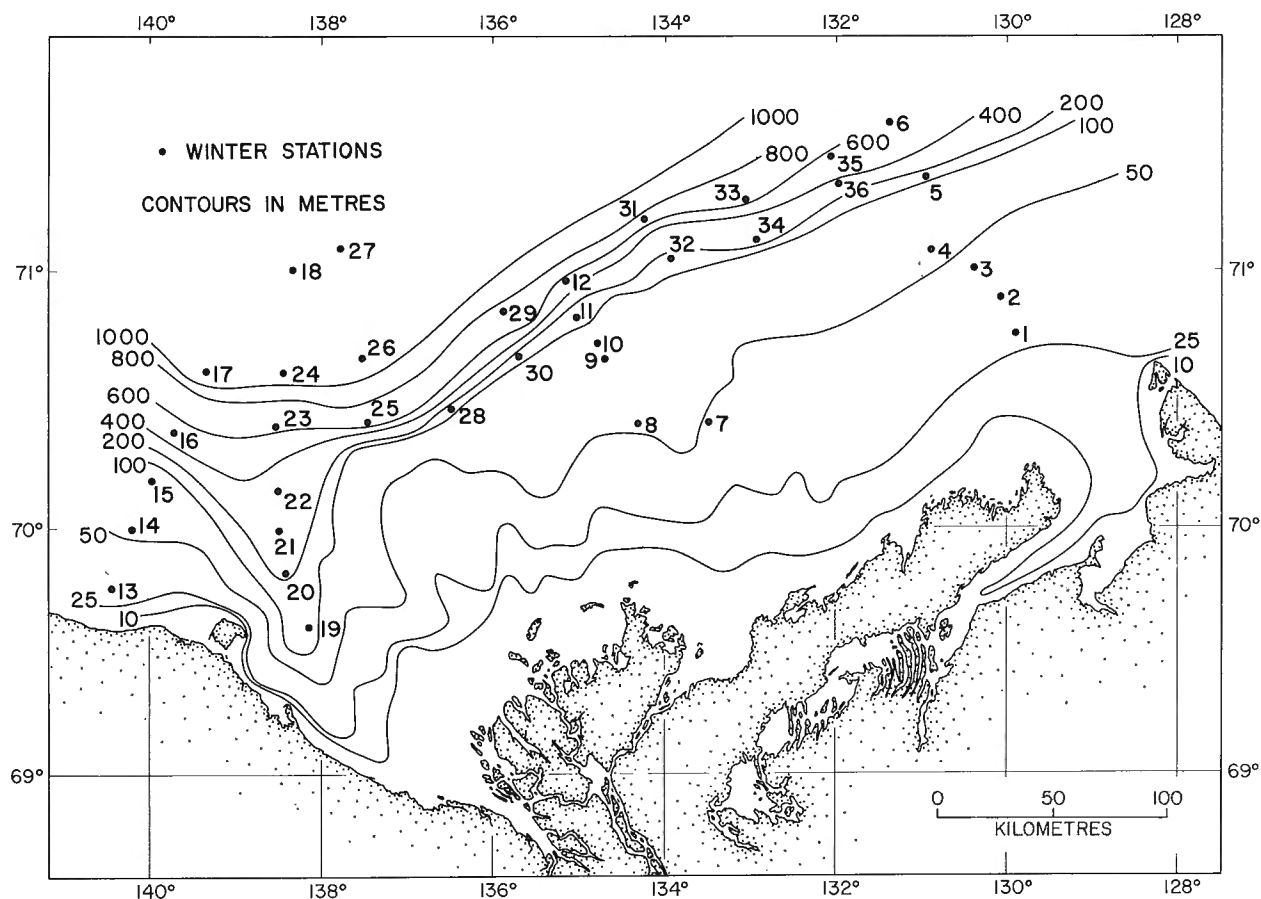
Figure 6. Location of winter stations.

The locations of winter stations (March-April, 1972) are shown in Figure 6. The recorded winter relationship of salinity and temperature with depth (Fig. 7) indicates a practically isothermal surface layer at about -1.5°C and the density of water is defined by its salinity. The surface layer contains a sharp halocline which is less pronounced at the eastern section due to progressively more saline surface waters towards the east. Except for the less extensive stratification in the upper 10 m, the winter density-depth profiles are reasonably similar to the summer cross sections (Fig. 8) with the heavier subsurface water rising along the continental slope. This phenomenon is also demonstrated by the horizontal distribution of surface salinities (Fig. 9). At the mouth of Mackenzie Canyon the surface salinities are greater than 30‰. Waters of this salinity are found between 30 and 40 m below the surface at the offshore western stations about 200 km from shore. These observations support the model proposed by Coachman and Barnes (1963) in which they suggested that the subsurface water in the Eurasian Basin of the Arctic Ocean is rising through the submarine canyons along the Siberian continental slope.

Ice, Oceanography, and Primary Production

Along the southeastern continental margin of the Beaufort Sea during the winter the ice exists principally in three zones: (1) the offshore polar pack, (2) the shore-fast ice along the coast, and (3) the year-old ice between the two zones (Anonymous, 1970). The polar pack is mainly old ice, 3-4 m thick and it is continuous. The year-old is 1-2 m thick, and generally covers seven-eighths of the sea surface. This ice is relatively unstable, and even during the winter may develop leads.

The extent of summer ice varies from year to year, and during 1970 light summer ice conditions prevailed and there were large areas of open water on the shelf. Initially a patch of open water is formed at the entrance of Amundsen Gulf as early as April and becomes a major centre of ice disintegration. This polynya expands to the west, and by mid-July the break-up along the coast becomes significant. During the period of melting in August the ice edge gradually moves seaward and in an ordinary year, the pack will retreat 180-300 km off the Canadian coast. The extent of open water depends on the direction of the prevailing winds; persistent northwesterly winds will drive the polar pack shoreward. Freeze-up in the Beaufort Sea is usually in the second week of October, but may vary from late September in congested seasons to early November if the pack has moved well offshore.

The thick cover of ice and snow is a major inhibitor to a sustained primary production in the water column. On the sea floor at shallower localities ice-scouring of the bottom disturbs the benthos (Carey et al., 1974). In that respect, the physical environment of the Beaufort shelf is more adverse for biological activities in comparison with other continental shelves at lower latitudes and with similar physiography.

The rates of primary production under polar ice are negligible during winter (e.g. English, 1961), but during the open season may be high, except in the nearshore regions, which are covered with the turbid waters of Mackenzie River (Grainger, 1974). In the open water of the offshore and beyond the plume of the Mackenzie runoff, exact measurements of primary productivity are lacking. To have some indication of what the production rates might be, standing crops of total biomass collected during the summer of 1970 and winter of 1972 are used.

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Figure 7.

Winter relationships of salinity and temperature with depth in the Beaufort Sea. (Asterisks indicate poor data).
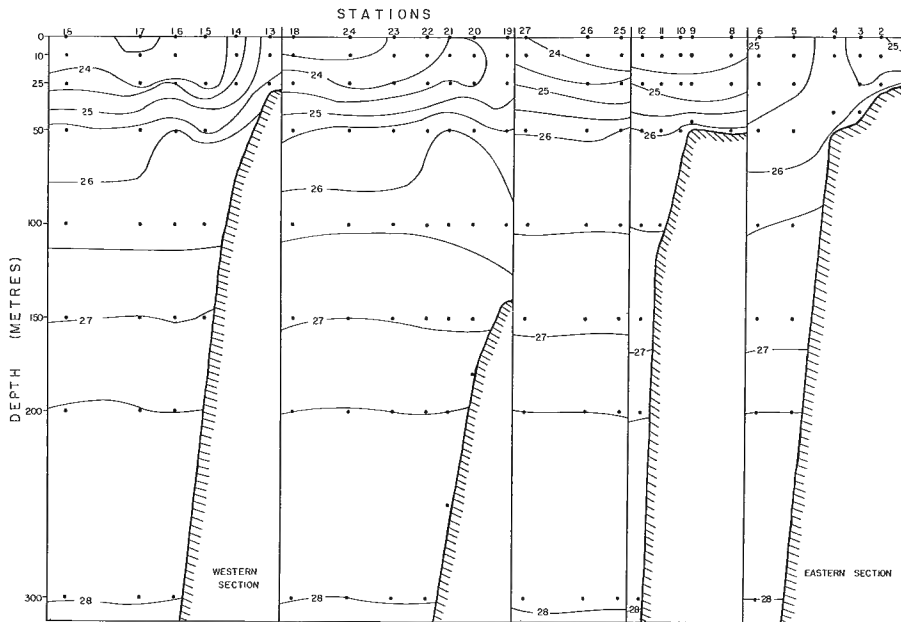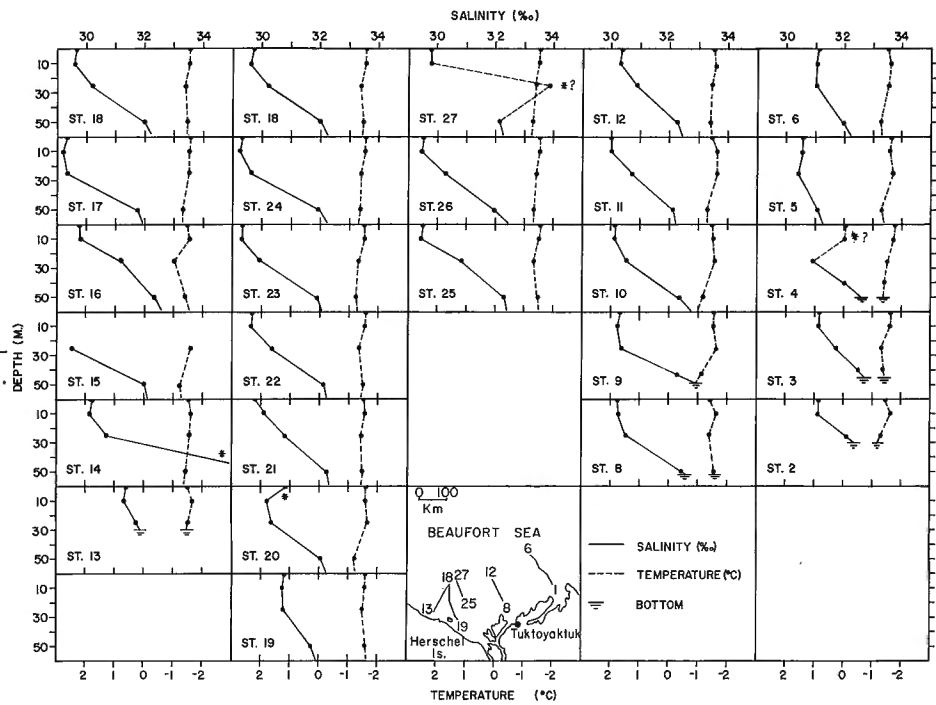
Figure 8.

Relation of winter density with depths in the Beaufort Sea. (see caption of Figure 5 for definition).

Figure 10 shows the distribution of the standing stocks on the continental shelf during summer, including a few stations off the shelf along the edge of the polar pack. The average standing stock of these collections is 37.1 mg/m³ water filtered. Similar methods of collecting were used on the Labrador shelf during 1973 (van der Linden, 1973) where an average of 9.1 mg/m³ was measured. These numbers indicate that summer standing stocks over the Canadian portion of the Beaufort shelf are comparatively high. They are highest to the east of the delta where a maximum of 367 mg/m³ was measured. Small patches of high biomass were also found along the continental margin and to the west of Herschel Island.

The lowest standing stocks were found offshore and along the margin of the polar pack. A zone of low values also extends over parts of the Mackenzie Canyon to its headward portion in Mackenzie Bay.

The distribution pattern of the standing stocks reflects the local water mass properties. High standing stocks are maintained in areas of sustained supply of nutrients and under normal marine conditions. The data seem to indicate that such areas exist off Cape Bathurst and along the outer shelf where waters rich in nutrients may be supplied as a result of upwelling. West of Herschel Island the area of high biomass may indicate the presence of nutrient-rich Bering Sea waters (Mountain, 1974). However, in addition to local factors, the
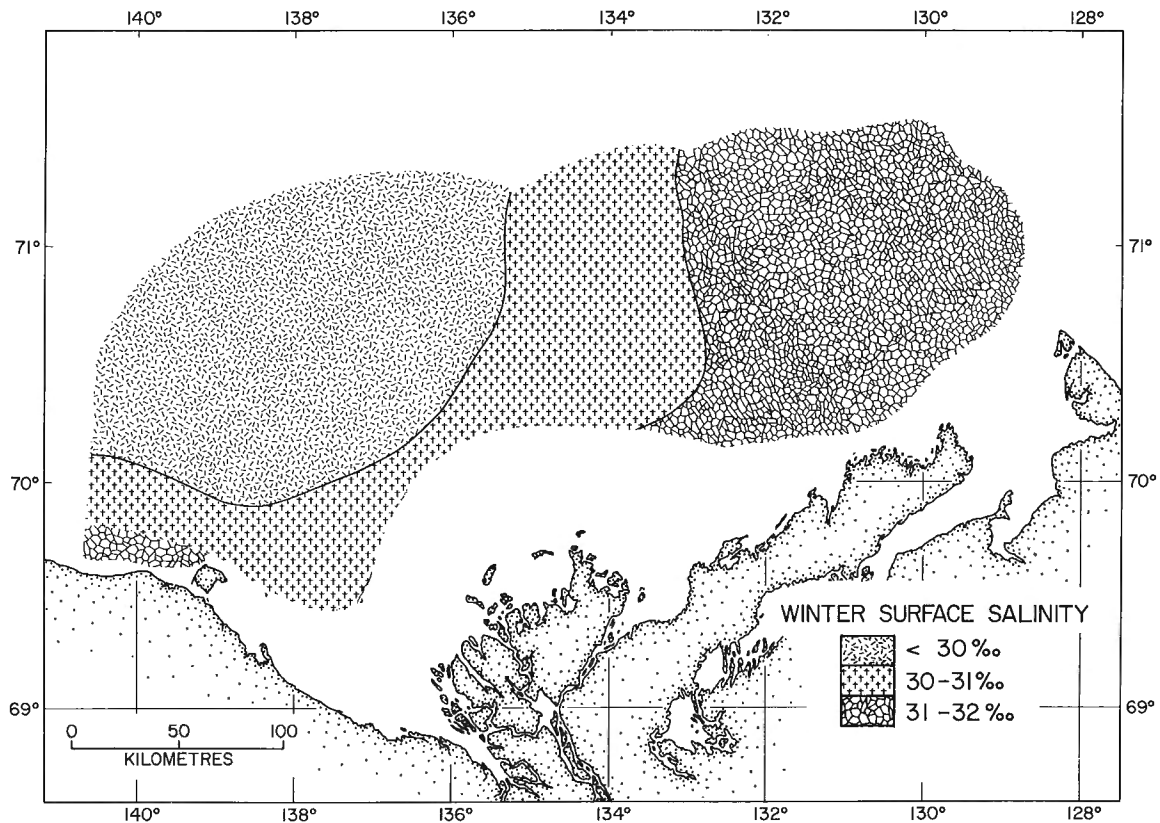
Figure 9.   *Distribution of winter surface salinities.*
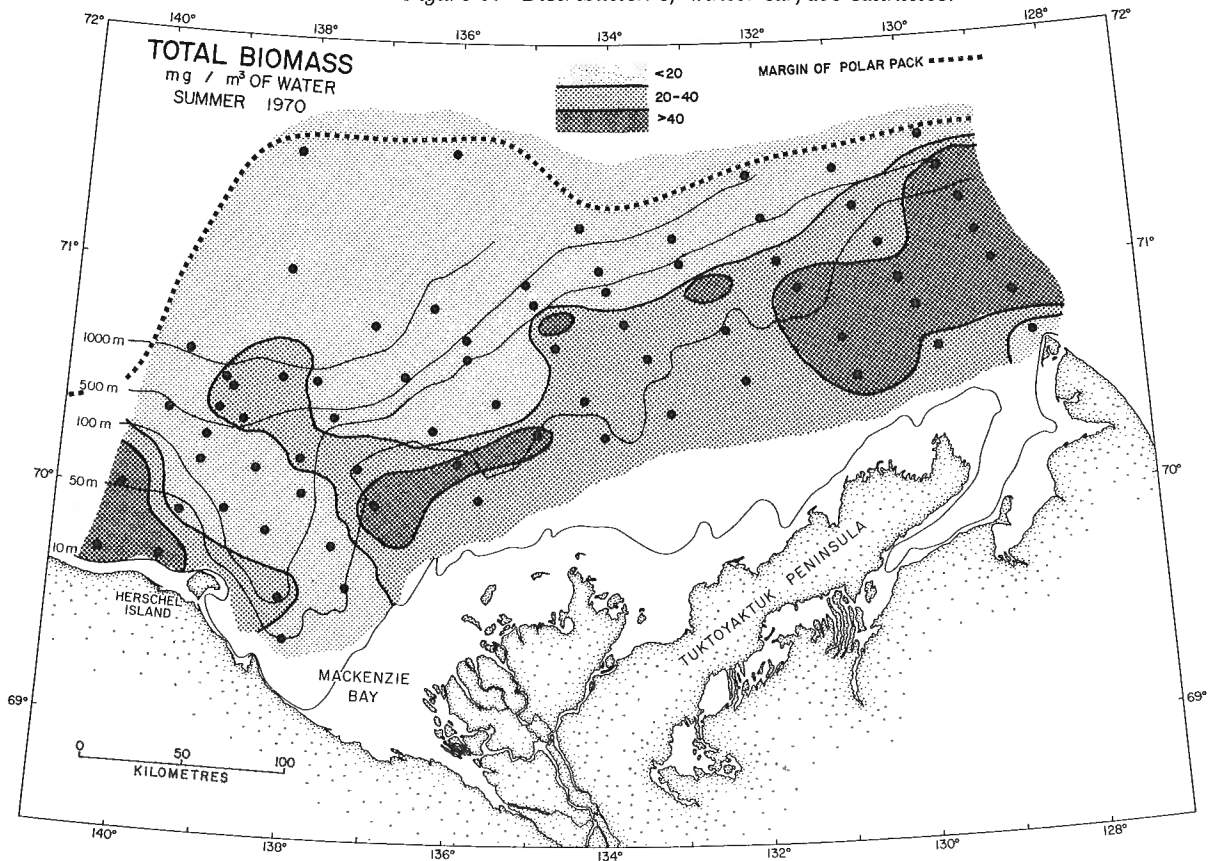
Figure 10.   *Distribution of standing stock (dry wt. mg/m³ water filtered) of total plankton in the water column during September 1970.*

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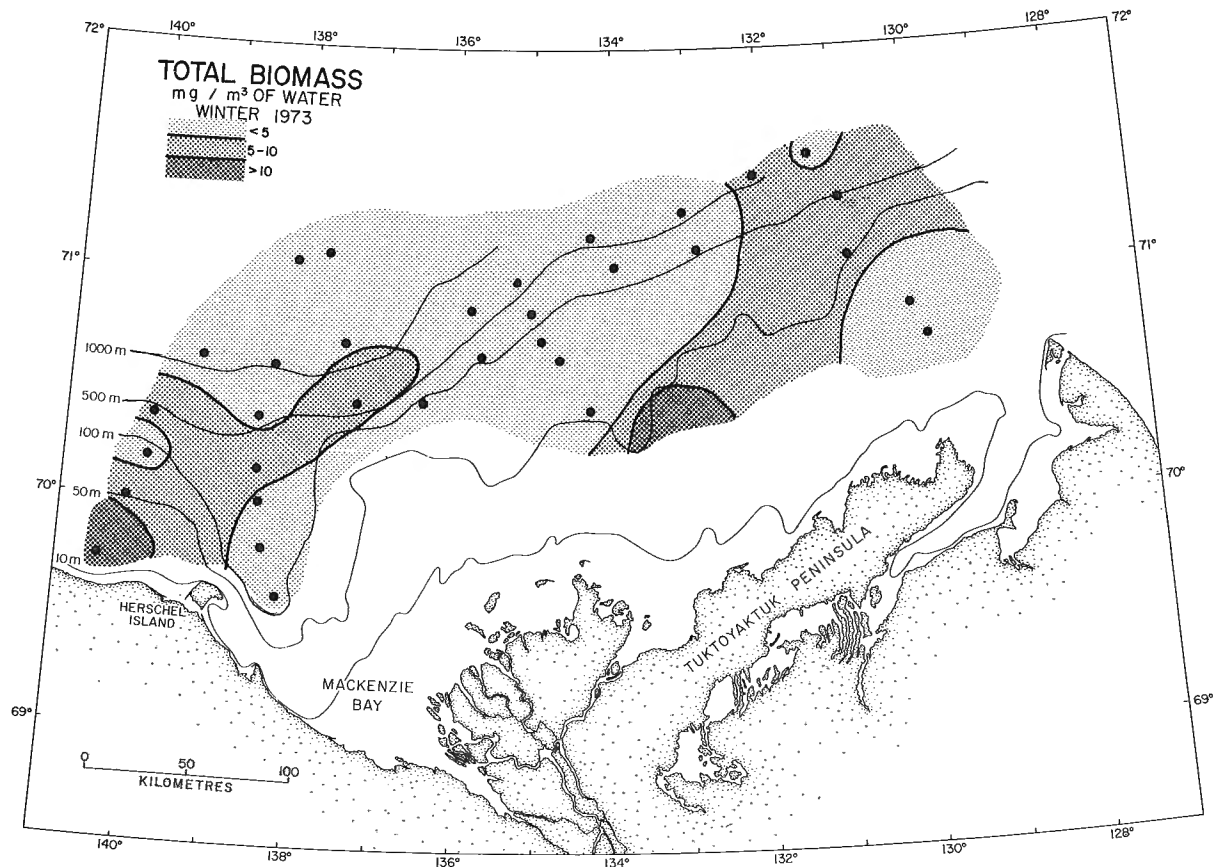
Figure 11. Distribution of standing stock of total plankton in the water column during March-April, 1972.

standing stock at any locality is dependent on the migration of the water mass, which may be largely wind-driven on the shallow continental shelf. Therefore, the overall pattern of standing stock may exhibit high temporal variability and the pattern shown in Figure 10 may not be representative for the whole summer season. Nevertheless, high numbers of foraminifera are also found in sediments off Cape Bathurst (Figure 24) at the nearshore stations to the east of Herschel Island and to the north of Mackenzie delta, which suggest that these areas are capable of maintaining relatively high rates of organic production.

