Circulation of Surface Waters in Parts of the Canadian Arctic Archipelago Based on Foraminiferal Evidence[1]

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ABSTRACT. Planktonic foraminifera are present both in bottom sediments and surface waters on the shelf area averaging 400 metres in depth to the west of a line between Cape M'Clure and Cape Meecham, but in M'Clure Strait proper to the east of this line in the surface waters only. The evidence is used to suggest a slow net eastward movement of water from the ocean through M'Clure Strait in the past with increased rates at the present time.

RÉSUMÉ. *La circulation des eaux de surface dans certaines parties de l'archipel arctique canadien, d'après l'étude des foraminifères.* Dans la zone du plateau, d'une profondeur moyenne de 400 mètres, à l'Ouest d'une ligne tirée entre le cap de M'Clure et le cap de Meecham, les foraminifères planctoniques sont présents à la fois dans les sédiments du fond et dans les eaux de surface; mais à l'Est de cette ligne, dans le détroit de M'Clure proprement dit, on ne les trouve que dans les eaux de surface. Cet indice suggère, pour le passé, un mouvement net des eaux de l'océan vers l'Est, à travers le détroit de M'Clure, avec des taux accrus dans le présent.

РЕЗЮМЕ. *Исследование циркуляции поверхностных вод в некоторых районах канадского арктического архипелага на основе изучения фораминифер.* Фораминиферы планктонического происхождения обнаружены как в донных отложениях, так и в поверхностных водах в районе шельфа на глубине в среднем 400 м к западу от линии, проходящей между мысом Мак-Клюр и мысом Мичам. Однако в самом проливе Мак-Клюр, расположенном восточнее от этой линии, фораминиферы находятся лишь в поверхностных водах. На основе полученных данных можно предположить, что медленное в прошлом результирующее движение воды в восточном направлении от океана через пролив Мак-Клюр, в настоящее время становится более интенсивным.

INTRODUCTION

The waters of the Canadian Arctic Archipelago are influenced in varying degrees by the Arctic Ocean and Baffin Bay. Since the general movement of the upper 200 m. of water is from the Arctic Ocean southward, the influence of arctic waters may be expected to be much the greater (Collin and Dunbar 1964). Oceanographic data to support this conjecture are sparse or absent altogether in areas where ice conditions prevent regular passage of ships. M'Clure Strait, which is the western extremity of the Parry Channel system leading into Baffin Bay, represents such an area (Fig. 1). The purpose of this paper is to present a study of the circulation of surface waters from the Arctic Ocean into the channel system, through the use of relative abundances of planktonic foraminifera found in bottom sediments and surface waters.

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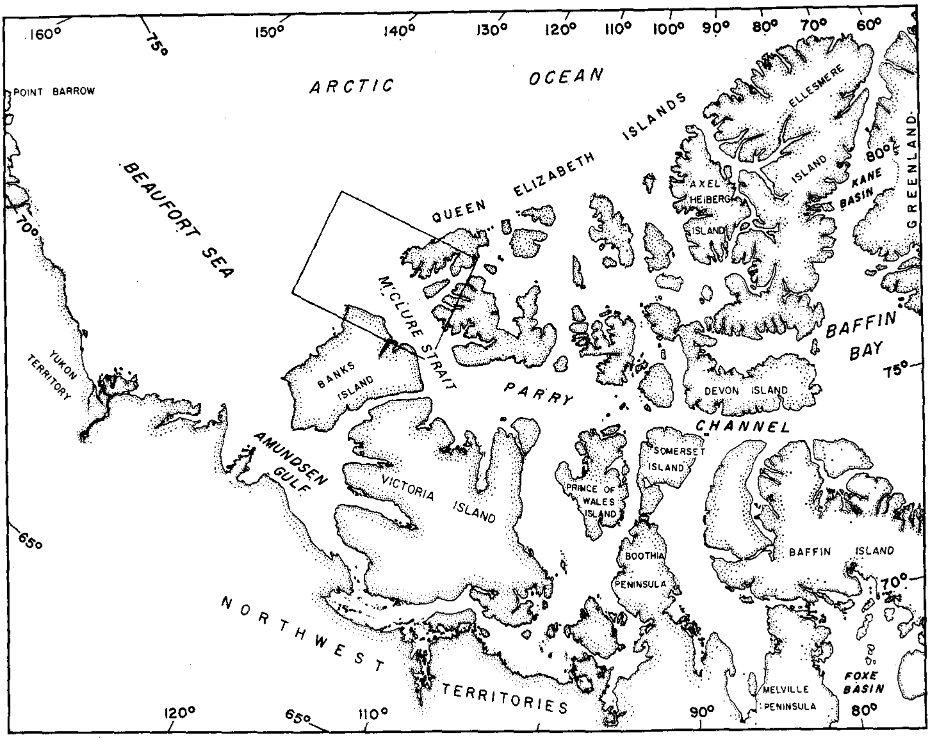

