Biological Productivity of the Southern Beaufort Sea: the physical-chemical environment and the plankton

E.H. GRAINGER

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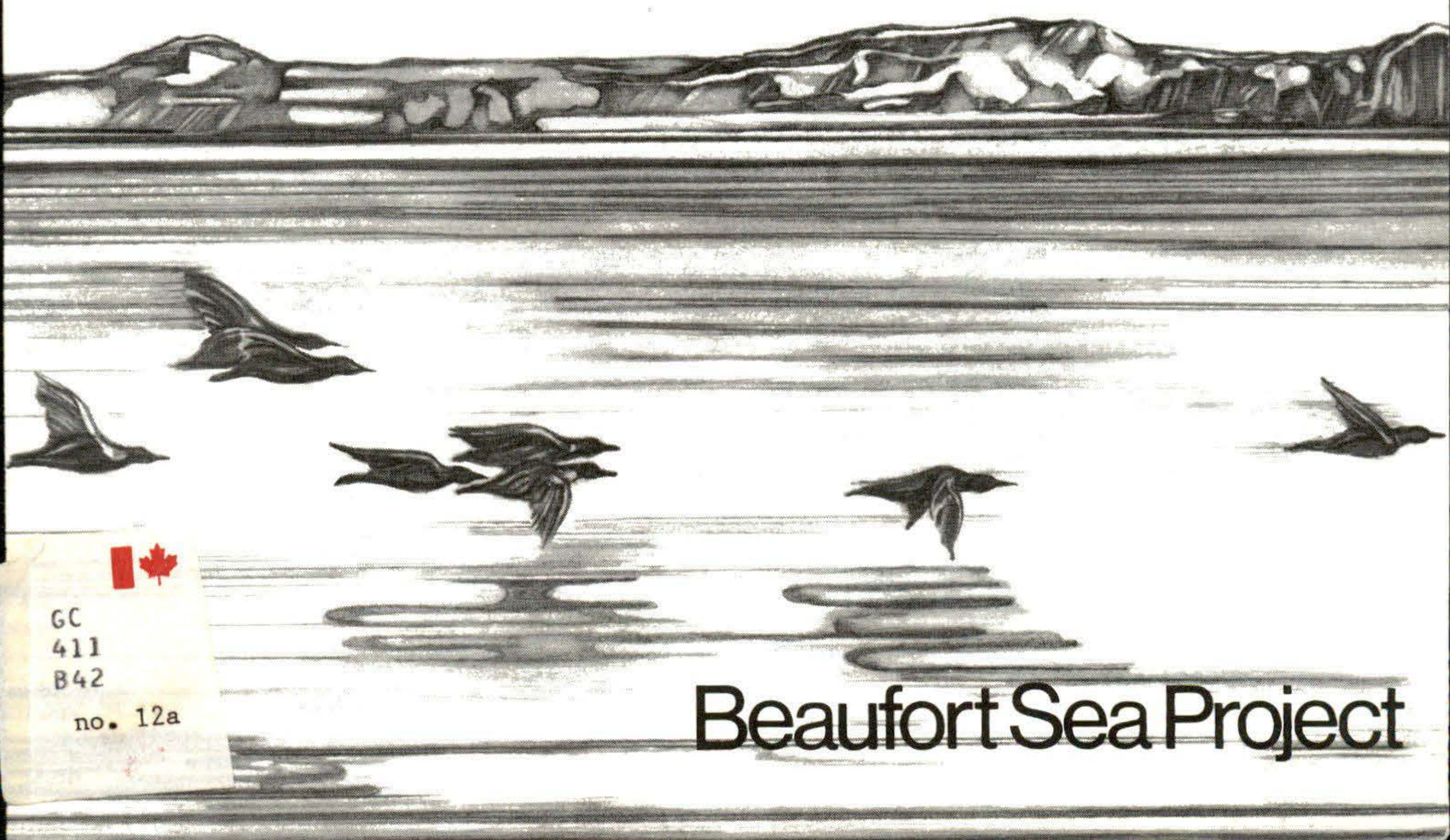