The distribution of the standing stock during the winter is shown in Figure 11. The average dry total biomass at the winter stations is 4.7 mg/m^3 of water filtered, which is approximately eight times smaller than the summer average. Although Figure 11 shows a pattern of relative weights of standing stocks, it is not very meaningful in terms of environmental differences. The range of weights is within the expected sampling and experimental error with only two stations showing values greater than 10 mg/m^3. At the shore-most station west of Herschel Island a maximum weight of 22 mg/m^3 was obtained, which may reflect the fact that the sea ice in that area is relatively less stable. During April 1972 extensive fields of hummocked ice and open leads were observed in this region. In conclusion, the data indicate that during the open season the continental shelf waters can sustain relatively high standing crops of plankton. The winter averages one-eighth of the summer standing crop, basically because of the presence of sea ice.

The polar pack of the Arctic Ocean is in constant motion in response to winds and currents. The ice may contact the bottom of the shallow continental shelf and under pressure may form gouges in the sediment (Reimnitz and

Barnes, 1974). Most of the bottom scouring takes place between depths of 10 and 50 m (Pelletier and Shearer, 1972) with a density of 15 to 20 scours per kilometre of ship track. The scouring of the sea floor may cause sediment mixing and the presence of stranded blocks of ice may induce increased bottom turbulence in areas where weak currents normally prevail. This influence of ice scouring on the benthos is not well understood, although Vilks (1976) found large numbers of foraminifera in the sediments of the intensely ice-scoured nearshore zone in Byam Martin Channel, Canadian Arctic Archipelago.

SURFICIAL SEDIMENTS

Distribution

All textural classes of sediment from clay to gravel are present on the floor of southern Beaufort Sea and are shown in the ternary textural diagram (Fig. 12), adapted from Shepard (1954) for the classification of marine sediments. Clearly the silty clays are the most abundant and sand, combined with gravel, is the least abundant.

The sediment types depicted in Figure 12 were plotted for each sampling station according to their major groups and subgroups. Sand and gravel occur on the Beaufort shelf west of Herschel Island, along the coast and in the Mackenzie Delta, and in isolated areas across the eastern portion of the Beaufort Shelf. The silty sediments are the next most widespread and are found in the inshore zone beyond the sands, and out to the 10-m isobath. However, they also occur in a zone, which varies in width between 50 and 100 km and extends across the eastern portion of the Beaufort Shelf. The remainder of the Beaufort Shelf, including the Mackenzie Canyon, is covered almost entirely by clay and silty clay.
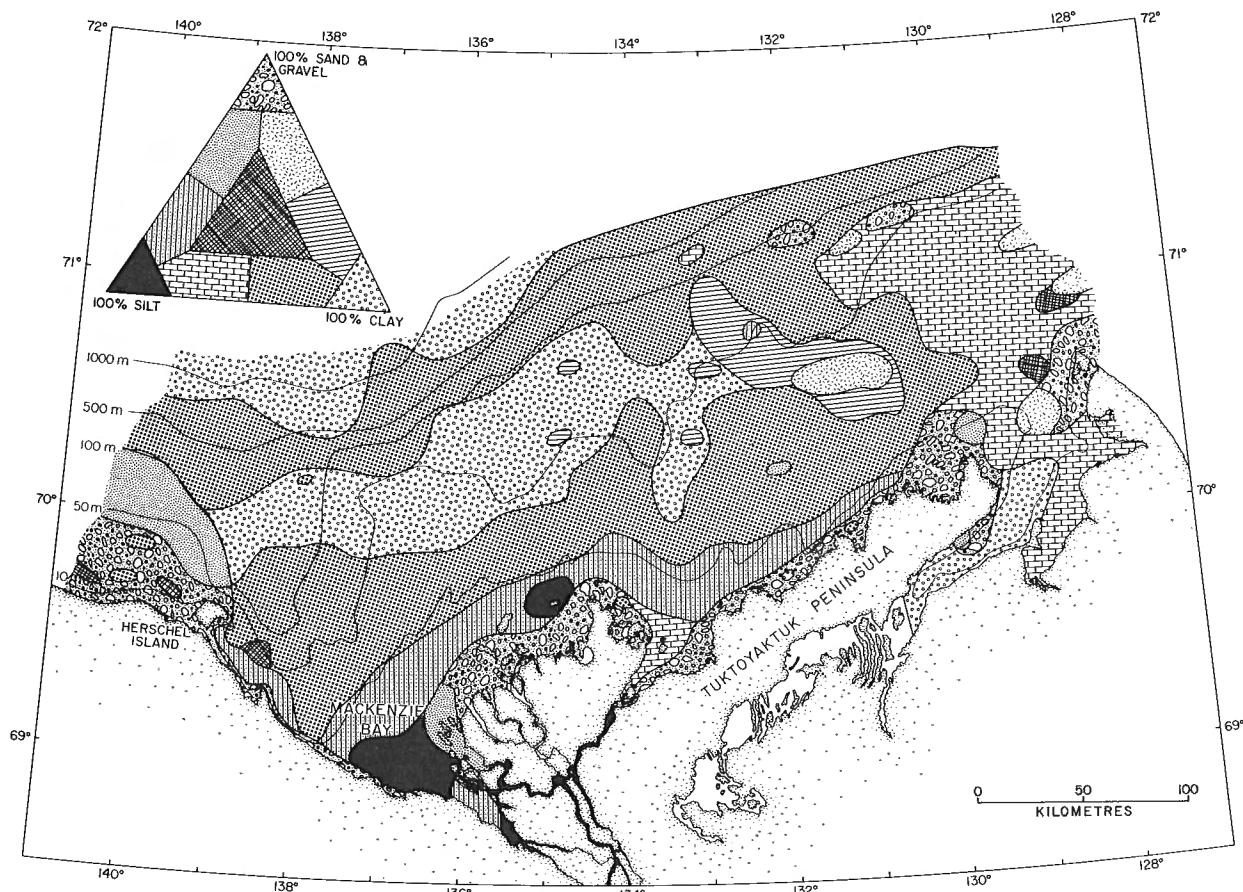
Figure 12. The distribution of main sediment types on the Beaufort Shelf. The ternary textural diagram of main sediment types is after Shepard, 1954.

Gravel (Fig. 13) is moderately widespread but generally is not abundant except for an area northwest of Herschel Island, and a smaller, somewhat isolated area on the extreme eastern end of the Beaufort Shelf. More than 150 samples contain no gravel in the intervening area. Gravels on the western portion of the shelf are thought to be ice rafted in origin, particularly as drifting ice which contains sediments is blocked from passage to the east by Herschel Island. Such ice releases its sediment load, which commonly is a mixture of many sediment types. On the eastern Beaufort Shelf, gravel may be relict beach or fluvial material that has been winnowed and subsequently exposed by the scouring action of bottom currents.

Sand (Fig. 14) is more widespread than gravel, and is generally more abundant. The greatest concentration of major deposits is in the area west of Herschel Island; other deposits lie along the coastal zone, and on the eastern portion of the shelf. In some bays and inlets along the coast, the sand is covered by a veneer of mud. Over Mackenzie Canyon and the central part of the shelf adjacent to the eastern flank of the canyon, sand is absent or scarce (less than 1%).

Silt (Fig. 15) is distributed most abundantly in Mackenzie Bay and the coastal areas bordering the Mackenzie Delta. Another prominent zone of silt extends across the eastern part of the shelf. In all other areas it constitutes less than 40 per cent of the bottom sediment.

Clay (Fig. 16) is present over the entire shelf, but its greatest concentration occurs on the floor of Mackenzie Canyon and the central part of the shelf east of Mackenzie Canyon. It thins out peripherally from this major concentration, and in a general shoreward direction.

Silt/Clay Ratios

The mean phi diameter of each sample is used with the silt/clay ratio for the determination of hydrodynamic vigour. Reliable values for sorting could not be obtained over the Beaufort Shelf as a whole because the mechanical analyses were not carried out beyond the 10-phi size. Skewness values are partly subject to the same analytical limits as those for standard deviation and sorting; therefore these moment measures are not considered.

Silt/clay ratios offer additional information in interpreting the hydrodynamic conditions on the floor of the Beaufort Sea. From earlier sediment analyses from the Bay of Fundy (Pelletier, 1974), from Baffin Bay (Pelletier et al., 1975), and other areas (Pelletier, 1973), it was determined that higher silt/clay ratios reflected conditions of considerable hydrodynamic vigour, and the lower ratios indicated quieter conditions. In the Beaufort Sea, the highest ratios (>5.0) calculated were for Mackenzie Bay and adjacent coastal areas (Fig. 17). Less than 10 km from shore the silt/clay ratios decrease markedly (<1.0), and are lowest (<0.25) in the central area over Mackenzie Canyon and the continental shelf. The ratio of 0.40 was contoured separately because it demonstrates the trends of sedimentation best. It generally outlines the area of least values of the silt/clay ratio (Fig. 17) which shows that the area enclosed by the 0.40 silt/clay boundary is the site of the least vigorous sedimentation. The 0.40 ratio also indicates that sediments, as well as discharging from Mackenzie River and moving easterly, may also move westerly from the eastern end of the continental shelf toward the area of quiet deposition immediately to the west and over Mackenzie Canyon. The isopleths of the silt/clay ratios generally parallel the coastline and isobaths except in the eastern part of Beaufort Sea where they transect the isobaths over the continental shelf.

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Figure 13.

The distribution of gravel.

	< 1 %
	1 − 5 %
	5 − 10 %
	10 − 20 %
	20 − 30 %
	30 − 40 %
	40 − 50 %

Figure 14.

The distribution of sand.

	0 − 1 %
	1 − 10 %
	10 − 20 %
	20 − 40 %
	40 − 60 %
	60 − 80 %
	80 − 100 %

Figure 15.
The distribution of silt.

0 – 20 %
20 – 40 %
40 – 60 %
60 – 80 %
80 – 100 %

1000 m
500 m
100 m
50 m
10 m

HERSCHEL
ISLAND

MACKENZIE
BAY

TUKTOYAKTUK PENINSULA

KILOMETRES
0   50   100
0   25   50
STATUTE MILES

Figure 16.
The distribution of clay.

0 – 20 %
20 – 40 %
40 – 60 %
60 – 80 %
80 – 100 %

1000 m
500 m
100 m
50 m
10 m

HERSCHEL
ISLAND

MACKENZIE
BAY

TUKTOYAKTUK PENINSULA

KILOMETRES
0   50   100
0   25   50
STATUTE MILES

11

Figure 17.

Map of the silt/clay ratios.

< .25	
.25 – .50	
.50 – .75	
.75 – 1.00	
1.00 – 2.00	
2.00 – 5.00	
> 5.00	
40	

Silt/Clay Ratios and the Hydrodynamic Environment

To quantify the depositional energy characteristics of different areas of the shelf, the curves adapted by Hjulström (1939) were used to obtain the depositional velocity of the mean grain size of samples containing fine and homogeneous sediments and Figure 11 of Pelletier (1973) was used for samples containing coarser and poorly sorted sediments. The energies were calculated from the equation:

$$\text{Energy/Volume} = \text{Density} \times (\text{Velocity}^2/2)$$

Assuming the density of water (in cgs units) to be unity, then the calculated value of energy/volume is a direct function of the square of the velocity, and the units are ergs/cm^3. This gives a universal unit that can be used to compare the hydrodynamic vigour in various aqueous sedimentary environments, and thus serve as a basis for classifying such environments. Hjulström values tend to be too high because the velocities were measured up to 1 m above the bottom. However, the energies so calculated represent minimal energies available in the environment, and neglect the higher energies required to initiate scour and sediment transport.

In Figure 18, a plot of the silt/clay ratios versus the phi mean diameters shows the relationship of these two textural parameters to the degree of hydrodynamic energy. The energy zones are defined on the basis of average current velocities and provide the basis for a schematic model of sedimentation. The upper limits of the model would be equivalent to an energy/volume value of approximately 5400 ergs/cm^3 with an equivalent current velocity of 104 cm/s. The energy/volume values between 113 and

613 ergs/cm^3 are based on current velocities of 15 to 35 cm/s (see Fig. 16). No samples were taken in the high energy zone similar to those reported for the high energy zones of the Bay of Fundy and Minas Basin (Pelletier, 1973, 1974) and the Scotian Shelf (Pelletier, 1973). It is interesting to note that although the sea floor northeast of Herschel Island is characterized by coarse sediments, the silt/clay ratios are low and the samples from this area occupy the intermediate energy zone close to the abscissa of Figure 18. These deposits are not in equilibrium with the existing hydrodynamic environment and ice rafting may be considered as an agent of deposition.

The energy/volume values of the lower limit of the intermediate zone (0.0017 to 0.0256 ergs/cm^3) are based on depositional current velocities of 0.058 to 0.226 cm/s. The predominant sediments are sands and silts with high silt/clay ratios. In the study area such sediments are found mainly along the coast to the north and east of the delta.

The lower limit of the low energy zone is designated at the energy/volume level of 0.0013 to 0.0015 ergs/cm^3, on the basis of depositional velocities between 0.051 and 0.055 cm/s. The sediment is at least 65 per cent silt with most of the remainder consisting of clay.

A zone of very low energy was selected to represent those areas influenced by only very low current velocities. The energy volume is correspondingly low and generally less than 0.0015 ergs/cm^3, based on depositional velocities below 0.055 cm/s. Sediments in this zone are predominantly clay with generally less than 35 per cent silt in the remainder. Fine sand may be present in proportions of 1 per cent or less.

12
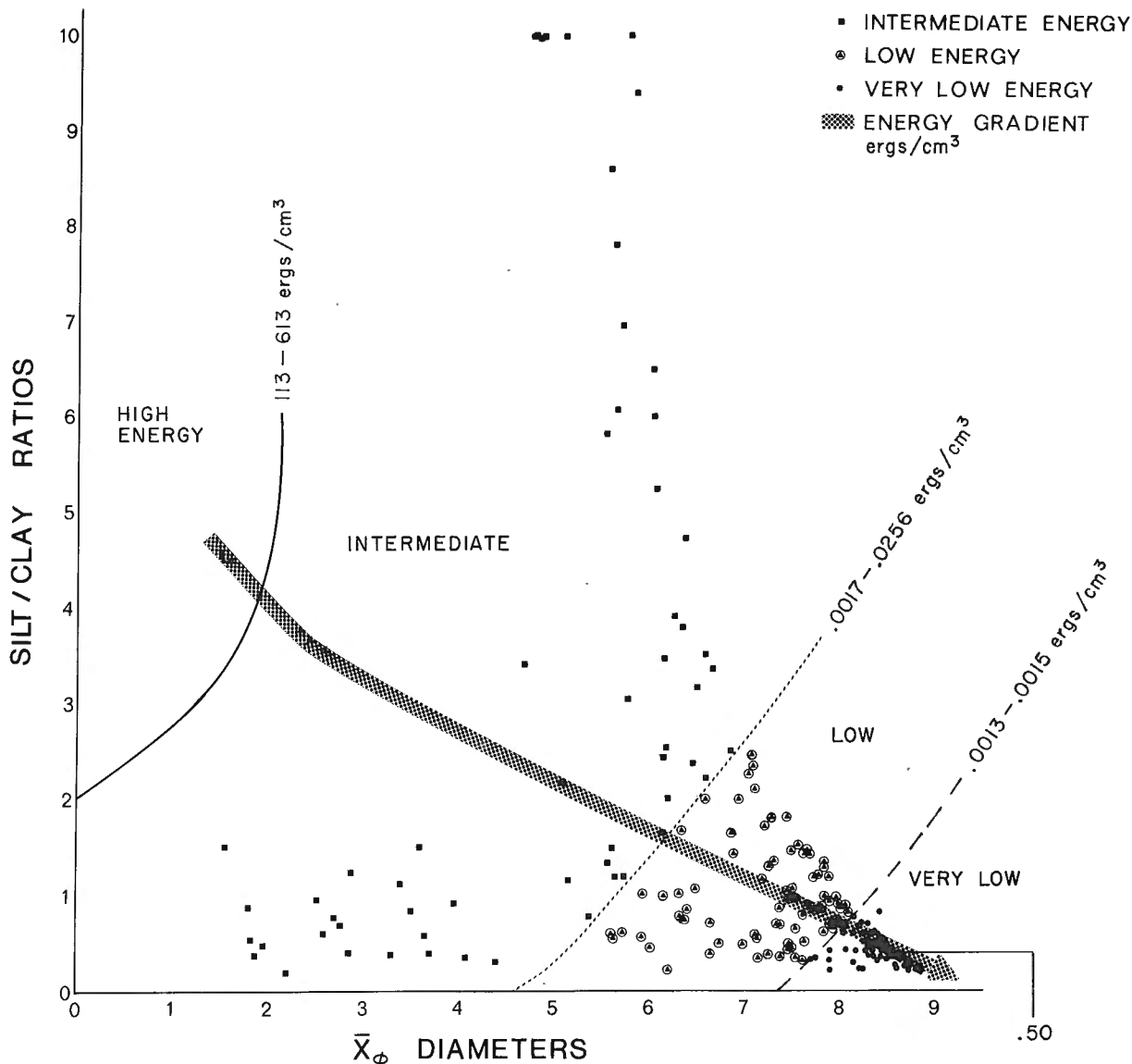
Figure 18. *Plot of silt/clay ratios versus phi mean diameter ($\overline{X}\phi$) shows the energy regimes for Beaufort Sea sediments.*

On the plot of silt/clay versus phi mean diameters (Fig. 18), the energy gradient is shown passing orthogonally through the energy zones. This is based on the premise that decreasing energy corresponds both to decreasing silt/clay ratios and decreasing grain size. The gradient approaches zero along the abscissa because the silt/clay ratio is zero along that axis. However, on the ordinate, the gradient extends asymptotically because the silt/clay ratios tend toward infinity at their greatest magnitude. Practically, however, an upper limit is drawn at some threshold value of the silt/clay ratio (in this case 10), because the ratio cannot be plotted at infinity.

Based on the graph of the silt/clay ratios versus phi mean diameters (Fig. 18), all samples for each arbitrarily chosen environment were plotted on a regional map of the Beaufort Sea (Fig. 19), and the various environments were delineated. As a rule, the energy decreases seaward from Mackenzie Delta and most coasts bordering Beaufort Sea.

The zone of intermediate hydrodynamic environment lies within the Mackenzie Delta, Mackenzie Bay, and Kugmallit Bay, the adjacent coastal areas west of Herschel Island, and the eastern portion of the continental shelf. The energy/volume values, to be expected as acting on these sediments would be 0.0256 to 613.0 ergs/cm³ as minimal depositional energy. These amounts overlap with the low and high-energy zones respectively.

The low energy environment extends seaward of the intermediate environment to the shelf-slope break west of Mackenzie Canyon, easterly along the 25-m isobath (approximately) west of Mackenzie Bay to a point midway along the Tuktoyaktuk Peninsula, and then northerly across the shelf to the upper part of the continental slope. The energy/volume values in this zone range between 0.0256 and 0.0015 ergs/cm³.