FIG. 1. Index Map. The area studied is outlined with a rectangle.

Planktonic foraminifera are characteristic of the upper layers of offshore oceanic waters (see Lobelich and Tappan 1964; Phleger 1960; Smith 1955). The presence of abundant planktonic foraminiferal tests in sediments and rocks is usually assumed to indicate deposition in an oceanic environment. An epicontinental environment is usually indicated by a scarcity or absence of planktonic tests, except for areas where distinct coastal waters are not present, such as the coast of southern California (Bradshaw 1959; Phleger 1960). In most areas one should expect to find a direct correlation between the distance from shore and the relative abundance of planktonic foraminiferal tests in sediments. This relative abundance is usually estimated by means of ratios of total benthonic to total planktonic specimens (Loeblich and Tappan 1964). However, the planktonic and benthonic foraminiferal assemblages represent different habitats and consequently their occurrence together in sediments is a fortuitous association. The relationship of planktonic and benthonic populations is not necessarily governed by the same ecological parameters. It is best to consider planktonic tests in sediment as inorganic particles derived from surface waters; the relative amounts of these particles, with respect to detritus from other sources, can then be used to determine the extent of oceanic influence on coastal waters.

FIELD WORK

Sediment samples, plankton tows and associated oceanographic data were collected between 27 May and 15 July 1968, using the sea ice as the sampling platform. Fifty bottom grab samples and 5 plankton tows were obtained within an area of 38,000 sq. km. (see Fig. 2). In addition, temperature readings and water samples were taken at Stations 12, 14, 15, 22 and 51 using Knudsen reversing water bottles fitted with double thermometer racks. Sediment samples were taken with a Dietz LaFond sampler and plankton was collected with a 360-micron net having a circular mouth opening of 0.5 m. in diameter. Several vertical tows were taken at each station, usually from 0 to 100 m. and 0 to 250 m. Plankton samples were preserved in 20 per cent alcohol or in 10 per cent formalin buffered with hexamethylene tetramine.

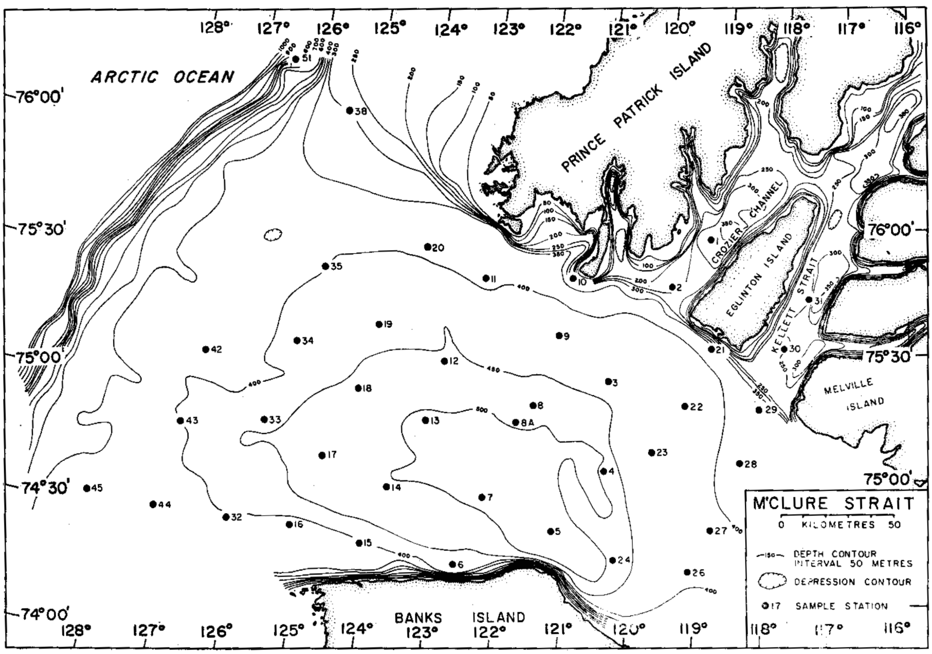

FIG. 2. Bottom topography of M'Clure Strait and adjacent channels.