The zone of very low energy occurs seaward beyond the boundaries of the low-energy environment. It extends from almost the head of Mackenzie Bay over Mackenzie Canyon, and across the immediately adjacent shelf to the east. The energy/volume values, derived from depositional velocities acting on the sediments, are less than 0.0015 ergs/cm³. Thus almost the entire central area of the southern Beaufort Sea can be characterized as a zone of very low hydrodynamic vigour.

13
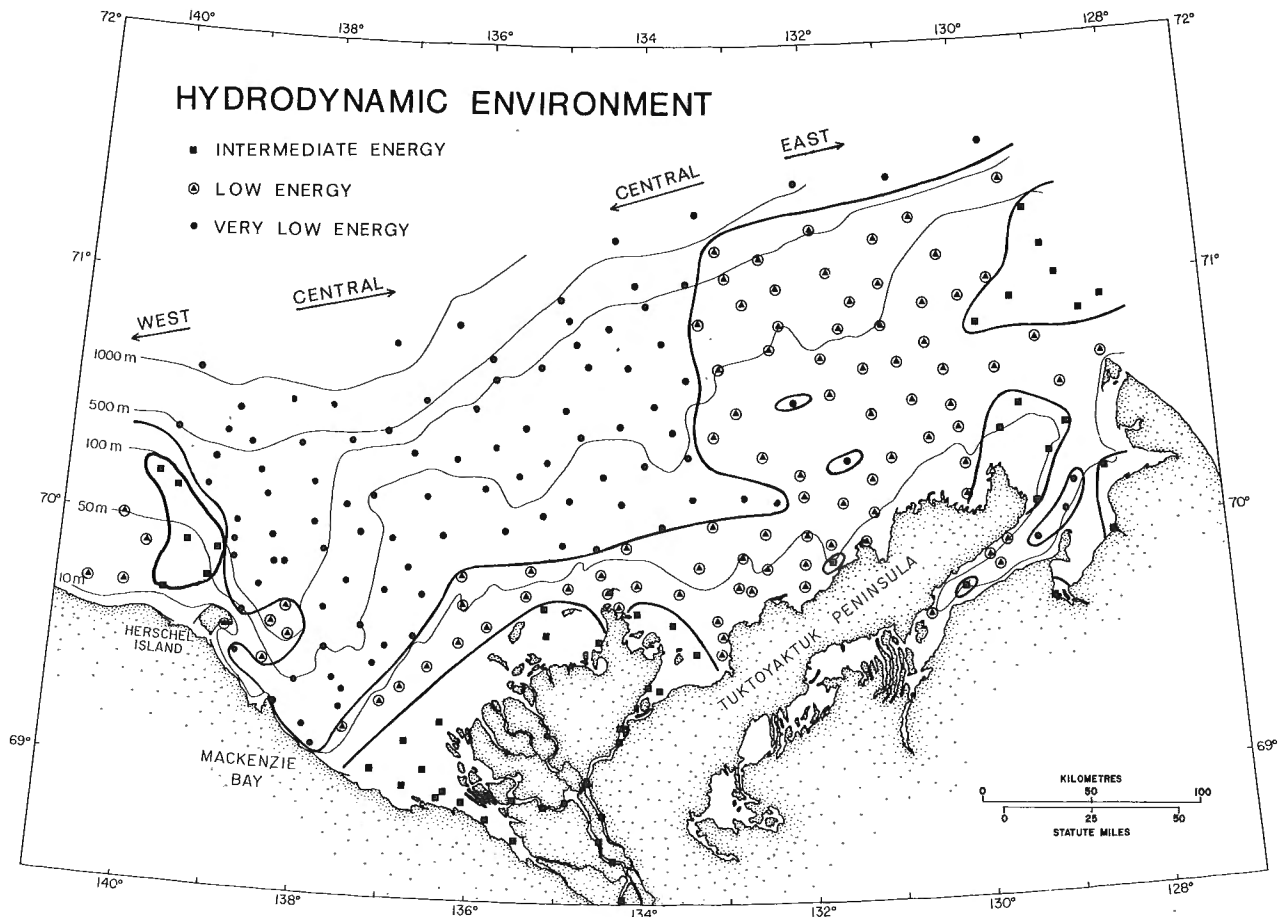
Figure 19. Distribution of hydrodynamic regimes on the Beaufort Shelf

Sediment Transport

Based on the textural analyses and interpretation of the results of the clastic ratios and presumed hydrodynamic environments in the southern Beaufort Sea (Fig. 19), a model of sediment transport was constructed to show the movement of sediments in the southern Beaufort Sea (Fig. 20). Long-shore drift takes place in both easterly and westerly directions along the coast, as shown by the growth direction of bars and spits adjacent to headlands and islands. Most sediments however come from Mackenzie River, from which a plume of sediments (Fig. 21) originates and moves a distance of 55 to 70 km seaward along the axis of Mackenzie Canyon. This plume veers easterly as it is influenced by the Coriolis force, and forms a distinctive band about 30 to 40 km wide where it dissipates off the eastern part of Kugmallit Bay. A similar sediment plume emerges from the eastern channel of Mackenzie Delta and merges with the plume from the western Mackenzie River in the western part of Kugmallit Bay. Some sediment also moves directly seaward along the Tuktoyaktuk Peninsula particularly in the eastern part where it appears to deposit to the edge of the continental shelf.

Flocculation of the clay particles occurs within and on the periphery of the sediment plume. Such particles, however, remain fairly small (Bornhold, pers. comm., 1975) and are carried seaward and deposited with organic mats. These organic mats appear to bind the sediments and organic particles and deposit them in quieter waters. These organic-inorganic suspensions are shown in photomicrographs (Bornhold, 1975) of suspended sediments obtained in the water column at different depths across the continental shelf.

During the winter the Arctic gyre migrates southward (R. Herlinveaux, pers. comm., 1975) so that a westerly current is then available to scour and transport fine material (silt and clay) to the west. A possible "race-track" model for sediment transport can be envisioned in which sediments continually move easterly and veer northerly off Liverpool Bay and continue to veer to the left so that the direction of movement is westerly. However this interpretation is unlikely to be correct as certain shear forces associated with the movement of the Arctic gyre south would tend to produce discontinuities along the boundary separating easterly and westerly moving sediments. Upwelling observed along the western continental shelf/slope break (see Bornhold, 1975) may introduce sediments to the outer shelf, and this may occur west of Mackenzie Canyon as well.

An ice rafted deposit occurs north of Herschel Island, and this is distinct from most other occurrences of gravel on other parts of the shelf. This origin is suggested by poor sorting, little fine sediment, and the low energy environment.

This model of sediment transport (Fig. 20) is in accordance with the observed movement of sediments from environments of higher hydrodynamic energy to those of lower. Concomitant with this movement, the sediment grain sizes decrease in the direction of sediment transport.

In summary, sediments on the floor of Beaufort Sea are mainly fine grained and consist predominately of clay and silt on the western and central areas, and somewhat coarser types in the eastern part. In the delta area and immediately offshore, this dispersal pattern is partly a result of the fine grained sediment discharge from Mackenzie River. Over the eastern portion of the shelf, the dispersal pattern is partly
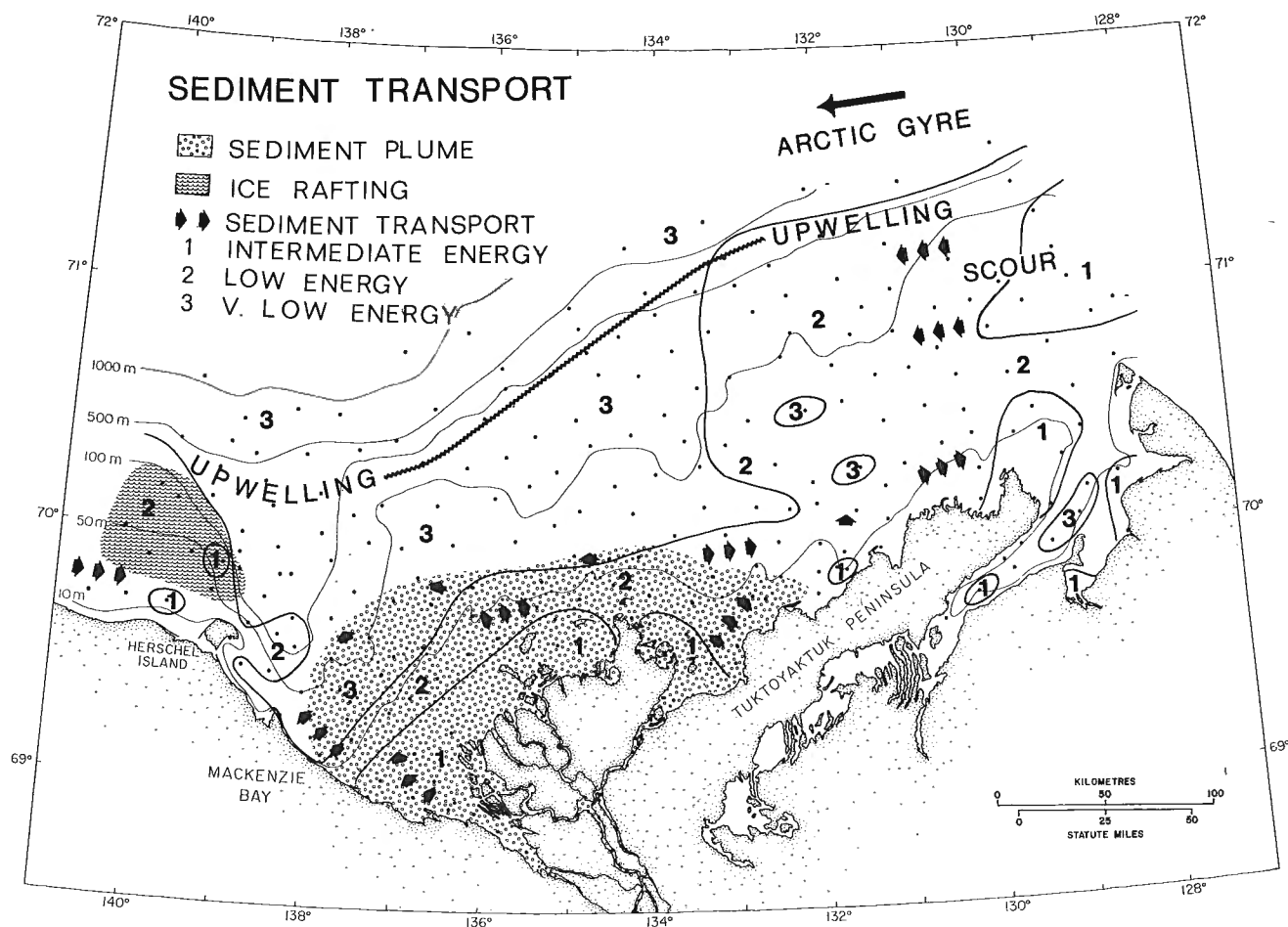
Figure 20. Model of sediment transport in the southeastern Beaufort Sea

due to sedimentation of fine particles over a relict surficial sand and partly to the intermittent erosion of the substrate by westward-moving bottom currents. Thus the eastern shelf appears to serve alternately as a depositional and erosional site. The area northwest of Herschel Island may be receiving ice rafted deposits.

ECOLOGY

Planktonic Foraminifera

The water column and sediments of the Arctic Ocean contain only one species of planktonic foraminifera, commonly known as **Globigerina pachyderma** (Ehrenberg). The generic affinity of this species has been questioned recently and it may appear in the literature as **Neogloboquadrina pachyderma** (Ehrenberg) (Srinivasan and Kennett, 1974) or as **Globorotalia pachyderma** (Ehrenberg) (Jenkins, 1967; Vilks, 1975). As a result of a detailed study of test ultrastructures (Vilks, 1973) we believe that **Globorotalia pachyderma** is the correct name for the planktonic foraminifera found in the Arctic Ocean. The summer distribution of planktonic foraminifera in the water column and sediments of the Beaufort Sea continental shelf between longitudes 128°W and 140°W was described by Vilks (1972). The study included the collection of oceanographic data, and the distribution of living foraminifera was correlated to water mass characteristics. The waters that are not influenced by the river runoff during the summer contained a foraminiferal standing crop comparable to that in temperate latitude outer continental shelves. During the winter and under the cover of ice, living planktonic·foraminifera in the water column are 200 times less numerous than in the ice-free season (Vilks, 1973).

Planktonic foraminifera thrive in offshore oceanic waters and normally occur in progressively smaller numbers as the influence of land runoff increases. Assuming that the effect of dissolution and selective deposition of tests is negligible, the distribution patterns of **G. pachyderma** in the sediments should therefore reflect the relative volumes of offshore waters on the continental shelf.

The number of **G. pachyderma** found in core tops is shown in Figure 22. The highest numbers occur at the offshore stations on the continental rise. On the continental slope the tests of **G. pachyderma** are present at almost every station at water depths greater than 100 m, but at shallower depths on the continental shelf the sediments are virtually barren of planktonic foraminifera.

Benthonic Foraminifera

Little has been published on the foraminifera found in the sediments of the Mackenzie River delta area. Carsola (1952), collected 15 sediment samples on the shelf between Banks Island and longitude 140° to the west at depths ranging from 37 to 1317 m. This report also included sampling stations on the continental shelf as far west as the Chukchi Sea. On the basis of the available data Carsola (1952) was able to show, with regard to the benthic environment, that the continental shelf can be divided in two regions along longitude 155°W. West of this line the foraminifera are similar to Chukchi and Bering Sea faunas but to the east a unique eastern Beaufort Sea continental shelf fauna exists, which is influenced by the outflow of large rivers such as the Colville and the Mackenzie.

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Loeblich and Tappan (1953), carried out a basically taxonomic study of foraminifera in the Arctic, including the continental shelf of the Beaufort Sea. At Point Barrow, Alaska, the most important factor that influences the distribution of foraminifera is the type of bottom. Loose sands and fine muds are relatively barren; the former is an unstable substratum and the latter is deficient in oxygen.

Cooper (1964) in a study in the Chukchi Sea found a relationship between sediment type and foraminiferal distributions. The relatively coarser sediments are associated with more diverse assemblages where the cold water species of **Elphidium** are slightly predominant. As a rule, **Eggerella advena** associated with **Spiroplectammina biformis** dominates the finer sediments. In general, the species found in the Chukchi Sea are circumpolar, with some affinity to Japanese faunas.

Echols (1974), reported on foraminiferal assemblages on the continental shelf in the Colville River delta area, which is approximately midway between Point Barrow and the Mackenzie River delta. In this report Echols (1974) demonstrated changes in assemblages with depth and distance from the shore. Nearshore faunas are dominated by Elphidiidae, inner shelf faunas by **Islandiella**, and outer shelf faunas by **Spiroplectammina biformis**, **Trochammina nana**, and **Virgulina fusiformis**.

Faunal Characteristics

A complete list of foraminifera found in surface and subsurface samples of the sediment cores, including foraminiferal number and diversity for each subsample, is published elsewhere (Vilks and Joice, 1976). The distribution of
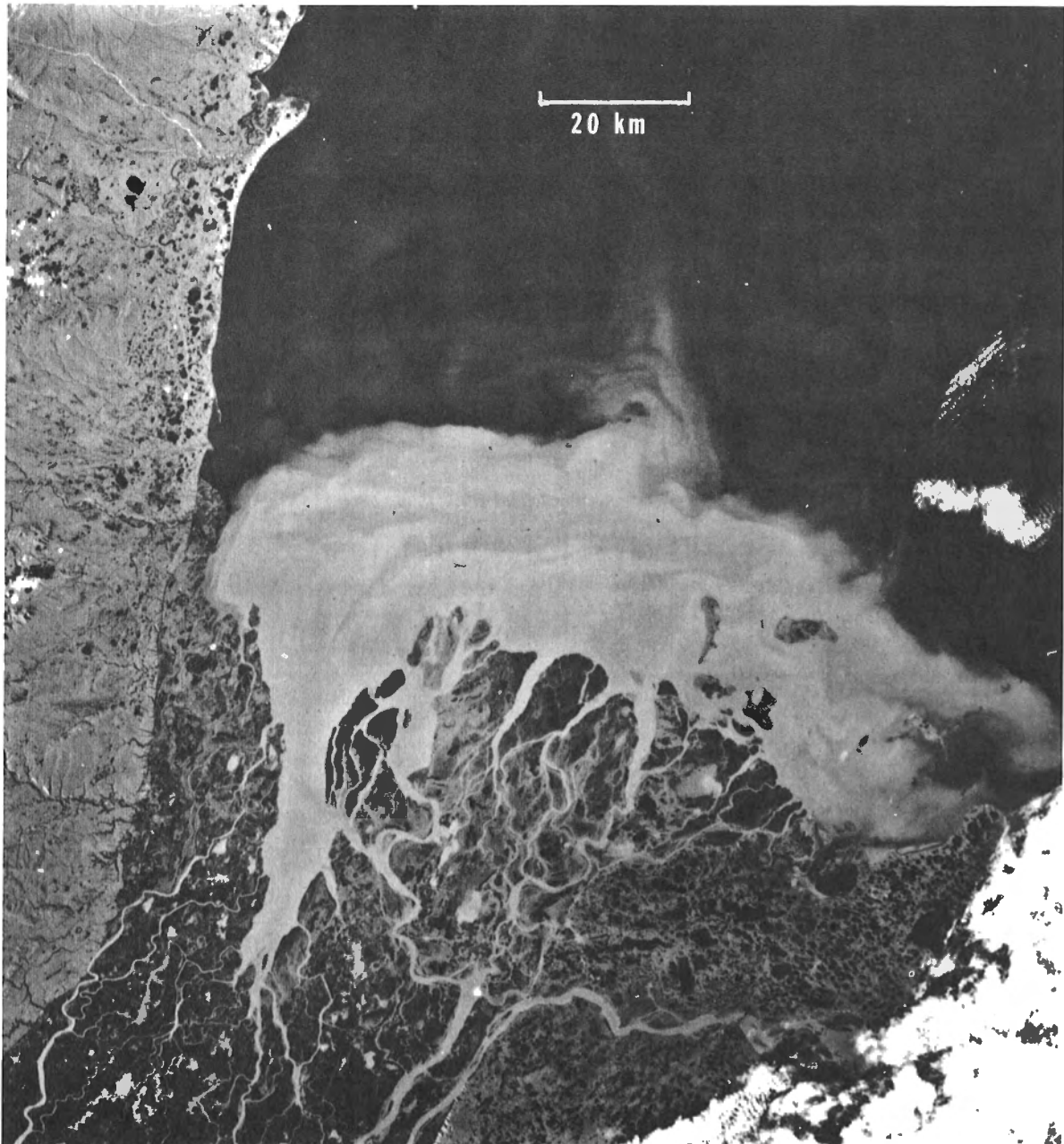
Figure 21. Satellite photograph of the sediment plume from the Mackenzie Delta, taken 1 September 1973.

benthonic foraminifera in the surface sediments is determined from core top samples collected from the continental shelf and slope (Fig. 23). Altogether 80 species and 48 genera were identified (see Table 1, Appendix 2), of which 20 species are arenaceous and the remainder calcareous.

The most widely represented genus is **Lagena** with seven species, next is **Elphidium** with four species, followed by **Fissurina, Reophax,** and **Cribrostomoides** with three species each.

The fauna is typical of continental shelf assemblages in the Arctic Basin and the surrounding seas. Only five species found here have not been previously recorded from the Arctic sediments and these are: **Epistominella takayanagii** Iwasa, **Globulina landesi** (G.D. Hanna and M.A. Hanna), **Lagena hispidula** Cushman, **Rectobolivina columellaris** (Brady), and **Cribrostomoides neobradyi** (Uchio).

The shallow water species suggest some influence from the shallow North Pacific. **Epistominella takayanagii** is common in Japanese waters of the continental shelf (Ikeya, 1971). **Globulina landesi** has been found in the shallow waters of Japan (Cushman and Ozawa, 1930) and in Late Quaternary sediments of Denmark (Feyling-Hanssen et al., 1971). **Lagena hispidula** was originally described by Cushman (1913) from deep sea samples in the North Pacific and the species has been found subsequently in deep sea sediments in the south and north Atlantic Ocean. **Rectobolivina columellaris** is a cosmopolitan species of both shallow and deep waters of the oceans. Only one species which is similar to **R. columellaris,** was found in shallow water to the west of Herschel Island.

Cribrostomoides neobradyi has been described from sediments in the San Diego Trough in 1100 m of water off California and is also common in the Gulf of St. Lawrence and Bay of Fundy. In our study area four specimens were found in one core-top sample taken below 1850 m of water.