Field logistics were provided by the Polar Continental Shelf Project based at Mould Bay, Northwest Territories. A DeHavilland Otter aircraft was used to carry equipment to fly-camps on Prince Patrick and Banks islands and a Sikorsky S-55 helicopter was used for local transportation and for work at the sampling stations.

PREVIOUS WORK

Planktonic foraminiferal tests in the upper layers of bottom sediment of the Arctic Ocean are not as abundant as in the other oceans at corresponding depths.

Ericson and Wollin (1959) found *Globigerina pachyderma* (Ehrenberg) in such sediments of the Arctic Ocean between 83°N. and 86°N., 60°W. and 100°W., at water depths ranging from 1,450 to 2,460 m. They reported 34 per cent as the average abundance of planktonic tests in the coarse fraction of sediment and a high of 80 per cent. Unfortunately, they did not compare their planktonic abundances with total population. Green (1959) reported increasing amounts of *G. pachyderma* at deeper stations in the Arctic Ocean. He estimated planktonic foraminifera to be up to 90 per cent of the total population at depths of 2,800 m. His work covers the area between 80°N. and 87°N., 81°W. and 96°W. Carsola (1952) found abundant planktonic foraminifera in sediments of the Beaufort Sea about 90 km. from shore and in the Chukchi Sea about 190 km. from the Alaskan coast. Wagner (1962) found an average of 63 per cent of *G. pachyderma* in the total population at stations on the continental shelf off Ellef Ringnes Island, Northwest Territories; this increased to 91 per cent on the continental slope. Phleger (1952) reported on planktonic foraminifera found in the channels of the Canadian Arctic Archipelago. He noted that planktonic foraminifera represented 20 per cent and 18 per cent of the total population in Kane Basin and Kennedy Channel respectively but less than 1 per cent at various localities in the Parry Channel system and in Baffin Bay. Vilks (1969) found planktonic foraminifera in sediments of Hazen Strait that increased in number towards Prince Gustaf Adolf Sea to a maximum of 282 tests per gram of sediment.

Bé (1960) gave a quantitative account of living planktonic foraminifera in the surface waters of the Arctic Ocean. He found that foraminifera were more abundant in June than in September, but that the average standing crop was 50 times smaller than in the North Atlantic. Tibbs (1967) reported on the presence of living planktonic foraminifera in the Beaufort Sea between the surface and a water depth of 700 m. Plankton tows were taken along a traverse from 140°W. to 170°W. and between 74°N. and 75°N. Planktonic foraminifera were found to be more abundant in the eastern portion of the track and not present to the west of 157°W. It is interesting to note that at the western extremity he found planktonic foraminifera only below 500 m. of water.

BOTTOM TOPOGRAPHY

Reasonably continuous bottom soundings are now available for the channels of the Queen Elizabeth Islands as a result of the activities of the Polar Continental Shelf Project and the Canadian Hydrographic Service. The bathymetric information was interpreted in terms of geological history and physiographic development by Pelletier (1962, 1966), Horn (1963, 1967), Marlowe and Vilks (1964), Marlowe (1968) and Vilks (1969). It was concluded that the present submarine features of Prince Gustaf Adolf Sea, Hazen Strait and Hecla and Griper Bay were originally fluvial valleys, modified by lobes of ice during the Pleistocene. The ice moved towards the Arctic Ocean through this pre-Pleistocene trunk system.

Bottom features of M'Clure Strait and the adjacent channels also show evidence of glacial erosion. This is indicated by U-shaped transverse profiles, relatively steep and straight shorefaces, and small and discontinuous basins (see Fig. 2).

Along the shores of Prince Patrick Island the 50-metre isobath follows the coastline at some distance thus delimiting a flat shelf. This shelf is negligible around Eglinton Island and is absent in Kellett Strait off Melville Island and M'Clure Strait off Banks Island. The initially flat profile of the shelf is broken by a sharp increase in slope down to the depth of about 200 m. in Crozier Channel and Kellett Strait and down to 350 m. in M'Clure Strait. Thus the floors of both Crozier Channel and Kellett Strait hang about 150 m. above the floor of M'Clure Strait. This is a typical feature of a glacially modified fluvial system.

In contrast to its flanks, the sea floor of M'Clure Strait below 400 m. has a relatively low relief. A median rise found along the axis of Peary Channel and Prince Gustaf Adolf Sea (Pelletier 1962) is not present in M'Clure Strait despite its greater width. A prominent feature in the Strait is the relatively deep basin off Banks Island, extending to over 500 m. This basin is closed towards the Arctic Ocean with a 400-metre isobath that outlines a poorly defined rise. The minimum depth on the rise is nowhere less than 350 m.

REGIONAL CLIMATOLOGY AND OCEANOGRAPHY

This area of the Arctic is dominated by the polar continental climate with cold winters and light precipitation. Freezing conditions prevail during 9 months of the year and mean daily minimum temperatures above freezing are recorded only in June, July and August. The mean annual precipitation is 4 inches (10.15 cm.) or less (Petterssen *et al.*, 1956). In view of the low rate of precipitation and the short summer, the influence of land-runoff on the general circulation and

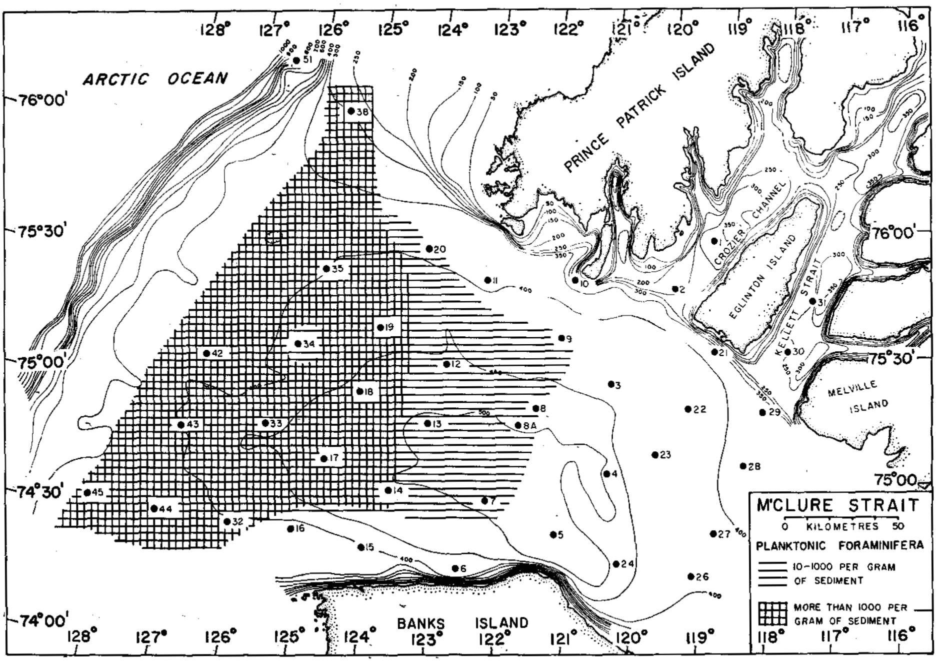

FIG. 3. Distribution of planktonic Foraminifera in surface sediments of M'Clure Strait.

properties of sea water is negligible. The extent of direct terrestrial influence is demonstrated by the extent to which planktonic foraminifera are killed by the runoff along the shores, for example, the surface sediments off Banks Island are barren of planktonic tests only within a zone of about 30 km. wide along the shore (Fig. 3).