Eleven cores from the shelf contained a number of specimens that are similar to but much smaller and flatter than **Protelphidium orbiculare** (Brady). A new species, **Protelphidium nanum,** is herewith described in Appendix 1.

Faunal Abundances

The average foraminiferal abundance is 853 specimens per sample or 24 tests/cm^3 of wet sediment. The largest count is 6000 and the smallest is one test per sample. The distribution is patchy (Fig. 24) but regional trends can be recognized. The most extensive zone of relatively high abundances occurs on the shelf north of the Mackenzie delta, with smaller zones in the shallow water and relatively coarse sediments at the eastern and western extremities of the study area. The continental slope and Mackenzie Canyon sediments contain a small number of tests, except for the two deep stations at the ends of Traverses KL and IJ. Foraminifera are also sparse in the coarse sediments of the continental shelf east of the Mackenzie Delta.

In comparison with the continental shelf sediments of other areas in the Canadian Arctic, foraminifera in the Mackenzie delta region are sparse. For example, in Hecla and Griper Bay and Hazen Strait an average of 62 tests/cm^3 of sediment was estimated (Vilks, 1969) and in McClure Strait the average is approximately 200 tests/cm^3 (Iqbal, 1973).
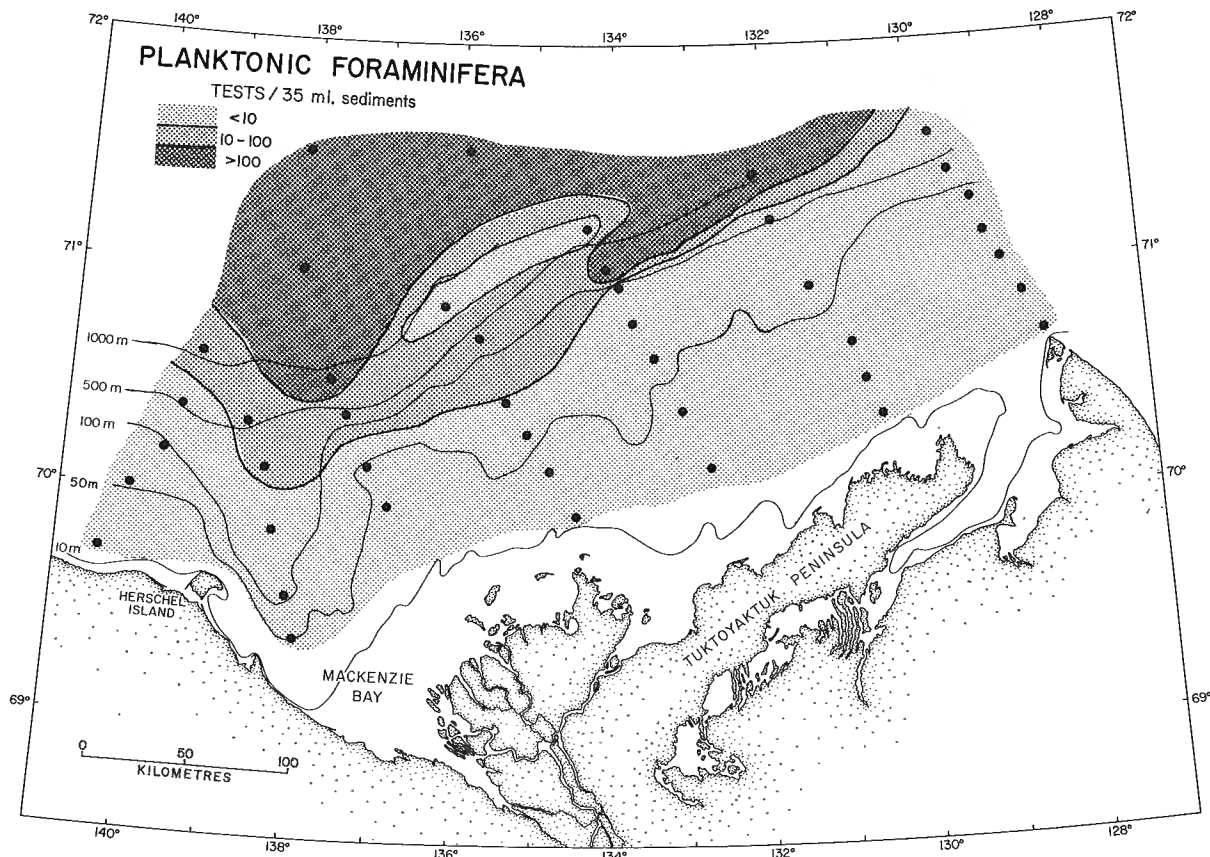
Figure 22. The numbers of **Globorotalia pachyderma** (Ehrenberg) in core-top samples (tests per 35 ml sediment)
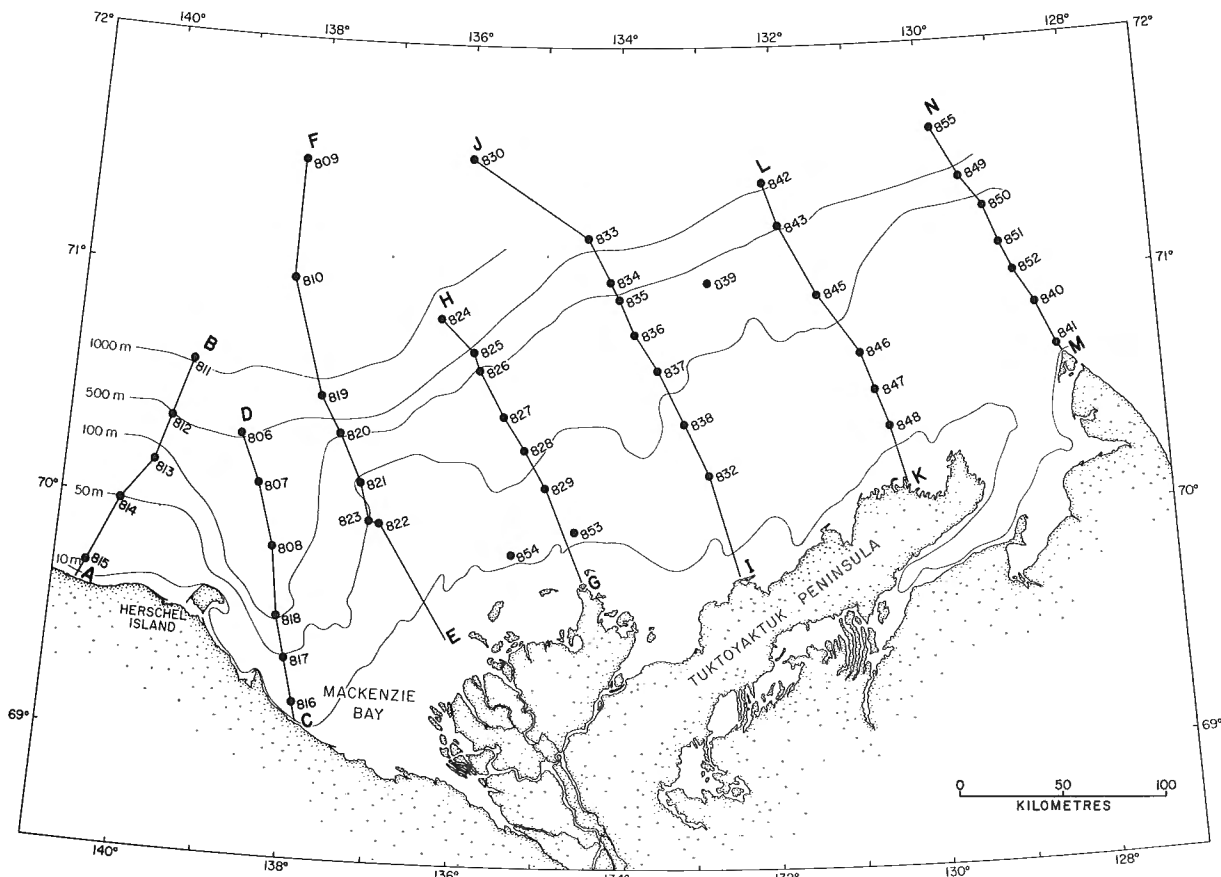
Figure 23.   Coring stations arranged along Traverses AB to MN.
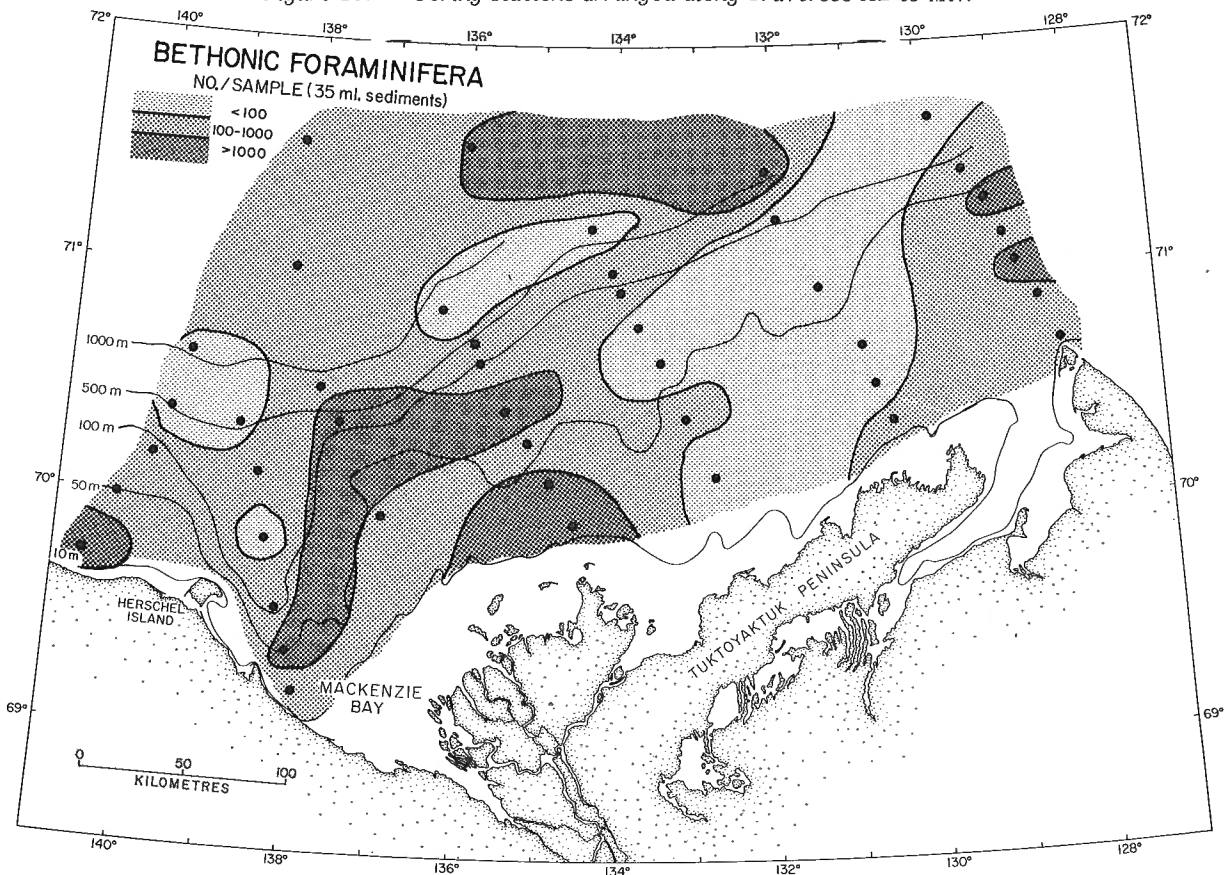
Figure 24.   Number of benthonic foraminifers per core-top sample

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Diversity

Diversity of animal communities is used to imply the extent of which the environment is imposing physiological stress on the species (Buzas and Gibson, 1969; Sanders, 1968). The diversity is commonly found to be inversely proportional to environmental stress expressed in terms of such factors as salinity, unstable substratum, high latitudes, irregular and relatively drastic changes in the physical environment, etc.

Faunal diversities can either be measured by counting the number of species per sample or by other means that normally exclude the necessity for making assumptions concerning the underlying distribution. One of these is the information function (MacArthur and MacArthur, 1961) that measures the number of species and their proportions at each station and is defined as

$$D = -\Sigma_{i=1}^{S} \; p_i \; \ln \; p_i$$

where p_i is the proportion of the ith species and S is the total number of species in sample. Species that occur in small fractions contribute little to the value of D, but when $p_i = -0.37$, $(p_i \ln p_i)$ is at its maximum. The calculated D values are generally low where the area is dominated by one species and high where many species occur in relatively equal proportions. It is clear that the information function depicts more accurately the faunal diversity than a species count to which rare and abundant species contribute equally.

The foraminiferal diversities on a continental shelf range from 0 (one species) to approximately 2.5. Buzas and Gibson (1969) calculated diversities of foraminifera found off New York and along a traverse from Cape Cod to Bermuda. The diversities in the marginal marine environment of the shallow water (about 30 m and less) were smaller than 1.5, in the normal marine environment of the continental shelf (150 m) approximately 2.5, and, at abyssal depths (5000 m), the values were close to 3.5.

In the Beaufort Sea, foraminiferal diversities calculated from the core-top sediments ranged from 0 to 2.27 (Fig. 25). On the continental shelf to the north and west of the delta the diversities are less than 1.5. Values higher than 1.5 were calculated at localities on the western continental shelf, along the continental slope, and around Herschel Island. Extremely low diversities were found on the central continental shelf and on the continental rise.

The diversity pattern can be explained in terms of local oceanographic conditions. Low diversities facing the delta indicate the extent to which the fresh effluent of Mackenzie River influences the marine faunas. Along the continental slope and to the east and west of the delta the diversities higher than 1.5 indicate relatively normal marine conditions with bottom salinities greater than 32‰.

The distribution of foraminifera in the sediment is also a function of **post mortem** disolution or redistribution of tests. These factors may be responsible for the small number of tests (see Fig. 24) and low diversities found on the central continental shelf (Fig. 25).

In summary, foraminiferal diversity on the Canadian continental shelf of the Beaufort Sea is lower than on continental shelves of lower latitudes. Reduced salinities are causing low diversities in front of the delta and low diversities on the continental rise are probably due to low nutrient supply and high rates of sedimentation. Relatively high diversities occur along the upper continental slope and at the eastern and western extremities of the study area.

Distribution of Species

Environmental parameters discussed in previous sections vary across the continental shelf because of bathymetric variations, river runoff, currents, etc. A number of species found in the sediment are distributed in patterns that may demonstrate environmental preferences. Figure 26 shows the distribution of **Elphidium clavatum** as a percentage of the total foraminifera counted in each sample. The species occurs in amounts greater than 40 per cent along a broad zone parallel and adjacent to the delta and extending eastward almost to the Amundsen Gulf. The relative amounts gradually decrease offshore and the species is absent below 900 m. The distribution pattern of **E. clavatum** in nearshore waters is directly influenced by the runoff of Mackenzie River. It is a well known species on the inner shelves of the Arctic to nearshore waters south of Cape Hatteras down to latitude 30°N (e.g. Sen Gupta, 1972).

Almost mutually exclusive with **Elphidium clavatum** is the distribution of **Islandiella teretis** (Fig. 27). **I. teretis** occurs in low relative percentages on the continental shelf in water less than 100 m deep. On the continental slope it is found in amounts between 20 and 40 per cent of the total fauna, and at depths greater than 500 m and is the predominant form except for station 359 at a depth of 2000 m. To the west of Herschel Island, **I. teretis** occurs in relatively high numbers in the shallow nearshore zone.

The distribution pattern of **I. teretis** demonstrates the sensitivity of this species to excessive influence of runoff and low salinity. On the Beaufort Shelf it is present in relatively low numbers in waters less saline than 33‰, except for the eastern and western nearshore stations. At lower latitudes **I. teretis** is a common continental shelf species of cold waters with salinities not lower than 32‰ and summer temperatures not greater than 10°C (e.g. Vilks, 1968).

Elphidium clavatum and **Islandiella teretis** are the two most abundant species and, with a few exceptions, they account for at least 30 per cent of foraminifera found in the core top samples (Table 1). Because of fewer numbers, the distributions of the other species do not show easily recognizable patterns and are not included here.

Mollusca

Much of Canada's coastal region such as the southeastern Beaufort Sea reflects fluctuations in relative sea level, a legacy of the geologic events that affected the area during the Pleistocene epoch, and in many areas changes are still occurring. It is important to know whether these shifts were transgressive or regressive, and their vertical extent. This knowledge is particularly important for an area where coastal or offshore installations are anticipated.

Molluscs, particularly pelecypods and gastropods, have proven to be useful indicators of the rise or fall of sea level, and also of other environmental changes on the basis of several criteria. Many species are restricted to fairly narrow depth ranges and fossil specimens may easily be recognized as being in situ or otherwise. Pelecypods with the valves intact or found in known living position and undamaged gastropods may reliably be assumed to have been undisturbed after death, and therefore indicative of the exact time and place of burial. Separated pelecypod valves and broken and worn pelecypod and gastropod shells would indicate reworking in various degrees.

In order to understand the ecological implications of fossil assemblages in an area, knowledge of the distribution and environmental requirements of the species presently living in the area is essential. The collecting programs for this study have given excellent bottom-sample coverage of southeastern Beaufort Sea (Fig. 28).
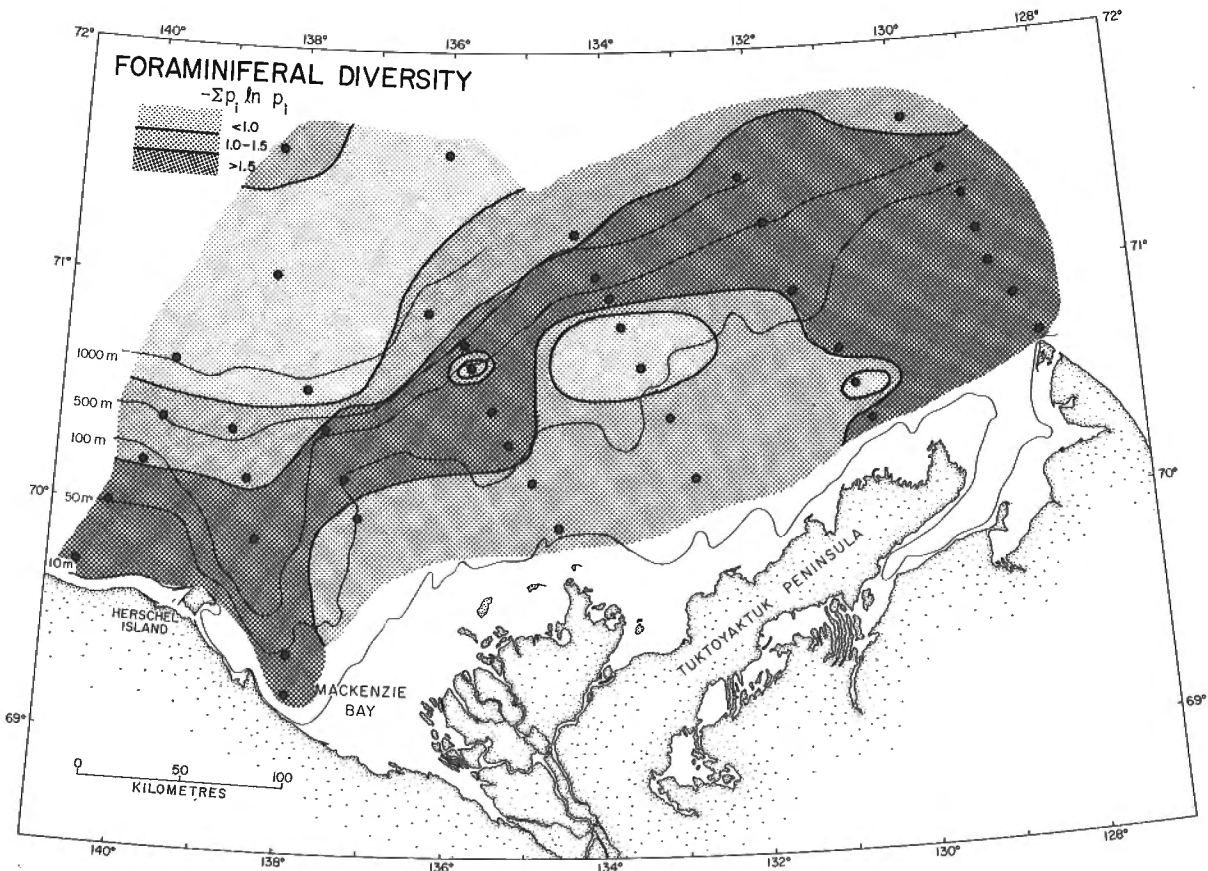
Figure 25.   *Foraminiferal diversities calculated from the core-top samples.*
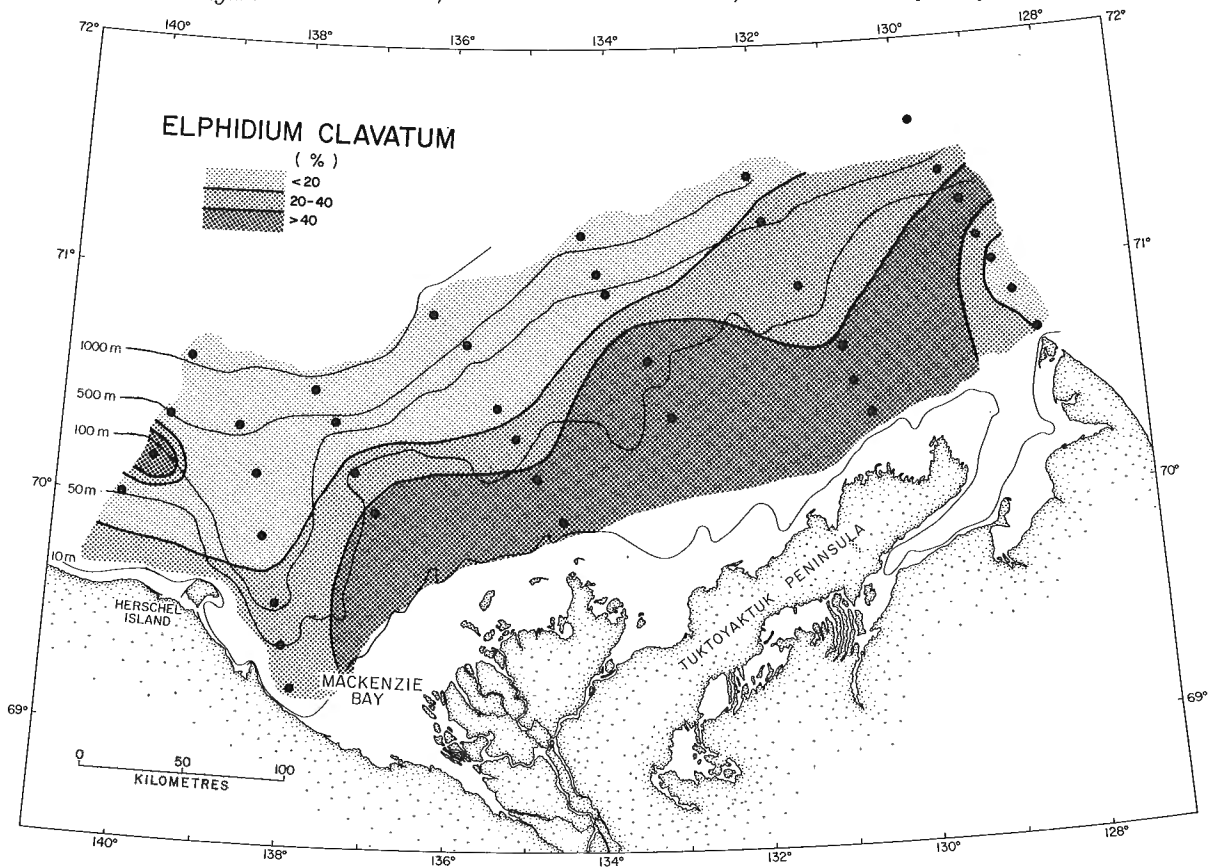
Figure 26.   *Distribution of* **Elphidium clavatum**.
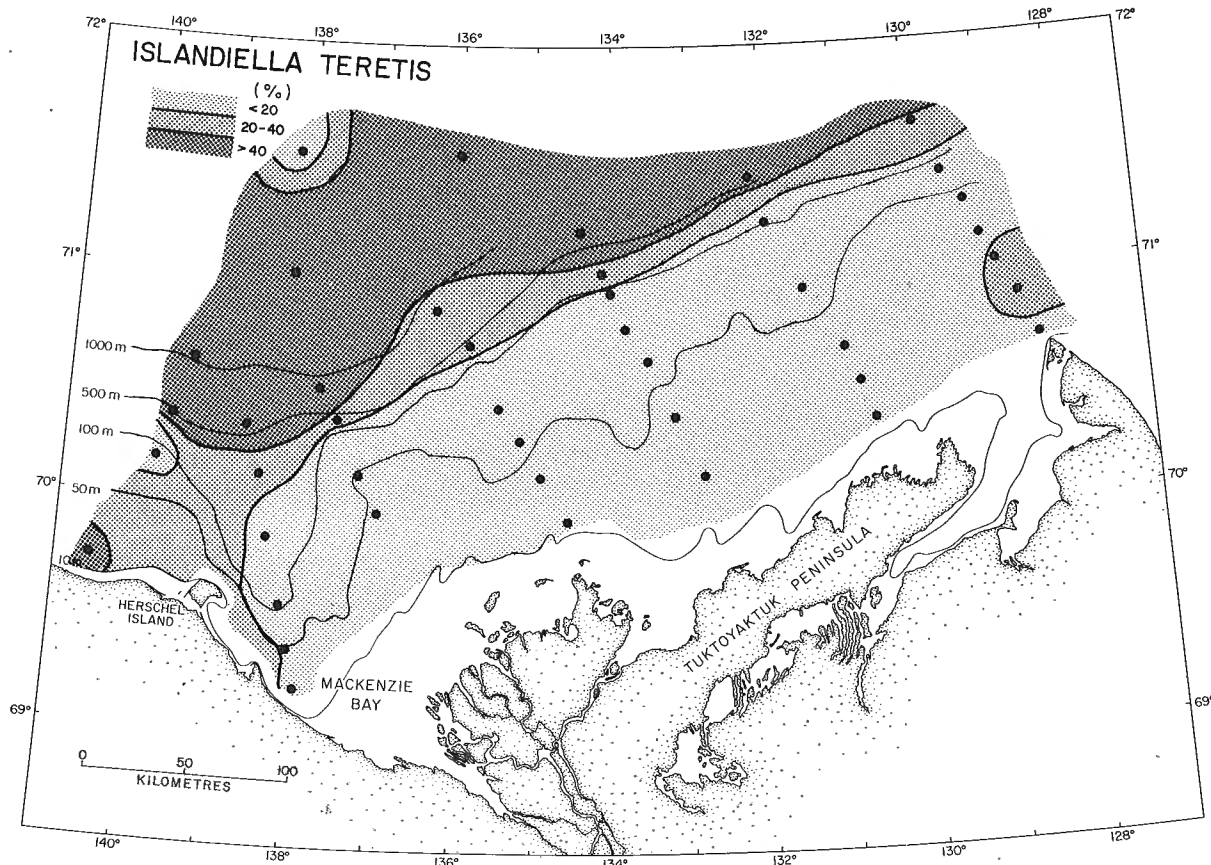
*Figure 27.   Distribution of **Islandiella teretis**.*
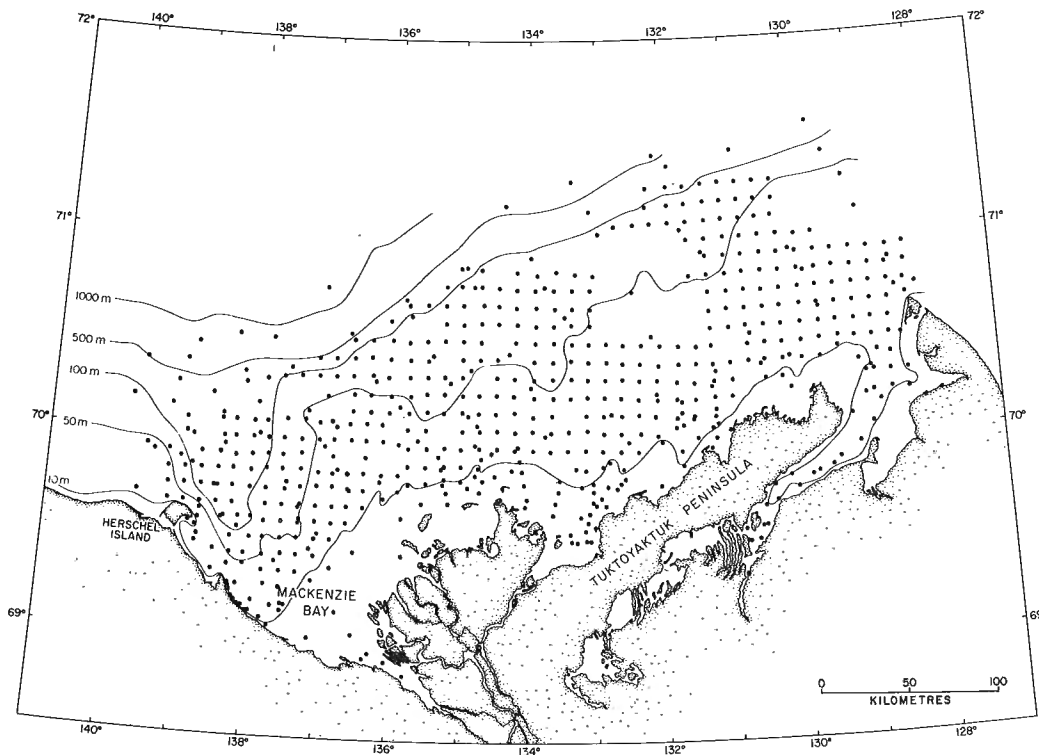
Figure 28.   Location of grab samples for molluscan studies.

From a total of 657 grab samples, 515 contained molluscs, either as identifiable shells or fragments only. Molluscan species were identified in 456 samples; in 303 of these the specimens were found to be in a condition indicating in situ preservation and defined as living. Figure 29 shows the general distribution of both living and presumably transported molluscs on the Canadian continental shelf of the Beaufort Sea (Wagner, 1977).

Although grab samples were taken to a depth of 1000 m, molluscan shells were not found in waters deeper than approximately 500 m and few living specimens were found deeper than 100 m. The largest concentrations of molluscs were present in the nearshore areas. Of the 17 most commonly occurring species (present at 15 or more localities), 15 were ubiquitous; two species were not found to the west of the delta. Table 2 (Appendix 2) shows that the area east of the delta supports the greatest variety of molluscs. It is interesting to note that the shallow waters facing the channels of the Mackenzie River are barren of molluscs.

A total of 101 species were identified, 76 of which were considered to be living on the basis of their condition. Thirty species were identified in the core samples, eight of which were not found in any of the grab samples. The occurrences of all species are given in Appendix 3.

Detailed ecological considerations of the molluscan species are discussed by Wagner (1977). This paper is concerned only with species that show strong preference for a particular depth of water (Table 3, Appendix 2). The calculations of the mean depth of species occurrence will be discussed in a following section.

A search of the literature indicates that 33 per cent of the species identified from southeastern Beaufort Sea are known from both the Atlantic and Pacific oceans, 51 per cent are recorded from the Atlantic but not the Pacific, and only 6 per cent are reported from the Pacific but not the Atlantic.

Ten per cent are apparently confined to the Arctic. These percentages indicate that molluscan faunas of Beaufort Sea have a strong Atlantic affinity and a weak faunal connection with the Pacific Ocean. Apparently the Bering Sea land bridge has been effective in restricting faunal migrations from the Pacific during the Upper Tertiary and Pleistocene.

HOLOCENE SEDIMENTATION AND PALEOECOLOGY

Changes in Sea Levels

Between 17 000 and 7000 years B.P. the mean sea level has risen by approximately 130 m due to the melting of the Wisconsin continental glaciers (Muller-Beck, 1966; Milliman and Emery, 1968). In heavily glaciated areas changes in the relative sea level were also influenced by isostatic rebound of the crust after removal of the continental ice. In such areas sea level advances during the early Holocene were followed by late Holocene retreat of the seas.

The history of postglacial sea levels in the Mackenzie Delta area is one of submergence, emergence, and possibly submergence again (Mackay, 1963). In the absence of the raised beaches that are characteristic of the eastern Arctic, the evidence for emergence comes basically from estuarine river terraces. However, the Mackenzie Delta area was never heavily glaciated (Mackay, 1963; Hughes, 1972) and became free of glacial ice several hundred kilometres from the coastline as early as 12 000 years B.P. (Prest, 1969). Thus, the postglacial rise in sea level along the coast of the southern Beaufort Sea may have been due mainly to the eustatic fluctuations (Mackay, 1972). It has been suggested that a stillstand occurred 20 m below present sea level, between 8000 and 5000 years B.P. (Hopkins, 1959; Mackay, 1963).
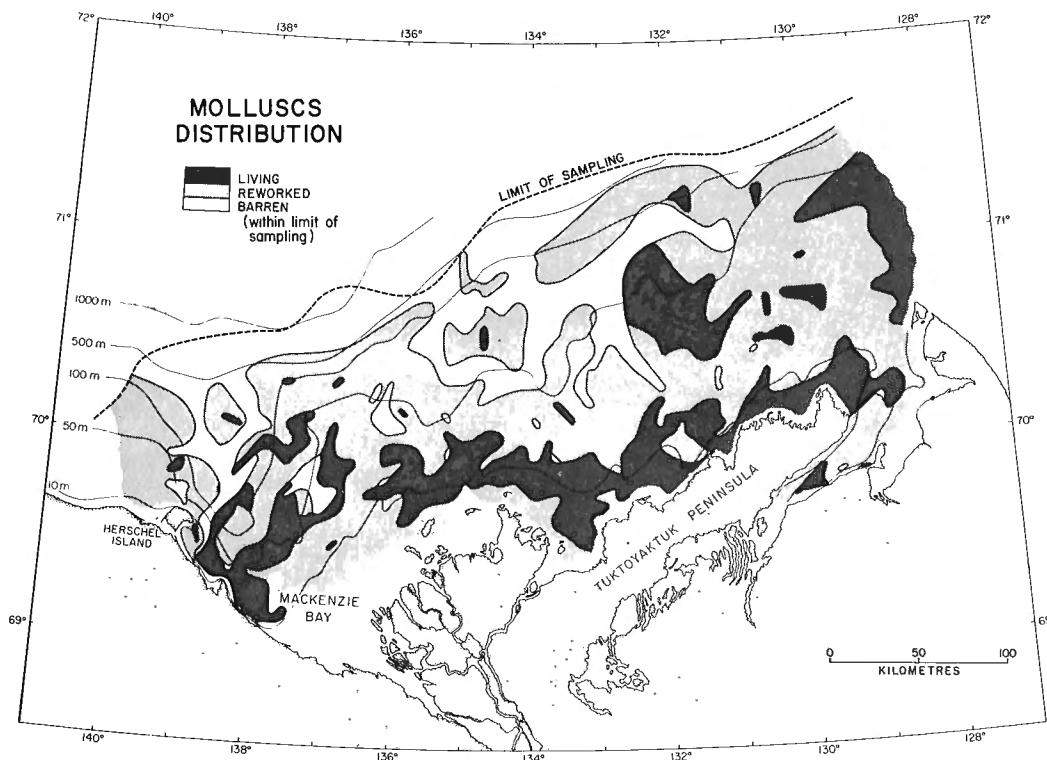
Figure 29.   Distribution of localities where molluscs were found in situ and transported.

As the evidence for the changes in sea level has been mainly land based, it is of interest to evaluate these changes with faunal evidence in sediment cores. Both foraminiferal and molluscan species show some preference for a specific range of water depth and will be used to infer possible changes in paleodepth on the basis of specimens found in sediment cores.

Depth Range of Species

The range of depths at which the various species occur is great and varies from traverse to traverse (Table 1, Appendix 2). In order to condense the possibly useful information of species depth ranges, specific depths of species occurring in the core-top samples were calculated. The equation

$$\ln D_A = \sum_{i=1}^{N} f_{A_i} \ln D_i; \; D_A = e^{\ln D_A}$$

was used where D_A is a specific depth of species A; N is the number of stations at which species A is being found; f_A is the frequency of species A and D is the depth of water at each station. D_A then is the mean depth of species A weighted by the frequencies at which the species occurs at the various depths. Because more stations occur at relatively shallow depths, the frequency curve of depths is skewed. By taking the natural logarithm of depths, the distribution is normalized, thus, making the mean depth more representative. The definition of paleodepth (D) is

$$D = D_A f_A + D_B f_B + D_C f_C \cdots D_S f_S = \sum_{i=A}^{S} D_i f_i$$

where D_A, D_B, D_C, etc. are the specific depths of species A, B, C, etc. occurring in the core interval concerned; f_A, f_B, f_C, etc., are the frequencies at which the various species occur; and S is the total number of species in the sample.

The specific depths of foraminiferal species were calculated considering the areas to the west of the delta (Traverses AB, CD), to the north of the delta (Traverses EF, GH, and IJ), and to the east of the delta (Traverses KL, MN) as three separate entities (Fig. 23). The decision was based on the possibility that a causal relationship of species with water depth may not exist and that the depth ranges may to some extent reflect the different oceanographic and sedimentary conditions occurring at similar depths on the continental shelf. The different environmental features on the eastern, western, and central sections of the shelf discussed above coincided with differences in species diversities and distribution patterns of the two major species.

Table 4 (Appendix 2) shows the specific depths of foraminifera calculated from the three regions separately and Table 3 (Appendix 2) shows the specific depths of molluscs from grab samples of the whole area. Most of the foraminiferal species have reasonably similar mean depths on the continental shelf, with a few important exceptions. For example, the mean depth of one of the most abundant species **Islandiella teretis** is smaller by several orders of magnitude to the west of the delta than to the north and east. Other such species are **Cassidella complanata** and the bathyal **Stetsonia horvathi**. A number of species occur at shallow depths to the west and east of the delta, but at continental slope depths to the north. These varying specific depths indicate those species more sensitive to a sustained influence of Mackenzie waters and that can withstand the changing conditions imposed by the migration of the sedimentary plume over the continental shelf.

To test the validity of using the specific depths as a tool for paleodepth calculations in sediment cores, the calculated depths of core-top samples were plotted against the depths at which cores were taken (Fig. 30). The correlation between the two variables for foraminifera is good (the correlation coefficient $r = 0.75$ and $\alpha = 0.001$). The correlations for molluscs have a similar relationship, although less significant ($r = .58$ and $\alpha = 0.01$; Fig. 31). As a rule, in shallow water the calculated depths are greater than the actual depths, but in deeper water the relationship is reversed. The over-estimation of shallow depths both for molluscs and foraminifera indicates that distinct shallow water species are missing and species found at the shallowest localities are also important in the sediments of the inner shelf. The under-estimation of the deep depths may be due to two factors. Firstly, on the continental slope the few foraminiferal species restricted to the bathyal depths are not important in the total faunal assemblage. Secondly, in each sample, a large number of specimens consist of species that are also found along the continental margin. In the case of foraminifera, it is difficult to distinguish between in situ specimens and those that were transported with the sediment. In the case of the molluscs, the shell fragments and single shells were found at localities 400 m deeper on the continental slope than the paired valves considered to be in situ examples. The presence of the transported shallow water molluscs in the deep offshore waters suggests that both ice rafting and/or sediment slumping along the continental margin are important sedimentary processes.

In an area of distinct faunal depth zones and minimal **post mortem** transport of tests and shells, the calculated depths should be close to the measured depths of water where samples were taken. However, the depth zonation of foraminifera and molluscs may be established primarily in response to oceanographic differences associated with terrestrial influence rather than to the depth of water itself. In view of the different oceanographic settings on the continental shelf to the west, north-northeast, and east of the delta, the correlation between the calculated depth and the actual depth was determined separately for the three areas. Northnortheast of the delta (Traverses EF, GH, and IJ of Fig. 32) the correlation between the actual and calculated depth is best and the trend is closest to the x=y line. The correlation between the two parameters is poorest to the west of the delta (Traverses AB and CD). In Mackenzie Canyon and on the continental shelf to the west of Herschel Island the depth zonation of species is poor mainly because of the upwelling of the saline offshore waters. Sediment slumping at the continental margin of Traverse AB is also evident with the presence of the shallow water **E. clavatum** in the sediments of the continental slope. On the central part of the continental shelf, differences in oceanographic parameters are associated with depth of water. A prominent estuarine influence remains on the inner shelf with the more saline offshore waters along the deeper continental slope.