Beyond the influence of land, seasonal changes in surface waters are caused by the addition of meltwater and partial removal of sea ice. The seasonal development of a slightly warmer brackish surface water at the time of the decay of the ice is a characteristic feature of ice-covered waters (Collin 1962). The seasonal zone remains close to the surface during summer in areas of permanent ice cover, and mixing of this brackish water with underlying layers is primarily a function of the extent to which ice is being removed. During summer the seasonal layer is not found beyond 10 m. under permanent ice in the Arctic Ocean (Collin 1962). In M'Clure Strait in 10 per cent of open water the seasonal layer extends to 20 m. and in Lancaster Sound, where water is free of ice for several weeks during summer, it may extend to 100 m. In winter the seasonal surface layer becomes part of the low-salinity and low-temperature arctic surface water, which may extend down to 50 m. Owing to its localized origin, it may exhibit pronounced lateral variations in salinity. In the main Arctic Ocean, surface salinities are lower in the Canadian Basin (about 29 parts per thousand) and higher in the Eurasian Basin (about 33 parts per thousand) according to Coachman and Barnes (1962).

Below the surface layer and down to 100 m. is a layer characterized by a strong halocline but with relatively small changes in temperature. Between 100 and about 250 m. is found the transition zone to the relatively high temperature and high salinity water believed to be of Atlantic origin. Along the continental slope opposite the entrance to M'Clure Strait the Atlantic water is present at about 270 m., where it is characterized by maximum temperature of 0.4°C. and maximum salinity of about 34.9 parts per thousand.

The movement of water through the Canadian Arctic Archipelago is towards the south and southeast (Bailey 1957). This movement is obstructed by sills that allow only the surface 200 m. of water to spill from the Arctic Ocean into Baffin Bay. Currents in M'Clure Strait have not been measured directly, but from measured density distributions across Prince of Wales Strait, Viscount Melville and Lancaster Sounds, Bailey (1957) inferred a net southeasterly movement through the islands.

Temperature and salinity measurements taken in the spring and summer of 1968 (Fig. 4) are in general agreement with previous observations, which indicate that waters in M'Clure Strait are more like those of the Arctic Ocean and Beaufort Sea than the waters of eastern Lancaster Sound and Baffin Bay. From these observations the water below 200 m. could be identified as the Atlantic layer. At a water depth of 100 m. the salinity and temperature values are similar to those of the Beaufort Sea (Collin 1962) and compare closely with data reported by Worthington (1953) from his station 6, which is about 50 km. to the west of the present study region. Temperatures and salinities at depths of less than 50 m. show greater variability in time and space. For example, more saline surface waters were recorded at station 22 than at the other 4 stations detailed on Fig. 4.

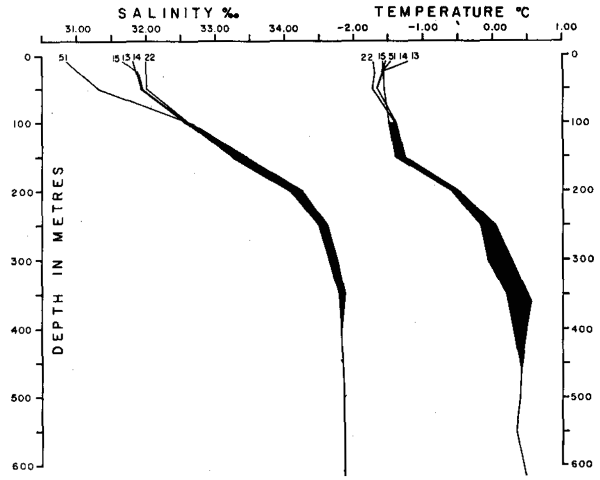

FIG. 4. Relationships of temperature and salinity with depth in M'Clure Strait in spring of 1968. Numbers indicate stations.

The difference could be attributed to the rate at which surface waters were diluted by melt-water between 11 June when the station was occupied, and 8-14 July when the other stations were visited. At station 51 the salinity was 0.7 parts per thousand less than at stations inside the channel. However, relatively low surface salinities (less than 30 parts per thousand) are apparently characteristic of the Beaufort Sea regardless of season (Worthington 1953; Bailey 1957; Collin 1962).

PLANKTONIC FORAMINIFERA

The number of living planktonic foraminifera counted in each plankton tow is shown in Table 1. All planktonic foraminifera were identified as *Globigerina pachyderma* (Ehrenberg). The average number of tests per 1,000 m.^{3} of water was 309, which is about 4 times larger than the average number of tests per 1,000 m.^{3} in the Arctic Ocean (Bé 1960) and about half as large as the number of tests per 1,000 m.^{3} from slope waters of the North Atlantic Ocean (Bé 1959). Locally, the highest number of tests per 1,000 m.^{3} I observed was at station 18

TABLE 1. Planktonic Foraminifera collected in vertical tows.