Although the foraminiferal correlation between the calculated and actual depths in the core top samples is good, there is a significant discrepancy between the slopes of line x=y and the other regressions (see Fig. 32). A similar discrepancy was found using the molluscan species (Fig. 33). The relationship is very poor to the west of the delta (Traverses AB and CD); it is better along Traverses EF, GH, and IJ and best along Traverses MN and KL, at the eastern extremity of the study area. Here the calculated depths follow closely the actual depths of water to the extent that the calculated regression is similar to the x=y line at a high level of significance.

Paleodepth

Absolute paleodepth calcualtions in core intervals are not very meaningful because of the discrepancies between the calculated and measured depths on the basis of the surface samples. However, assuming that the error at any core station is constant, differences between the calculated depths on the basis of the surface sample and any core interval below may indicate sedimentary or ecological changes with time.

The differences between surface and subsurface paleodepths (ΔD) of sediment cores were plotted along four traverses (Fig. 34-37). In general, the plots are not very conclusive, which demonstrates the complexity of the sedimentary environment and weak correlation between foraminiferal species and bathymetry. Nevertheless, certain trends are apparent.

Although the calculated paleodepths fluctuate considerably across the zero-line, on the average the data indicate that west of the delta the water was shallower in the past (Traverse AB, Fig. 34) and on the shelf east of the delta water was deeper in the past (Cores 838 and 835, Fig. 35; Cores 848 and 846, Fig. 36 and Cores 841, 852 and 851, Fig. 37). Along the continental margin, the paleodepths were shallower in the past (Core 833, Fig. 35; Cores 845 and 843, Fig. 36, and Core 849, Fig. 37). The calculated paleodepths suggest a depression of the sea floor west of the delta and along the continental margin and a slight elevation of the continental shelf east of the delta.

A comparison between molluscan and foraminiferal paleodepths (Table 5) shows little agreement. From a comparison of 28 core intervals, only one pair was similar within a range of 5 m; in 14 intervals molluscan paleodepths were deeper and in 13 intervals foraminifera indicated a deeper paleodepth.

Figure 30. Relationship between water depths at coring stations (measured depths) and calculated depths according to foraminifera.

Figure 32. Relationship between measured and calculated depths along traverses to the west (AB,CD), north (EF, GH, IJ) and east (MN, KL) near the Delta according to foraminifera.

Figure 31. Relationship between measured depths and calculated depths according to mollusca.
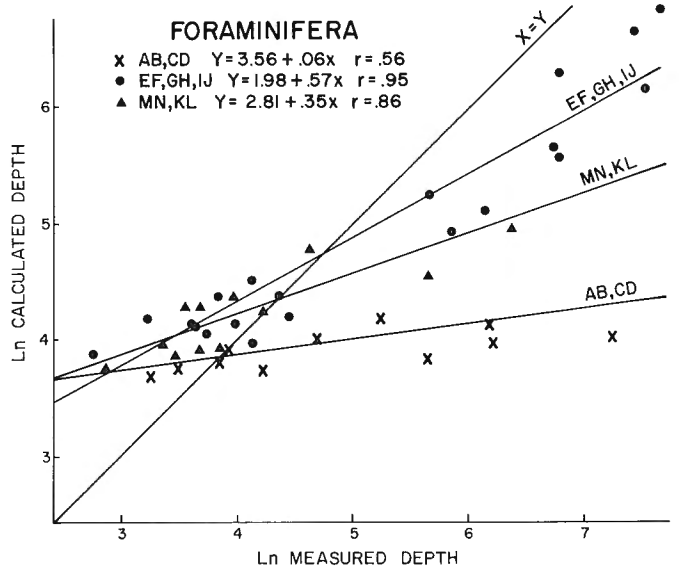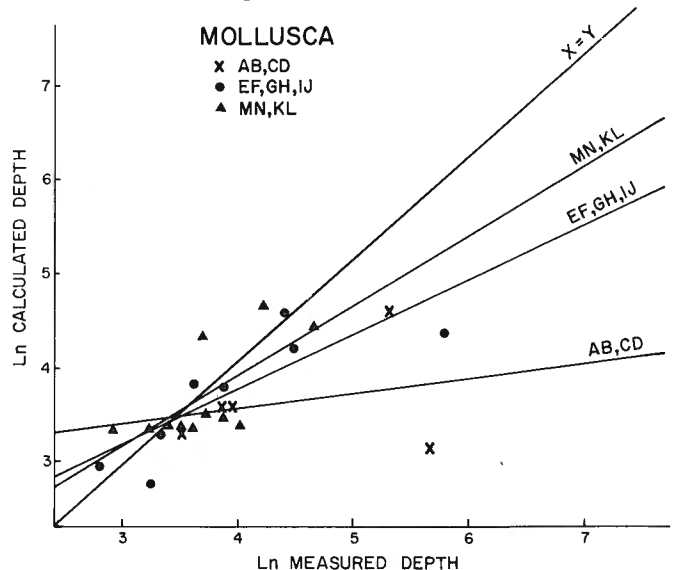

Figure 33. Relationship between measured and calculated depths along traverses to the west (AB,CD), north (EF, GH, IJ) and east (MN, KL) near the Delta according to mollusca.

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The fluctuation of the ΔD curve in some of the cores may reflect fluctuations in the sedimentary environment and the extent of **post mortem** transport of foraminiferal tests. Empty tests and sand grains of comparable size have similar hydrodynamic properties and may be transported by currents together with the sediment. Molluscan shells may behave differently in an area of bottom currents and may remain in situ with the coarser sediment. Ice rafting may be more important in the transport of molluscan shells.

Sediment and Faunas in Cores

The results of foraminiferal, molluscan, and textural analysis of surface sediments are used here to synthesize the ecological baseline for possible paleoecological models derived from similar analysis of sediment cores. The foraminiferal information useful for paleoecological studies includes: 1) the total number of foraminifera per sample, 2) the ratio of planktonic to total number of foraminifera, and 3) the relative percentages of **Elphidium clavatum** and **Islandiella islandica.**

The total number of foraminifera per subsample indicates relative validity of the sample, e.g. small numbers are not reliable. In addition, core intervals devoid of foraminifera may indicate fluvial deposition and therefore may have a time-stratigraphic value. The ratio of planktonic over total foraminifera is a useful indicator of changes in offshore influence on the continental shelf with larger ratios showing greater influence of oceanic waters. Increasing estuarine influence is shown by higher percentages of **Elphidium clavatum** and increasing bottom salinities by higher percentages of the outer-shelf species **Islandiella teretis.**

The maximum length of piston cores did not exceed 12 m and normally the finer sediments yielded longer cores. To describe possible trends in the Holocene sedimentation and paleoecology the percentage ranges of clay, silt, sand, and gravel in each of the core subsamples are discussed in conjunction with the faunal analysis.

Traverse AB

Traverse AB (Fig. 38a, b, and c) to the west of Herschel Island consists of three short cores on the continental shelf and two long cores on the relatively steep and irregular slope. On the continental slope the sediments are basically silt and clay with a trace of sand occurring in the upper half of core 811 and close to 10 per cent sand in the surface layer of core 812 (Fig. 38a). The short cores (813, 814, and 815) contain gravel and sand in addition to fine sediments. The lithology in the shoremost core (815) changes from the relatively coarse sediments with 30 per cent sand and gravel at the surface to only 5 per cent sand at the bottom of the core.

The foraminifera along Traverse AB change with distance from shore and with water depth. In general, the planktonic **Globorotalia pachyderma** and the benthonic **Islandiella teretis** are predominant in the offshore cores whereas **Elphidium clavatum** is in the inshore sediments. However, in each core there are a number of significant changes. Below 350 cm in core 811 the ratio of planktonic to total foraminifera increases sharply as a result of reduced numbers of benthonic species (Fig. 38b). Although **I. teretis** is predominant in core 812 (Fig. 38c) the nearshore **E. clavatum** appears in greater numbers in the upper half of the core, without the expected decrease in the planktonic species. In the surface sediments of the two nearshore cores (815 and 814) the offshore **I. teretis** is predominant, but is not present in the subsurface sediments.

The changes in foraminifera suggest changes in oceanographic and sedimentary environments. The small numbers of benthonic foraminifera in the lower half of core 811 indicate a period of rapid sedimentation as a result of turbidity currents or slumping. The faunal change in core 812 indicates that **E. clavatum** has been transported downslope in increased amounts from core 813, where it is a predominant species. The high relative percentages of **I. teretis** in the nearshore surface sediments may indicate an increased influence of oceanic waters along the coast west of Herschel Island. This is a relatively recent phenomenon that could reflect the decreasing influence of the Mackenzie waters west of the delta.

Only two species of molluscs were identified from grab samples taken at the coring stations along this traverse. They are the benthonic pelecypod, **Yoldiella lenticula,** and the pelagic pelecypod, **Arctinula groenlandica.** Two of the five cores were barren of molluscs in the intervals sampled; the others yielded only unidentifiable fragments.

Traverse CD

The sediments along the axis of Mackenzie Canyon are predominantly silt and clay, with minor amounts of sand and gravel (Fig. 39a). A zone of sandier sediments occurs between 300 and 500 cm in core 818, with a maximum of 27 per cent sand, without gravel, and with a reduced silt fraction. This sandy zone is not reflected by a change in the foraminiferal content.

Foraminifera collected from the eight cores change slightly in the proportion of the significant species. At the continental margin there is a slight increase in the number of planktonic tests in the upper half of core 807 (Fig. 39b) and the relative percentage of **I. teretis** is considerably higher than **E. clavatum** above 500 cm of the core (Fig. 39c). Of significance are the relatively high percentages of **I. teretis** in the nearshore core 816.

The increased amounts of the offshore species in the surface layers of core 807 in addition to larger fractions of the planktonic species indicate a progressively increasing influence of the oceanic waters in Mackenzie Canyon. The large proportion of **I. teretis** throughout the nearshore cores reflect the extension of offshore influence past Herschel Island and to the head of Mackenzie Canyon.

Except for **Bathyarca glacialis,** the molluscan species found in the cores were also obtained from surface samples taken at the coring stations. Shallow water species, e.g. **Portlandia arctica siliqua, Yoldiella fraterna, Y. lenticula, Cyclichna occulta,** and **Retusa umbilicata** (see Table 3, Appendix 2, for mean depths) were present in cores taken in both shallow (<50 m) and deeper (>50 m) waters. **Bathyarca glacialis,** a somewhat deeper water species (mean depth = 79 m) was present in both shallow and deeper cores, whereas **Thyasira flexuosa** (mean depth = 178 m) was found only in core 807 taken at a depth of 290 m. The majority of specimens from the deeper cores, however, were shallow water species. In the grab samples, many specimens appeared to be collected in situ. Some specimens in the cores were complete, but most were fragmentary.

Traverse EF

The sediments along the eastern flank of Mackenzie Canyon and the continental rise consist of clays with a few isolated horizons of slightly coarser sediments (Fig. 40a). The layer of sandy sediments in core 820 (at 400 cm) contained molluscan shells that were dated at 3500 years B.P. (Lowdon and Blake, 1973). Based on this date, the average sedimentation rate in this region is calculated to be 100 cm/1000 years.

The rapid rates of sedimentation on the continental slope are probably due to sediment slumping and/or turbidity currents. The two deep sea cores, 810 and 809, show distinct layers of silt-clay turbidites on x-radiographs (Vilks et al., 1977). Although sediment analysis of core 819 did not provide evidence for the presence of turbidites, the foraminiferal content of the upper 200 cm of the core suggests a downslope movement of sediment.

The sediments on the continental shelf and the upper slope along Traverse EF contain relatively large numbers of foraminifera throughout the length of the cores (Fig. 40b). Smaller numbers were recorded in the samples of the lower continental slope, where layers barren of fauna were found in the lower half of core 809.

Compared to the traverses to the west of EF, **I. teretis** is far less abundant on the continental shelf and becomes more abundant only in the cores from the slope beginning with core 820 in 350 m of water (Fig. 40c). The predominant species throughout core 820 is **Islandiella islandica**, which is a common species in the sediments of the continental margin within the area of study. Core 819 was taken at a depth of 885 m where **I. teretis** is nearly the only species present below a depth of 150 cm in the core. Above 150 cm both **E. clavatum** and **I. islandica** occur in approximately equal numbers.

The two deep sea cores 810 and 809 contain typically bathyal species such as **Eponides tener** and **Stetsonia horvathi** as well as **I. teretis**. In intervals where the bathyal species are absent, large numbers of **I. islandica** are normally present.

Molluscs were reported from grab samples taken at two of the seven coring stations along this traverse. Five species were identified, in contrast with 10 species recognized in the cores. Only one species, **Portlandia arctica siliqua**, was present in both grab and core samples. Shallow water species were predominant in the fossiliferous intervals of both shallow and deeper water cores.

The occurrence of typical shelf species in sediments from the continental slope and rise is used as evidence for the displacement of material downslope. The inner shelf species **E. clavatum** was found at water depths close to 900 m in core 819, but was not found in the deeper waters. The outer shelf-upper slope species **I. islandica** occurs sporadically in isolated layers in both deep sea cores 810 and 908. Thus, it is possible that the source of the turbidites is somewhere on the upper half of the continental slope, and turbidity currents originating at the continental margin do not extend to bathyal depths.

Both deep sea cores contain layers that are barren of benthonic foraminifera and core 809 is barren of fauna below 875 cm (Fig. 40b). These barren layers are explained in terms of disturbances at the sediment-water interface, which destroy the microfauna at the site of turbidite deposition. Whether the sediments are barren or the fauna are merely reduced in numbers, will depend on the frequency of turbidity currents and the abundance of foraminifera in the source area. In the upper part of the deep sea cores the turbidites contain shallow water foraminifera, but below 900 cm in core 810 and below 250 cm in core 809 the turbidite layers are barren of benthos. The barren turbidite layers may have been deposited during the Wisconsin glacial maximum when the continental shelf was exposed and the marine environment would have been under the influence of heavy ice conditions, thus, diminishing biological production.

Traverse GH

The sediments along this traverse are coarser than the sediments to the west (Fig. 41a). The shoremost core (829) contains up to 27 per cent sand in the surface layer, but less than 10 per cent throughout the remainder. In core 828 sand exceeds 90 per cent of the total in the 50-100 cm and 200-250 cm intervals. The sediment in core 827 is reasonably similar to core 829, except that more sand is present in the lower layers of the core. The sand content is decreasing towards the outer edge of the continental shelf but core 824 from the continental slope contains several sandy layers.

The faunal content in the cores taken along this traverse is variable. Large numbers of foraminifera were found in the surface layers of all the cores on the continental shelf and the upper slope, but the numbers were low in the sediments of core 824, taken in the deepest waters of this traverse (Fig. 41b). Below the top 50 cm, the continental shelf core (829) contains layers of sediments that are barren of foraminifera and the faunal content in cores 828 and 826 varies from high to low in closely spaced intervals. Core 825 from the continental slope is comparatively rich in fauna throughout, whereas core 824, downslope from core 825, contains less than ten benthonic foraminifera in most of the core and no fauna between 200 and 300 cm.

As expected, planktonic foraminifera are absent from the cores on the continental shelf adjacent to the delta. On the continental slope throughout core 825, planktonic tests are present in reasonable numbers, but are absent from core 824 downslope from core 825. Dissolution, because of greater depths, can be ruled out on the basis of the presence of **Stetsonia horvathi**. The calcareous tests of this bathyal species are minute, thin-walled, and very fragile, and therefore would dissolve before the more robust planktonic **Globorotalia pachyderma**.

The percentages of **Elphidium clavatum** and **Islandiella teretis** are plotted in Figure 41c. **I. teretis** is practically absent from the continental shelf, but is one of the major species in core 825 on the continental slope. **E. clavatum** is the predominant form in the nearshore core 853, in the surface sediments of core 829, throughout most of core 827, and the bottom part of core 826.

The variability in the percentages of **E. clavatum** reflects the complex sedimentary regime on the continental shelf. In the surface sediments of Traverse GH a distinct estuarine influence extends approximately 50 km from the shore to core 829. In core 828 the simpler inner shelf-estuarine fauna is replaced by more diverse assemblages with high numbers of **Eoeponidella pulchella**. The diverse fauna in the surface layer of core 827 contains large numbers of **Spiroplectammina biformis** and **Islandiella islandica**. **S. biformis** and a number of other arenaceous species are important constituents of the fauna along the continental margin. In core 826, **S. biformis** predominates the fauna in the upper 2 m of sediment.

On this traverse, north of Mackenzie Delta, both grab samples and cores from the two deepest stations were barren of molluscs. Molluscs were present in grab samples from four of the five stations on the shelf (deepest station, 87 m), and with the exception of **Bathyarca frielei**, the species obtained were indicative of shallow conditions. **B. frielei** was collected from a depth of 87 m, and has a calculated mean depth of 124 m. Only shallow-water species were recovered from the cores, and only two of these species, **Portlandia arctica siliqua** and **Yoldiella lenticula**, also occurred in the grab samples.

The sedimentary and faunal evidence along Traverse GH are useful for the synthesis of a paleosedimentary model. A unique feature of the distribution of sediments along Traverse GH is the lack of gravel in the sandy layers and the distinct horizons of high silt content in the fine sediments. The low contents of gravel suggest that ice rafting has been a minor mechanism in transporting sediments to the area. The well sorted sand may be relict and may have been deposited as a beach during the marine transgression. The high silt content in cores 829 and 827, and in the lower part of core 826 may be equivalent to the surface sediments in nearshore areas adjacent to the Mackenzie River delta, where the sediment originates from the plume of river effluent (Fig. 21). The sediment texture profiles along traverse GH suggest a preserved ancient beach at cores 828 and a delta front at cores 827 and 826.

Owing to the widely differing rates of sedimentation in each of these cores, correlation of events across the continental shelf is fragmental. Nevertheless, the evidence of transgressing seas on the basis of sediment data is supported by the changes in distribution patterns of foraminifera in the subsurface sediments. In core 829 the existing inner shelf-estuarine environment replaces the nearshore environment as evidenced by the layers barren of fauna below the surface. In cores 827 and 826 the existing outer shelf assemblages are replaced by inner shelf-estuarine faunas in the subsurface layers of the core. On the continental slope, sediments have been accumulating at a relatively fast rate at core 825, but there is no evidence for changes in the environment. The barren subsurface layers in core 824 indicate rapid deposition, probably by slumping of material devoid of Recent faunas. These are Late Wisconsin-Early Holocene sediments, deposited during the time when seas transgressed the barren continental shelf and sediment erosion was accelerated.

Traverse IJ

Except for core 838, the sediments on the continental shelf of this traverse are sandy (Fig. 42a). Sediments in cores 832, 836, and 837 contain between 90 and 100 per cent sand. Layers of silt occur at 100 cm in core 832 and at the bottom of core 836. The surface sediments of core 838 contain 50 per cent sand, and except for a horizon of clay at the 100 cm level, the sand in the remainder of the core is slightly less than 20 per cent. The cores on the continental slope consist largely of silt and clay with a slightly larger fraction of silt in core 835 and a layer of silty sand at the bottom of core 833.

The number of foraminifera per subsample on the continental shelf varies from nil to approximately 1000 specimens per sample (Fig. 42b). On the continental slope the three cores are rich in foraminifera throughout their length. Planktonic foraminifera are absent from the sediments of the continental shelf, but appear in small numbers at the top of the continental slope and increase in numbers down the slope.

The relative percentages of the estuarine-nearshore **Elphidium clavatum** are smaller along Traverse IJ than in the sediments to the west (Fig. 42c). In the nearshore core 832 a layer rich in foraminifera was found at 50 cm between two barren layers. Although the surface sediments are predominated by **E. clavatum,** the layer at 50 cm contains an entirely different fauna, which is diverse and consists of such species as **Eoeponidella pulchella, Buccella frigida,** and **Valvulineria hamanacoensis.**

Farther away from the shore and in deeper water, core 838 contains a continuous record of foraminifera. Throughout the core, the predominant species with few exceptions is **E. clavatum.** Intervals with lower percentages of **E. clavatum** contains increased numbers of

Spiroplectammina biformis, which indicates periodic incursions of the shelf-edge environment towards the inshore-line.

The remainder of cores on the continental edge and slope are rich in foraminifera and contain species that are typical of that environment. In core 835, E. **clavatum** is still one of the major species but **Spiroplectammina biformis** and **Islandiella islandica** are also important. The predominant species of core 834, which was taken in deep water, are **Islandiella teretis** and **I. islandica.** Core 833 situated in 823 m of water contains only **I. teretis.** The bathyal core 830 is also predominated by **I. teretis,** but the fauna is more diverse with the typical deep water species **Eponides tener** and **Stetsonia horvathi** present.

This traverse, also north of the delta, was least productive of molluscs, with only five species identified from grab samples and four species from the cores. No species was common to both grab samples and cores. Core 832, at the shoreward end of the traverse, yielded only unidentifiable fragments of apparently marine molluscs from the upper part of the core, but a freshwater pelecypod, **Pisidium idahoense,** was found in the 175-180 cm interval.