Station	*Depth (m.)*	*Total Living Foraminifera*	*Number of Foraminifera per 1000 m.^{3}*	*Volume of Water Filtered (m.^{3})*
42	0–100	0	0	17
	0–250	1	23	44
33	0–100	5	284	17
	0–250	13	295	44
18	0–100	21	1193	17
	0–250	29	658	44
	0–400	11	157	70
13	0–100	12	682	17
	0–250	22	499	44
8A	0–100	2	113	17
	0–250	1	23	44
5	0–100	1	57	17
	0–250	6	36	44

at the entrance of M'Clure Strait, with decreasing numbers observed both towards the ocean and towards the island. The trend is only partly in agreement with the number of dead tests in the surface sediment, where more planktonics were found on the outer shelf. However, in view of the fact that repeated tows at each station show extremely high variability, and that only 6 plankton stations were occupied, the results are unreliable for quantitative considerations. Nevertheless, these plankton tows have provided qualitative evidence that living planktonic foraminifera are found in M'Clure Strait as far east as 121°W. and in the upper 100 m. of the water.

The number of planktonic foraminiferal tests per gram of dry sediment were counted in 40 samples and the relative abundances have been plotted in Fig. 3. Planktonic tests were not found in Kellett Strait and less than 1 test per gram of sediment was counted in Crozier Channel. In M'Clure Strait the hachured pattern representing 10 to 1,000 tests per gram of sediment parallels the shoreline at a distance of about 15 nautical miles as far east as 121°W. Beyond this point planktonic foraminifera in sediment are either absent or less than 10 per gram of sediment. The pattern showing the occurrence of more than 1,000 tests per gram of sample reflects the sharp increase in the number of planktonic tests in surface sediment at the more oceanic stations. This 1,000-plus pattern extends only about 5 nautical miles into M'Clure Strait and is found closer to Banks Island than to Prince Patrick Island. M'Clure Strait is defined as the area to the east of a line drawn from Cape Manning on Prince Patrick Island to Cape Prince Alfred on Banks Island. Area to the west of this line is defined as Continental Shelf. At Banks Island the number of planktonics increases from less than 1 per gram of sediment at stations 15 and 16 to more than 1,000 only 2 to 3 nautical miles seaward. The maximum number of tests counted per gram of sediment is 4,878 at station 38.

DISCUSSION

On the Continental Shelf seaward of M'Clure Strait, sediments are almost 10 times richer in planktonic foraminifera than surface sediments at the entrance of the Strait. The decrease continues eastward, and beyond 121°W. planktonic foraminifera in the sediment are very few. The progressive decrease in planktonic tests seems to indicate that in spite of the relatively deep channel and proximity of the Arctic Ocean, the eastward circulation of water through M'Clure Strait has been very slow or non-existent. This conclusion is based on the assumption that greater numbers of planktonic foraminiferal tests in bottom sediments reflect higher productivity and possibly a larger number of living animals in the oceanic waters directly above. By the same token the scarcity of planktonic foraminifera in sediments can indicate the presence of a water mass other than oceanic between the islands. It is therefore possible to postulate a difference between the 2 water masses entirely on biological evidence. At present, oceanographic data within and around the study area (Canadian Oceanographic Data Centre, Ottawa) do not provide sufficient evidence to show that, with reference to temperature and salinity, water in M'Clure Strait is different from water in the western Arctic Ocean.

The interaction between the 2 distinct water masses has been slow or non-existent for some time. To determine the probable time interval represented by foraminifera in each sample, it is necessary to consider the depth of penetration of the sampler, and local sedimentation rates. Although exact penetration depth of a Dietz-LaFond sampler cannot be determined, 10 cm. is a reasonable assumption. The present local rates of sedimentation are not known, but to have some idea what these rates may be, data from Hecla and Griper Bay, which is about 100 km. to the north, can be utilized. Here on stratigraphic evidence, the rate of sedimentation was calculated to be in the order of 4.4 cm. per 1,000 years (Vilks 1969). Assuming this rate of sedimentation as the average in M'Clure Strait and assuming that in the present sampling operations the Dietz-LaFond sampled at least 10 cm. of the ocean floor sediment, each sediment sample could represent at least 2,500 years. The sampling technique was not suitable for making studies of the changes in conditions within this time interval, therefore the foraminiferal number in each sample of sediment is considered to represent the average conditions for at least the last 2,500 years.