Traverse IJ is unique because the sediments are barren of foraminifera or contain few specimens. On the continental shelf the sharp discontinuities in faunal characteristics in terms of numbers and species indicate a fluctuating nearshore environment. Relatively quiescent periods at the sediment-water interface associated with slow rates of sedimentation are represented by high numbers of foraminifera. A barren layer may indicate a single event that was catastrophic to the fauna. During a period of transgressing seas, or during storm surges, the coastline provides sediment that may be dumped in a relatively thick layer over a short period of time. The barren layers of cores 837 and 836 close to the edge of the shelf also consist of well sorted sands that may be relict and at present sufficiently unstable to prevent the establishing of meiofauna, such as foraminifera. Both cores also lacked molluscs.

A unique feature of Traverse IJ is the lack of evidence for sediment slumping, which was apparent along the other traverses to the west. On the continental slope foraminifera were present throughout the cores, but were lacking the shallow water species that were found in the other bathyal cores. Although cores 834 and 833 were taken only 20 km apart with the latter downslope, there is no foraminiferal evidence for sediment slumping between the two coring sites.

Traverse KL

Along this traverse the sandy sediments extend farther offshore than along the traverses to the west (Fig. 43a). Layers containing over 90 per cent sand are present in cores 843, 845, and 846. The shoremost core 848 contains silty sand above 100 cm and silty clay below, and core 842 collected in 600 m of water consists of fine sediment with isolated sandy layers.

The fine sediments of core 848 are rich in foraminifera throughout; smaller numbers were found in the coarse sediments of core 846 and fluctuating numbers in the various layers of core 845 (Fig. 43b). The inverse relationship in sediment size and foraminiferal number also holds in core 843, the sandy sediments of which contain fewer than 100 tests per sample. On the continental slope the upper 300 cm of core 842 are rich in foraminifera. Below this layer down to 600 cm there are about 100 tests per sample, and the bottom 300 cm of the core are barren of recent foraminifera. Appreciable numbers of planktonic foraminifera are present only in the upper half of core 842 in association with the high numbers of benthonic tests.

The nearshore species, **Elphidium clavatum** is predominant throughout cores 848 and 846 which indicates the extent of estuarine influence in time and space (Fig. 43c). A layer with large numbers of **Spiroplectammina biformis** was found towards the bottom of core 846. The diverse fauna of cores 845 and 843 are locally typical of the outer shelf. They contain large proportions of **Islandiella islandica** and **Protelphidium orbiculare** in addition to **Islandiella teretis** and **Elphidium clavatum**. The upper half of core 842 is predominated by **Islandiella teretis** with the exception of the layers close to the surface where **Islandiella islandica** also is an important form.

On the shelf east of the delta, molluscan faunas exhibit a greater variety of species than elsewhere. Certain ubiquitous species are present, but there are also species apparently confined to this area. Thirteen species were identified from surface samples at the coring stations, but only five species were present in core samples. Species from the cores did not match with those from the surface samples, but they did correspond with suites found in cores to the west of this traverse.

The sediment cores along Traverse KL do not show variations in fauna that would reflect changes in the oceanographic environment on the continental shelf. On the continental slope the barren layer below 500 cm of core 842 can be associated with the Late Wisconsin to Early Holocene period. During that time rates of sedimentation were increased on the continental slope as a result of accelerated erosion of the shoreline by transgressing seas. A marine fauna could not establish itself because of the harsh conditions combined with fast sedimentation rates.

On the continental shelf the sedimentation rates can be estimated by using the ^{14}C date for molluscan shells from the 10-30 cm interval of core 845. The recorded radiocarbon date is 700 ± 180 years B.P., and taking into consideration the possibility of sampling disturbance this close to the top of the core, the shells may have been collected anywhere from the surface to 30 cm deep in the sediment. However, the results indicate that the rates of sedimentation could be in the order of 30 cm/1000 years.

Traverse MN

The sediments along this traverse are less sandy than along the traverses to the west. Although the cores are short, variability in sediment size is apparent (Fig. 44a). The sand content increases at the expense of clay, with a nearly constant proportion of silt. A unique feature is a layer of gravelly sediments at the 100-130 cm interval and at the bottom of core 852. In core 849 the sediments are basically silty clays, but the core terminates in a layer of sediments containing 96 per cent sand.

Except for a few barren layers, the number of foraminifera in these cores is higher than in the cores of the other traverses (Fig. 44b). Planktonic foraminifera are present in small numbers throughout the cores on the continental shelf. Along other traverses planktonic tests are absent on the continental shelf, except for Traverse CD along the axis of Mackenzie Canyon. Below approximately 450 cm of core 855 the ratios of planktonic to benthonic foraminifera are sharply reduced to less than 0.1 as a result of increasing numbers of benthonic foraminifera. The lower half of the core also contains traces of gravel which are absent in the upper half.

The percentages of the estuarine-inshore species **Elphidium clavatum** are low throughout the cores regardless of distance from shore (Fig. 44c). However, the species is present in every interval, including core 855 taken on the slope.

The percentages of the outer shelf-slope species **Islandiella teretis** are high in the sediments of the inner shelf cores in comparison to **E. clavatum**, for example, in core 852 where **I. teretis** is the predominant species, although the coring site is closer to the shore than to the continental margin. Cores along the westernmost Traverse AB also showed high percentages of **I. teretis** close to the shore. On the basis of this evidence, it was concluded that offshore bottom waters are hugging the coast west of Herschel Island. A similar situation may exist off the Baillie Islands, at the eastern extremity of the Beaufort Sea continental shelf.

Four of the seven cores yielded identifiable molluscs. All of these cores were taken in water depths of less than 50 m. Mollusc-bearing grab samples also came from depths of less than 50 m with the exception of one sample from 69 m. Species recorded from the surface samples were shallow-water species, as were those from the cores. Only three species were common to grab samples and cores and two of these, **Clinocardium ciliatum** and **Liocyma fluctuosa**, are species reported in this study only from the area east of Mackenzie Delta. Three other species from the cores, **Mya arenaria**, **Oenopota reticulata**, and **Trichotropis** sp., are unique to this traverse.

The layers barren of foraminifera, do not correlate with any specific features in sediment texture. The sediments rich in sand are equally rich in foraminifera, except for the sandy layer at the bottom of core 849. The large number of foraminifera, high diversity, and presence of gravel (ice-rafted sediments?) indicate that the cores did not penetrate late Holocene sediments. The low content of clay sized sediments and low numbers of **Elphidium clavatum** indicate that this region, which is well east of the delta front, is little influenced by the effluent plume of Mackenzie River.

CONCLUSIONS

Recent Environment

The marine environment on the continental shelf of the southeastern Beaufort Sea is dominated by the outflow of Mackenzie River and the presence of sea ice. In the absence of winds, the Mackenzie outflow moves eastward along the coast, but strong easterly winds can reverse the circulation. There is evidence of upwelling off Cape Bathurst and along the outer shelf where high standing stocks of plankton were collected during September 1970. During April 1972, the same areas yielded only one-eighth of the summer standing stock largely because of the presence of sea ice.

Regions of very low hydrodynamic energy are found along the axis and the eastern flank of Mackenzie Canyon and the continental shelf facing the Mackenzie Delta where sediments consist basically of clays and they presumably are sites of high rates of sedimentation. Higher energy levels are postulated on the continental shelf to the east of the delta where there are extremely well sorted sands. At the present, little sediment is being deposited on the shelf to the east of the delta.

The main source of sediment is Mackenzie River. Upon entering the sea, sediment-laden fresh water flows north and east on top of the marine water. The fine sediment that may have been initially deposited in the shallow Mackenzie Bay and on the continental shelf off Tuktoyaktuk Peninsula is redeposited in the deeper water of Mackenzie Canyon. Thus the pattern of sediment transport is counterclockwise, to the east along the shore and to the west on the continental shelf.

The ice scouring of the sea floor may be responsible for the irregular distribution of the less common foraminiferal species thus obliterating useful species-environment relationships. The two most common species **Elphidium clavatum** and

Islandiella teretis were found in patterns that could be explained in terms of water salinity. **Elphidium clavatum** predominates the foraminiferal assemblages on the continental shelf where the influence of the Mackenzie out-flow is most persistent, such as reduced salinities and excessive amounts of suspended matter in the water column.

Islandiella teretis is a dominant species on the outer shelf, the continental slope, and the nearshore areas of high bottom salinities at the western and eastern extremities of the study area. The distribution pattern of the planktonic foraminifer **Globorotalia pachyderma** is influenced by near-shore waters; therefore, the number of this species found in the sediment can be correlated with the extent of oceanic influence.

The number of molluscan species found in the sediment is large, although the number of specimens per sample is small. Very few living or undisturbed specimens were found in waters deeper than 100 m and sediments are barren of molluscs below 500 m. It is evident that the diverse molluscan fauna consists basically of inner shelf species, although the shallow bays leading to the channels of the Mackenzie Delta are barren of molluscs.

Paleoenvironment

The faunal record in the sediment cores indicates that on the continental shelf only postglacial sediments were recovered. On the continental slope several long cores contain sections that are virtually barren of foraminifera or lack fauna altogether. These sediments may have been deposited during the last glacial period when conditions along the continental margin were less favourable for faunal growth.

It is possible that on the continental shelf the penetration of the corer was arrested by the denser glaciofluvial sediments and the length of the cores could roughly indicate the thickness of the post-transgression sediments. This assumption is supported by a postglacial sediment isopach map that was compiled by Shearer (1970) on the basis of continuous seismic profiles. According to the map the postglacial sediment is 3 to 5 m thick on the shelf north and east of the delta. In Mackenzie Canyon these sediments are more than 20 m thick. Within the area of thin Holocene sediments only short cores were recovered (Traverse EF), whereas in Mackenzie Canyon the cores were up to 11 m long (Traverse CD).

On the basis of core recovery, ^{14}C data, and faunal discontinuities, the rate of sedimentation may be in the order of 3-30 cm/1000 years on the continental shelf, more than 100 cm/1000 years in Mackenzie Canyon, and 20-30 cm/1000 years along the continental margin-upper continental slope at depths greater than 1000 m.

With few exceptions, sediment types found at the surface are similar to those found in the cores. Sandy sediments containing some gravel are present to the west of Herschel Island, along a few horizons in the deep sea cores and on the shelf off Baillie Islands at the eastern extremity of the area of study. Most of the gravelly sediments are assumed to be ice rafted and are found in areas where sedimentation rates are thought to be low. Well sorted sand is present in a few layers along the axis of Mackenzie Canyon and throughout some of the cores to the east of the delta. It is possible that clean sands east of the delta represent ancient strandline deposits.

The sediment cores taken from Mackenzie Canyon, and the continental margin and slope consist almost entirely of silts and clays with very sparse visible bedding or changes in silt/clay ratios. Apparently, fine sediments have been deposited continuously in the canyon and along the continental margin at least during the Holocene, and also in the deep sea and on the continental slope during some of the pre-Holocene glacial periods.

At present depths on the continental shelf the thick sequences of fine river-borne sediments in Mackenzie Canyon and along the continental margin could not have been deposited directly from the sediment plume discharging from the delta. At present, the plume migrates to the east along the coast, where the clays settle upon contact with seawater. However, the residence time of these fine sediments is probably short in the high energy environment and the resuspended sediments arrive at the site of deposition as a result of a lateral transport along the sea floor.

The transport of sediments along the sea floor also involves the redistribution of foraminiferal tests. Large numbers of the nearshore index species **Elphidium clavatum**, which occur in offshore sediment cores, can indicate either chronologic changes in the extent of sediment redistribution or changes in the migration of the sediment plume. Two sediment cores collected from the continental slope on the eastern and western flanks of Mackenzie Canyon (812 and 819) show increased relative percentages of E. **clavatum** in the surface layers without a corresponding decrease in the ratio of planktonic over total foraminifera. The evidence indicates that the environment has not changed and that increased **post mortem** transport of the nearshore species has taken place along the continental slope and thus increased sedimentation rates. Using the same evidence, core 807 taken along the axis of Mackenzie Canyon indicates increased offshore influence. In the lower half of the core E. **clavatum** is the predominant species, but it is a minor constituent in the upper half. The change is associated with the increased dominance of the planktonic **Globorotalia pachyderma.**

One of the causes for the shoreward eddy in the canyon is the eastward migration of the Mackenzie runoff (e.g. Bornhold, 1975). Using the suggested sedimentation rates for the Canyon cores of approximately 100 cm/1000 years, the increased migration of the offshore waters up Mackenzie Canyon has taken place for the last 5000 to 6000 years. This is the period during which the eustatic sea level has changed little and waters over the continental shelf have been at the present depth and sufficient for the existing anticlockwise current system. In the nearshore cores at both sides of Herschel Island evidence also exists for an increased offshore influence on the inner shelf of the Yukon coast. These smaller shoreward eddies may be triggered by the anticlockwise current system on the continental shelf to the east.

The thin layer of Holocene sediments on the continental shelf east of the delta may contain a preserved record of migrating shorelines. The record is fragmental owing to the widely differing sedimentation rates and insufficient sampling. Nevertheless, several inner shelf cores contained barren layers below the present fauna and in outer shelf cores the diverse faunas were replaced in the lower layers by the inner shelf-estuarine E. **clavatum.** The well sorted sands as a rule contained small numbers of foraminifera with an occasional barren layer. The paucity of preserved foraminiferal tests is in accordance with the view that these sediments may be remnants of ancient beaches. On the other hand, off Baillie Islands the sandy sediments are rich with a diverse foraminiferal fauna and contain gravel which has been deposited during the Late Holocene.

The preponderance of fragmental shallow-water molluscan species in the deeper grab samples points to mechanical transport of specimens from the inner to the outer shelf and down the slope, and suggests that shallow-water forms in the deeper cores do not represent much shallower conditions in the past.

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PLATE 1
AND
APPENDICES 1 AND 2
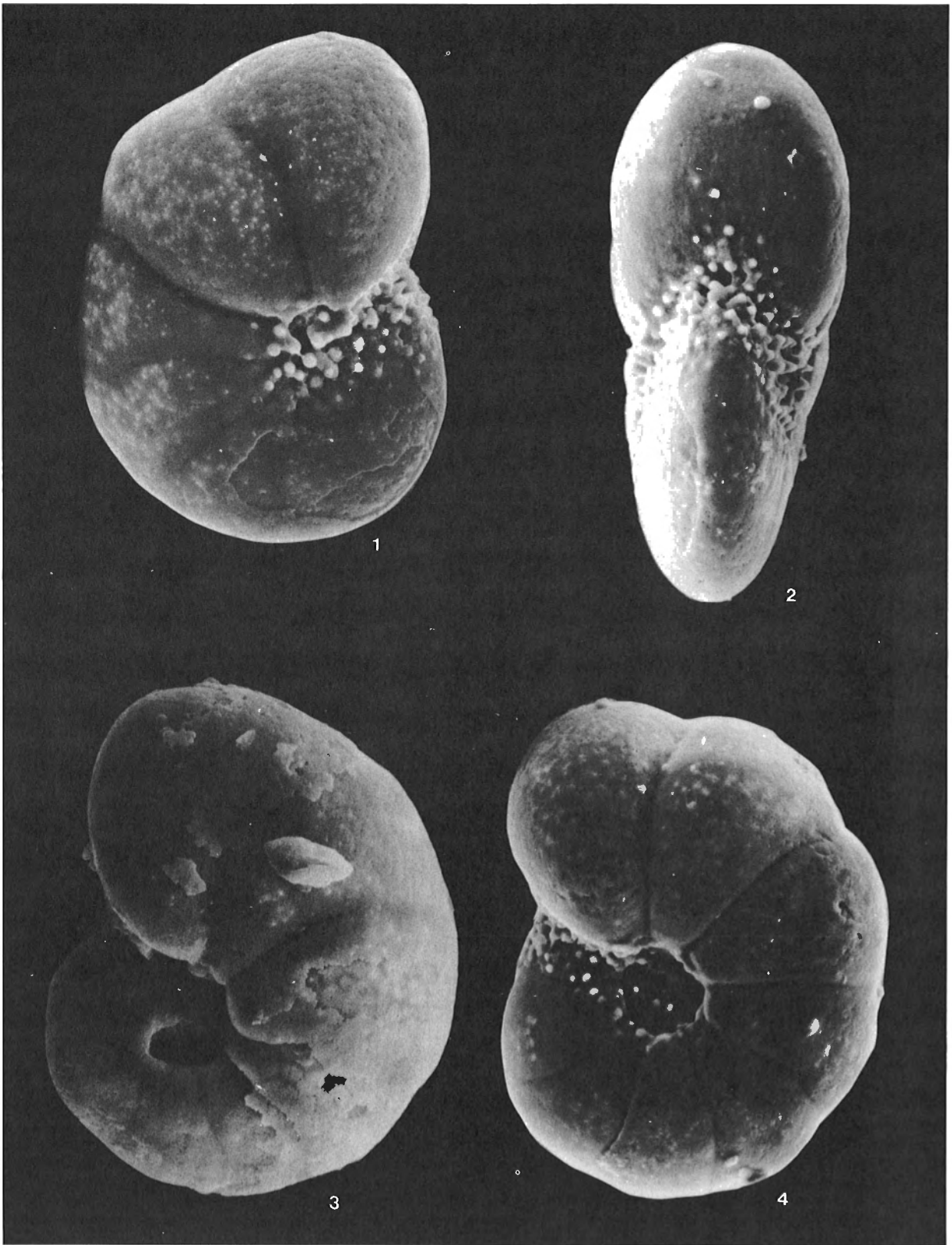
PLATE 1

Figures 1-4 **Protelphidium nanum** n. sp.

Core station 832, Latitude 70°08.5'N, Longitude 132°47.9'W. Water depth: 25 m, Core interval: 0-5 cm (The distance between the white squares in 30 µm).

Figure 1. Side view x 590 GSC Paratype no. 54642
      2. Apertural view x 610

3. Side view x 700 GSC Paratype no. 54643
4. Side view x 490 GSC Paratype no. 54644

APPENDIX 1

Family Elphidiidae Galloway, 1933

Subfamily Elphidiinae Galloway, 1933

Genus **Protelphidium** Haynes, 1956

Protelphidium nanum n. sp. (Plate 1, Figs. 1-4, Text fig. 1)

Test small, planispiral and involute, sides gently concave, periphery broadly rounded, 8 to 9 chambers in the last whorl increasing in size gradually; sutures gently curved, distinct and slightly depressed, near the umbilical region granular; test wall calcareous, hyaline and finely perforate, granular umbilical area; aperture at least six pores at the base of the final chamber.

Remarks: The species differs from **Protelphidium orbiculare** by the smaller size, smaller number of chambers and slightly depressed umbilical region resulting in concave sides. Average maximum diameter 163 µm with a range of 120-260 µm. **P. nanum** occurs in small numbers at localities between depths of 24 and 69 m. It is abundant in core 832 taken at 25 m.

Dimensions of Holotype: Largest diameter 260 µm, shortest diameter 209 µm, width 121 µm, 9 chambers.

Type Locality: Lat. 70°08.5'N, Long. 132°47.9'W. Core 69-050 VC 832

Types: Holotype GSC no. 54641, core interval 50-55 cm text fig. 1.
Paratypes GSC no. 54642, core interval 0-5 cm plate 1, fig. 1, 2.

GSC no. 54643, core interval 0-5 cm plate 1, fig. 3.

GSC no. 54644, core interval 0-5 cm plate 1, fig. 4.
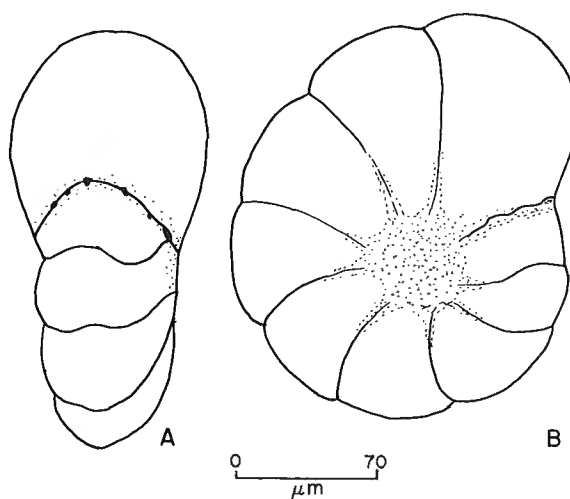
Text-figure 1. Line drawing of **Protelphidium nanum** Holotype, A-apertural view, B-side view. Maximum diameter 260 mm. Core 69 050VC 832, 50-55 cm. Holotype GSC no. 54641.

Table 1

Foraminifera in core top samples (Estimated numbers per 35 ml of sediment.)

Traverse AB

STATION DEPTH (m)	815 26	814 51	813 69	812 515	811 1426
Dentalina frobisherensis	8				
Oolina apiculata	8				
Parafissurina tectulostoma	8				
Rectobolivina columellaris	8				
Islandiella teretis	704	36	19	14	18
I. islandica	174	17	10	4	2
Protelphidium orbiculare	8	24	19		
Elphidium clavatum	312	17	103	1	
E. bartletti	16	15	2		
E. subarcticum	40	8	5		
Buccella frigida	64	5	2		
Pseudopolymorphina novangliae	64				
Eoeponidella pulchella	32	1	5		
Protelphidium nanum	8		4		
Fissurina marginata		1			
Melonis zaandami		1		3	
Lagena flatulenta		1			
Cibicides lobatulus		32		1	
Trochammina nana		4			
Recurvoides turbinatus		4			
Cribrostomoides crassimargo		2			
Astrononion gallowayi		3			
Nonionellina labradorica			2		
Glabratella wrightii			1		
Stetsonia horvathi			1		
Lagena laevis				1	
Eponides tener					1

Traverse CD

STATION DEPTH (m)	816 33	817 47	818 109	808 198	807 290	806 539
Islandiella teretis	144	352	6	3	68	39
I. islandica	316	368	76	3	85	6
I. norcrossi	32	48	2	1	1	1
Protelphidium orbiculare	24	80	4		2	
Elphidium clavatum	196	608	60	2	33	11
E. subarcticum	4	8	1		2	
E. groenlandicum	2					
Buccella frigida	12	8	18	1	5	2
Pseudopolymorphina novangliae	4	8				
Spiroplectammina biformis	8	24	21	20		
Cyclogyra involvens	2		1			
Silicosigmoilina groenlandica	2					
Cassidella complanata	14	32	4			
Fissurina marginata	2					
Trochamminella atlantica		8				
Elphidium bartletti		16				
Virgulina fusiformis		72	78	1		
V. schreibersiana			4			
Nonionellina labradorica		8	1			
Textularia torquata		24	7	2		
Trochammina nana		8	1	12	2	
Recurvoides turbinatus		24		6	1	
Astrononion gallowayi		8				
Parafissurina himatiostoma		8				
Sigmomorphina undulosa		8				
Cribrostomoides crassimargo		32				
Melonis zaandami				3	4	3
Glomospira gordialis				1		
Trochamminella bullata				2		
Cibicides lobatulus			1		1	
Saccammina atlantica					1	
Triloculina trihedra					1	
Lagena laevis						1
Patellina hauerinoides						1
Eoeponidella pulchella			15			
Globulina landesi			2			
Epistominella takayanagii			1			
E. arctica			2			
STATION DEPTH (m)	816 33	817 47	818 109	808 198	807 290	806 539

Traverse EF

	STATION	822	821	820	819	810	809
	DEPTH (m)	38	47	352	885	1657	2031
Elphidium clavatum		3120	754	528	48		
E. bartletti		48	8				
E. subarcticum		96	144				
Islandiella islandica		1872	1336	1152	12	1	131
I. norcrossi		32			4		
I. teretis		32	162	592	440	126	69
Buccella frigida		192	88	96			
Protelphidium orbiculare		304	89				
Virgulina fusiformis		64	56				
Spiroplectammina biformis		16	256	80			
Cribrostomoides crassimargo		16					
Triloculina tricarinata		32					
Lagena gracillima		16	16				
Quinqueloculina stalkeri			16				
Bolivina inflata		16			4		1
Pseudopolymorphina novangliae		64	9				
Globulina landesi		64	25				
Fissurina semimarginata		16					
Elphidiella groenlandica			2				
Pyrgo subsphaerica			8				
Recurvoides turbinatus			24				
Astacolus hyalacrulus			8				
Epistominella takayanagii			16				
Dentalina frobisherensis			8				
Cassidella complanata			16	80			
Elphidium oregonense			2				
Nonionellina labradorica				16			
Triloculina trihedra				16			
Astrononion gallowayi				48			
Eoeponidella pulchella				16			
Cibicides lobatulus				32			
Trochammina nana				48			
Oolina caudigera				16			
Melonis zaandami				16			
Eponides tener						54	57
Stetsonia horvathi						1	96
Lagena nebulosa						1	

Traverse GH

	STATION	853	829	828	827	826	825	824
	DEPTH (m)	16	37	55	62	87	470	880
Pseudopolymorphina suboblonga				1				
Lagena mollis							4	
Elphidium clavatum		867	554	123	880		84	
Islandiella islandica		32	482	51	1056		184	
Protelphidium orbiculare		112	112	55	16			
Spiroplectammina biformis		4			1104	112		
Islandiella teretis		4	14	10	480		200	2
Elphidium subarcticum		24	4	28	16			
Buccella frigida		28	90	6	32		32	
Elphidiella groenlandica		8		6				
Quinqueloculina stalkeri		12	4	4	16			
Pseudopolymorphina novangliae		12	36	55	16			
Globulina landesi		24		7				
Triloculina tricarinata		4						
Parafissurina tectulostoma		4			16			
Pyrgo subsphaerica		4						
Elphidium bartletti			8	41				
Islandiella norcrossi			6		64			
Melonis zaandami							16	
Laryngosigma hyalascidia			2					
Protelphidium nanum			2					
Triloculina trihedra			2					
Scutuloris tegminis			2					
Eoeponidella pulchella				10	96			
Parafissurina himatiostoma				1	16			
Cyclogyra involvens				1				
Trochammina nana					688	3	20	
Eggerella advena					32	5		
Textularia torquata					160	2		
Virgulina fusiformis					96		16	
Cassidella complanata					16		4	3
Recurvoides turbinatus					96			
Reophax fusiformis					32			
Bolivina inflata					16			
Textularia earlandi					16			
Astrononion gallowayi					32			
Virgulina schreibersiana					48			
Trochamminella atlantica					16			
Trochammina quadriloba					64			
Cibicides lobatulus							4	
Cribrostomoides crassimargo							4	
Epistominella takayanagii							4	
Fissurina cucurbitasema							4	
Stetsonia horvathi								1

Appendix 2; Table 1 (cont'd.)

Traverse IJ

	832	838	837	836	835	834	833	830
STATION / DEPTH (m)	25	42	62	80	80	289	823	1850
Elphidium clavatum	47	39	7		3	58		
Islandiella islandica	2		1		8	142		
I. teretis	4				18	196	5	876
Eoeponidella pulchella	23				2			
Buccella frigida		6					12	
Spiroplectammina biformis	5	19			195			
Scutuloris tegminis	1							
Textularia torquata		5			38			
Ammotium cassis		4						
Elphidium bartletti		1				2		
Elphidiella groenlandica		1						
Cribrostomoides crassimargo		1			2			
Recurvoides turbinatus		4			12	6	1	
Cassidella complanata		1			3	12		
Protelphidium orbiculare		1			2	6		
Trochammina nana					27	12	2	20
Eggerella advena					10			
Trochammina quadriloba					8			
Cribrostomoides jeffreysi					2			
Saccammina atlantica					1			
Reophax arctica					5			
Trochamminella bullata					5	4		
Melonis zaandami						18		
Nonionellina labradorica						8		
Globobulimina auriculata						2		
Lagena flatulenta						4		4
Islandiella norcrossi						2		
Virgulina fusiformis						4		
Textularia earlandi						2		
Triloculina trihedra						4		12
Astrononion gallowayi						2		
Epistominella takayanagii					1	2		
Elphidium subarcticum				1		4		
Reophax nodulosa							1	
Eponides tener								92
Stetsonia horvathi								8
Cribrostomoides neobradyi								16
Cibicides lobatulus								4

Traverse KL

	848	847	846	845	843	842
STATION / DEPTH (m)	18	25	32	54	104	585
Islandiella islandica	14		3	1	2	268
Elphidium clavatum	192		10	4	11	104
Protelphidium orbiculare	89	4	4	1	10	
Elphidium subarcticum	15	2	2			
Elphidium bartletti	24			6		
Buccella frigida	36	1	2	1	3	
Eoeponidella pulchella	15		1		1	
Spiroplectammina biformis	3		3		1	
Pseudopolymorphina novangliae	26					
Lagena gracillima	1					
Astacolus hyalacrulus	2					
Epistominella takayanagii	1					
Islandiella teretis				3	3	764
Recurvoides turbinatus				1	2	20
Silicosigmoilina groenlandica				1		
Trochammina nana					5	56
T. quadriloba					1	
Virgulina fusiformis						64
Cassidella complanata						32
Melonis zaandami						4
Recurvoides contortus						4
Cribrostomoides crassimargo						8
Trochamminella bullata						8
Epistominella arctica						16
Islandiella norcrossi						12
Lagena hispidula						4
Fissurina marginata						4
Parafissurina tectulostoma						4
Valvulineria arctica						4

Traverse MN

STATION	841	840	852	851	850	849	855
DEPTH (m)	29	36	40	40	48	69	286
Elphidium clavatum	70	96	400	40	936	242	
Islandiella islandica	28	80	432	8	224	280	4
Protelphidium orbiculare	122	152	88	19	272	61	
Spiroplectammina biformis	6		16	2	8	12	
Islandiella teretis	36	308	552	3	40	147	4
I. norcrossi	6		24		8	15	2
Elphidium subarcticum	18	76	64		8	20	
Buccella frigida	12	32	104	4	112	65	
Eoeponidella pulchella	18	8	72	1	216	22	
Reophax fusiformis	6	16					
Astrononion gallowayi	22	16	200	7		8	
Quinqueloculina stalkeri	2				16	5	
Cibicides lobatulus	2	80	96			2	
Elphidium bartletti	2	12	16			13	
Cassidella complanata	1	8	24	1	8	18	
Pseudopolymorphina novangliae	6			1	4	4	
Cribrostomoides jeffreysi		4					
Trochammina nana		4				1	
Cribrostomoides crassimargo		12		1		3	
Saccammina atlantica		8					
Globulina landesi		4			4		
Glabratella wrightii		4					
Epistominella takayanagii		4	8	1		3	
Dentalina ittai		4					
Nonionellina labradorica			16				
Fissurina semimarginata			8				
Virgulina fusiformis			8		8	1	
Protelphidium nanum				47	128	1	
Adercotryma glomeratum				1			
Ammotium cassis				1			
Valvulineria hamanacoensis					24	1	
Lagena semilineata					8		
Cyclogyra foliacea					1		
C. involvens					8		
Textularia torquata						1	

Table 2

Mollusca in cores and grab samples; W,N,E indicate the number of occurrences
to the West, North and East of the delta, respectively

	W	Nos. of Stn. N	E		W	Nos. of Stn. N	E
Yoldiella lenticula	45	29	7	Hiatella arctica	2	10	
Portlandia arctica arctica	24	23	1	Macoma torelli	2	6	
Bathyarca glacialis	10	1	1	Alvania cruenta	4		
Axinopsida orbiculata	9	1	1	Tellina sp.	2		
Thyasira flexuosa	7	5	2	Boreotrophon clathratus	1		
Yoldiella frigida	6	2	1	Cingula castanea alaskana	1		
Nuculana minuta	4	1	2	Colus togatus	1		
Astarte montagui forma typica	3	1	2	Lima hyperborea	1		
Portlandia arctica siliqua	19	68	58	Macoma loveni	1		
P. arctica aestuariorum	1	21	6	Margarites costalis	1		
Yoldiella fraterna	9	20	7	Oenopota declivis	1		
Nucula tenuis	6	12	11	O. decussata	1		
Retusa umbilicata	8	8	4	Philine quadrata	1		
Cylichna occulta	12	37	40	Lyonsia norvegica		1	
Liocyma fluctuosa	4	2	28	L. schimkewitschi		1	
Clinocardium ciliatum	1	5	24	Montacuta planata		1	
Macoma calcarea	8	10	22	Philine lima		1	
Astarte borealis	3	2	18	Plicifusus sp.		1	
Pandora glacialis	1	7	15	Turritellopsis acicula		1	
Astarte montagui striata	9	2	10	Serripes groenlandicus			7
Lyonsia arenosa	2	6	9	Thracia devexa			6
Tachyrhynchus erosus	2	2	4	Mya pseudoarenaria			4
Lunatia pallida	1	1	3	Astarte montagui warhami			3
Cerastoderma echinatum	1	1	1	Musculus corrugatus			3
Alvania janmayeni	2	1		Mya truncata uddevallensis			3
Bathyarca frielei	2	1		Amauropsis purpurea			2
Oenopota novajasemliensis	1	2		Astarte crenata			2
Cyrtodaria kurriana		19	6	Neptunea heros			2
Musculus niger		3	22	Solariella obscura			1
Mya truncata		1	8	Buccinum sp.			1
Nuculana pernula costigera		1	7	Lyonsiella sp.			1
Macoma moesta		2	5	Margarites olivaceus			1
Yoldia myalis		1	5	Modiolus modiolus			1
Yoldiella intermedia		2	2	Musculus discors laevigatus			1
Cerastoderma elegantulum		1	1	Neptunea ventricosa			1
Oenopota turricula		1	1	Odostomia cassandra			1
Nuculana pernula	8		2	Oenopota arctica			1
Lepeta caeca	2		1	O. cinerea			1
Cingula castanea	1	1		Trichotropis sp.			1
Macoma balthica	1		1	Volutopsius sp.			1
				Yoldia hyperborea			1

Table 3

Mean depths at which index molluscan species were found

SPECIES	WATER DEPTH (m)
Alvania janmayeni	34
Astarte borealis	34
Astarte montagui striata	39
Axinopsida orbiculata	83
*Bathyarca frielei	124
Bathyarca glacialis	79
Clinocardium ciliatum	30
Cylichna occulta	18
Cyrtodaria kurriana	9
Hiatella arctica	41
Lepeta caeca	118
Liocyma fluctuosa	18
Lunatia pallida	26
*Lyonsia arenosa	24
Macoma calcarea	32
Macoma torelli	36
Musculus niger	30
Mya truncata	27
Nucula tenuis	40
Nuculana minuta	51
Nuculana pernula	48
Oenopota novajasemliensis	30
Pandora glacialis	23
Portlandia arctica aestuariorum	7
Portlandia arctica arctica	52
Portlandia arctica siliqua	16
Retusa umbilicata	23
Serripes groenlandicus	28
*Solariella obscura	53
*Tachyrhynchus erosus	124
Thracia devexa	27
Thyasira flexuosa	178
Yoldia myalis	41
Yoldiella fraterna	16
Yoldiella frigida	58
Yoldiella intermedia	5
Yoldiella lenticula	37

* single locality

Table 4

Mean depths at which foraminiferal species were found

TRAVERSES	AB, CD		EF, GH, IJ		KL, MN	
	D	CV	D	DV	D	CV
Islandiella teretis	40	21	291	18	123	27
I. islandica	47	17	78	23	77	24
Protelphidium orbiculare	48	8	50	24	39	10
Elphidium clavatum	41	10	47	21	49	17
E. subarcticum	36	14	110	25	37	8
Islandiella norcrossi	44	11	60	16	77	24
Buccella frigida	44	21	60	23	43	10
Pseudopolymorphina novangliae	28	6	42	8	25	15
Spiroplectammina biformis	42	15	67	9	43	10
Cyclogyra involvens	49	15	55	-	48	-
Elphidiella groenlandica	33	-	30	17		
Silicosigmoilina groenlandica	33	-			54	-
Cassidella complanata	46	8	215	16	113	26
Fissurina marginata	38	6			585	-
Trochamminella atlantica	47	-	62	-		
Elphidium bartletti	40	9	46	8	34	14
Virgulina fusiformis	74	10	60	16	341	18
V. schreibersiana	109	-	62	-		
Nonionellina labradorica	54	7	329	2	40	-
Textularia torquata	61	11	65	3	69	-
Trochammina nana	105	16	79	16	414	14
Recurvoides turbinatus	64	14	65	10	455	11
Astrononion gallowayi	48	1	178	16	39	4
Parafissurina himatiostoma	47	-	62	1		
Sigmomorphina undulosa	47	-				
Cribrostomoides crassimargo	47	1	63	23	99	28
Melonis zaandami	304	11	363	3	585	-
Glomospira gordialis	198	-			585	-
Trochamminella bullata	198	-	140	13	585	-
Cibicides lobatulus	59	12	428	8	38	2
Saccammina atlantica	290	-	80	-	36	-
Triloculina trihedra	290	-	537	17		
Lagena laevis	527	0				
Pateoris hauerinoides	539	-				
Eoeponidella pulchella	43	17	65	16	44	7
Globulina landesi	109	-	34	11	42	4
Epistominella takayanagii	109	-	75	21	41	8
Epistominella arctica	109	-			585	-
Dentalina frobisherensis	26	-	47	-		
Oolina apiculata	26	-				

TRAVERSES	AB, CD		EF, GH, IJ		KL, MN	
	D	CV	D	DV	D	CV
Parafissurina tectulostoma	26	-	47	14	585	-
Rectobolivina columellaris	26	-				
Eponides tener	1426	-	1843	1		
Protelphidium nanum	35	13	37	-	46	2
Lagena flatulenta	51	-	731	14		
Glabratella wrightii	69	-	1995	1	36	-
Stetsonia horvathi	69	-	35	8		
Triloculina tricarinata			42	3	18	-
Lagena gracillima			40	14	50	6
Quinqueloculina stalkeri			75	26		
Bolivina inflata			47	-		
Elphidium oregonense			38	-	40	-
Fissurina semimarginata			33	15		
Pyrgo subsphaerica			47	-	18	-
Astacolus hyalacrulus			352	-		
Oolina caudigera			1657	-		
Lagena nebulosa			55	-		
Pseudopolymorphina suboblonga			470	-		
Lagena mollis			37	-		
Laryngosigma hyalascidia			32	5		
Scutuloris tegminis			68	3		
Eggerella advena			62	-	34	3
Reophax fusiformis			73	11		
Textularia earlandi			470	-		
Fissurina cucurbitasema			64	2	104	-
Trochammina quadriloba			42	-	40	-
Ammotium cassis			80	-	36	-
Cribrostomoides jeffreysi			80	-		
Reophax arctica			289	-		
Globobulimina auriculata			823	-		
Reophax nodulosus			1850	-		
Cribrostomoides neobradyi						
Recurvoides contortus					585	-
Lagena hispidula					585	-
Valvulineria arctica					585	-
Dentalina ittai					36	-
Adercotryma glomerata					40	-
Valvulineria hamanacoensis					48	-
Lagena semilineata					48	-
Cyclogyra foliacea					48	-

D = mean depth in metres,
CV = coefficient of variation of the mean

Table 5

Comparison between foraminiferal and molluscan paleodepths

CORE NO.	DEPTH (m) MEASURED	DEPTH (m) CALCULATED	INTERVAL IN CORE (cm)	CHANGE IN DEPTH MOLLUSCS	CHANGE IN DEPTH FORAM.
816	33	27	0-5	11 S	0
			100-105	11 S	0
			125-130	9 S	0
			150-155	11 S	0
			175-180	10 D	0
			275-280	11 S	0
			350-353	30 D	0
808	198	100	525-530	84 S	
			575-580	63 S	
			825-830	63 S	
			875-880	63 S	
			975-980	84 S	
807	290	23	400-405	175 D	4 S
			670	56 D	5 S
			675-680	175 D	5 S
			690	56 D	5 S
			699-701	56 D	5 S
			800-805	56 D	
			850-855	7 S	
			899-901	56 D	
			925-930	7 S	5 S
			949-951	0	
			1067	14 D	
			1075-1080	31 D	5 S
821	47	44	25-30	28 S	
			125-130	28 S	
820	352	79	125-130	63 S	18 S
			400-406	27 S	37 S
			475-480	63 S	
			575-580	63 S	
			705-710	63 S	
			725-730	42 S	55 S
			750-755	21 S	52 S
			775-780	52 S	
			850-855	63 S	56 S
			875-880	42 S	53 S
853	16	19	5-10	3 S	
			25-30	3 S	
			45-50	3 S	
826	87	67	250-255	44 S	
			275-280	30 S	12 D
			450-455	51 S	
			475-480	51 S	5 D
848	18	29	235	23 D	4 D
			275-280	13 S	6 D
845	54	30	10-30	25 D	13 S
841	29	30	78-83	12 S	4 S
840	36	30	245-250	0	
852	40	34	29-31	5 D	12 D
			49-51	4 S	19 D
			69-71	4 S	
			230-235	7 S	12 D
835	16	19	5-10	3 S	
			25-30	3 S	
			45-50	3 S	

S = shallower,   D = deeper than the present depth,   O = no change