In comparison with the sediment data, foraminiferal tests from plankton tows represent conditions only at the time of sampling. In M'Clure Strait these conditions may fluctuate from oceanic to non-oceanic relatively frequently because the area is marginal with respect to the oceanic environment. However, if the data from plankton tows are assumed to be reliable indicators of present conditions, then it may follow that in very recent times oceanic influence in M'Clure Strait has been greater than in the past. This is indicated by the presence of living planktonic foraminifera at station 5, which is outside the region of oceanic influence according to the sediment data.

In Prince Gustaf Adolf Sea plankton tows have not been taken, but sediments collected in 1963 by Marlowe (1968) show that here the oceanic influence extends as far south as the north tip of Lougheed Island. In this area sediments contain tests of planktonic foraminifera associated with benthic species that are most commonly found on the Continental Shelf off the Canadian Arctic Archipelago. In Desbarats Strait, at the southern tip of Lougheed Island, the oceanic assemblage of foraminifera is not found in surface sediments, but in sediment cores between 7 and 16 cm. below surface. A similar change in fauna was present in a core in Hecla and Griper Bay (Vilks 1969). At present, the locality of the core station is outside the region of oceanic influence, as evidenced by the inshore fauna in surface layers. Here from more than 35 cm. below the seabed the oceanic assemblage replaced the inshore assemblage, indicating more extensive oceanic influence in the past.

In Prince Gustaf Adolf Sea, Hazen Strait and Hecla and Griper Bay the offshore benthic assemblages and the tests of planktonic foraminifera, were found in sediments only at depths below 200 m. and in areas not separated from the Arctic Ocean by sills less than 200 m. deep. It was therefore concluded that in these areas living planktonic foraminifera are present only in the watercolumn below a depth of 200 m. and are carried with this water as it enters the channels between the islands. In M'Clure Strait this association at the 200-metre isobath was not found. Here the distribution of planktonic foraminifera in the sediment is related to the vicinity of the Arctic Ocean and to the distance from the shores of Prince Patrick and Banks Islands. The zone containing sediment rich in planktonic tests extends only about 80 km. in M'Clure Strait and is restricted to the flat central part of the bottom before reaching the marginal topographic rise on each side of the Strait (see Fig. 3).

The fact that planktonic tests in M'Clure Strait are not found in sediments closer to the shore is difficult to explain, keeping in mind the arid arctic conditions. It could be argued that living planktonic foraminifera are present in surface waters in large numbers during the summer, when the ice cover is reduced. This period coincides with extensive land run-off, restricting foraminifera from the nearshore zone. When in winter both the land and sea are frozen, the foraminiferal number in the watercolumn is reduced to such an extent, that their presence in the sediments of the nearshore zone is effectively masked by the more rapid sedimentation rates close to the land during summer. Thus in the summer the standing crop of planktonic foraminifera in the watercolumn is relatively large, but restricted within the central parts of M'Clure Strait. In winter the standing crop is small, but distributed throughout the water of the Strait.

SUMMARY

The water in the study area contains a typical high-latitude marine environment. It is unique in the extensive cover of ice and a low-temperature and low-salinity surface layer with warmer and more saline waters below. Owing to the small regional influence of runoff, oceanic waters approaching land are changed very slowly. The distribution of planktonic foraminifera in sediment and surface water may indicate the extent of water entering M'Clure Strait from the Arctic Ocean. Possible chronological changes in these conditions are as follows:

1) Relatively slow eastward movement of water through M'Clure Strait for at least the last 2,500 years. This is based on the abundance of planktonic foraminifera in the sediment on the Continental Shelf and the absence of these tests in the sediment of M'Clure Strait.
2) Increased rate of eastward movement of water in very recent times based on the presence of living planktonic foraminifera found in surface water to the east of the region containing sediments rich in fossil planktonic foraminifera.

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