Beaufort Sea Project

BIOLOGICAL PRODUCTIVITY OF THE SOUTHERN BEAUFORT SEA: THE PHYSICAL-CHEMICAL ENVIRONMENT AND THE PLANKTON

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1. SUMMARY

The south Beaufort Sea, immensely modified by the outflowing Mackenzie River, consists of a layer of low salinity water of Mackenzie River origin overlying one of higher salinity, of offshore, Arctic Ocean origin. The variable balance between these elements determines the extent of the river plume, and therefore the basic biological composition of the south Beaufort Sea. A changing sea-ice cover influences undersea light and provides a surface for the ice flora which supplies a primary food source for what appears to be an important trophic series. Undersea light is also influenced by particulate material in the water. Light penetration is shallow in the inshore plume waters, because of the high sediment load carried to the sea by the outflowing river. Nutrients, mainly nitrate and silicate, are added to the sea from the river. Levels remain high near shore, where consumption by plants is consistently low. Outside the plume, nitrate is probably the major factor limiting phytoplankton production; within the plume it is probably light, inhibited by river-contributed turbidity. A low annual primary production rate is indicated for all waters of the region, and especially for the area of the river plume. A low secondary (zooplankton) production is also indicated, and standing stocks are generally low by world standards.

The two-layered, estuarine structure of the inshore waters is expected to encourage rapid spread of pollutants through the system, either from offshore, from inshore or from terrestrial or river locations. Much of the character of the system is determined by river influences, so much so that quantitative changes in the river will be expected to alter the biological composition of the south Beaufort Sea. Even temporary elimination of the plume would wipe out the estuarine fauna and flora. Qualitative changes would also be expected, and pollutants from the river would quickly spread at least to the limits of the plume. The primary and secondary producers provide the basis of a food structure which supports fishes and mammals, both in the water column and in association with the sea ice cover. Relatively short food chains represent areas of the system of potentially great vulnerability to oil.

2. INTRODUCTION

Most of the information presented in this report was gathered over a period of a little more than two years, including the summers of 1973, 1974 and 1975. A few observations made earlier, in fact as long ago as 1951, are included to expand both the time and space range of the study. Field work done in 1971 and earlier was carried out as part of the regular programme of the Arctic Biological Station. Studies done in 1973 were supported by the Environmental-Social Program, Northern Pipelines, of the Task Force on Northern Oil Development, Government of Canada; those in 1974 and 1975 by the Beaufort Sea Project.

No part of the actual Beaufort Sea Project open-water study, and this applies to the work undertaken in 1974 and 1975, was carried out under favourable circumstances. The ship-supported surveys of the two summers failed so badly to achieve the schedules planned for them, that most of the data strength of the study originated therefore either in the year preceding initiation of the Beaufort Sea Project or through the use of helicopters on the early summer sea ice cover. This was largely the consequence of sea ice persisting over areas where studies from shipboard had been planned. It had important consequences to this study, and it showed in a very clear way the fallacy of underestimating the arctic by presupposing a capacity to perform in it under all conditions.

The present investigation did not achieve its expectations in terms of range of coverage, either in space or in time. A number of rather elementary questions concerning base-line features of this ecosystem therefore remain unanswered. Such gaps show the report to be even more of a preliminary one than it was hoped it would be when the plan was conceived.

About 120 stations were occupied in all (Figures 1, 2, 25, 26), nearly all of them during the summer, and most of them from shipboard in open water. Information was gathered on water temperature, salinity, light, dissolved oxygen, nitrate, phosphate, silicate, chlorophyll, particulate and dissolved organic carbon, bacteria and benthic and planktonic plants and animals. The object of the exercise was to define the present, relatively undisturbed Beaufort Sea biological system, to try to develop an understanding of its structure, in relation to the major variables of the present time, and in response to anticipated changes of the future resulting from oil exploitation. Current variables include seasonal phenomena causing variation in such things as sea ice cover and available submarine light, and alterations in Mackenzie (and other) river flow and consequent shifts in the balance between river flow on the one hand and offshore marine influences on the other. The sum of these opposing factors seems to determine the pattern of much of the biological structure of the south Beaufort Sea at any one time.

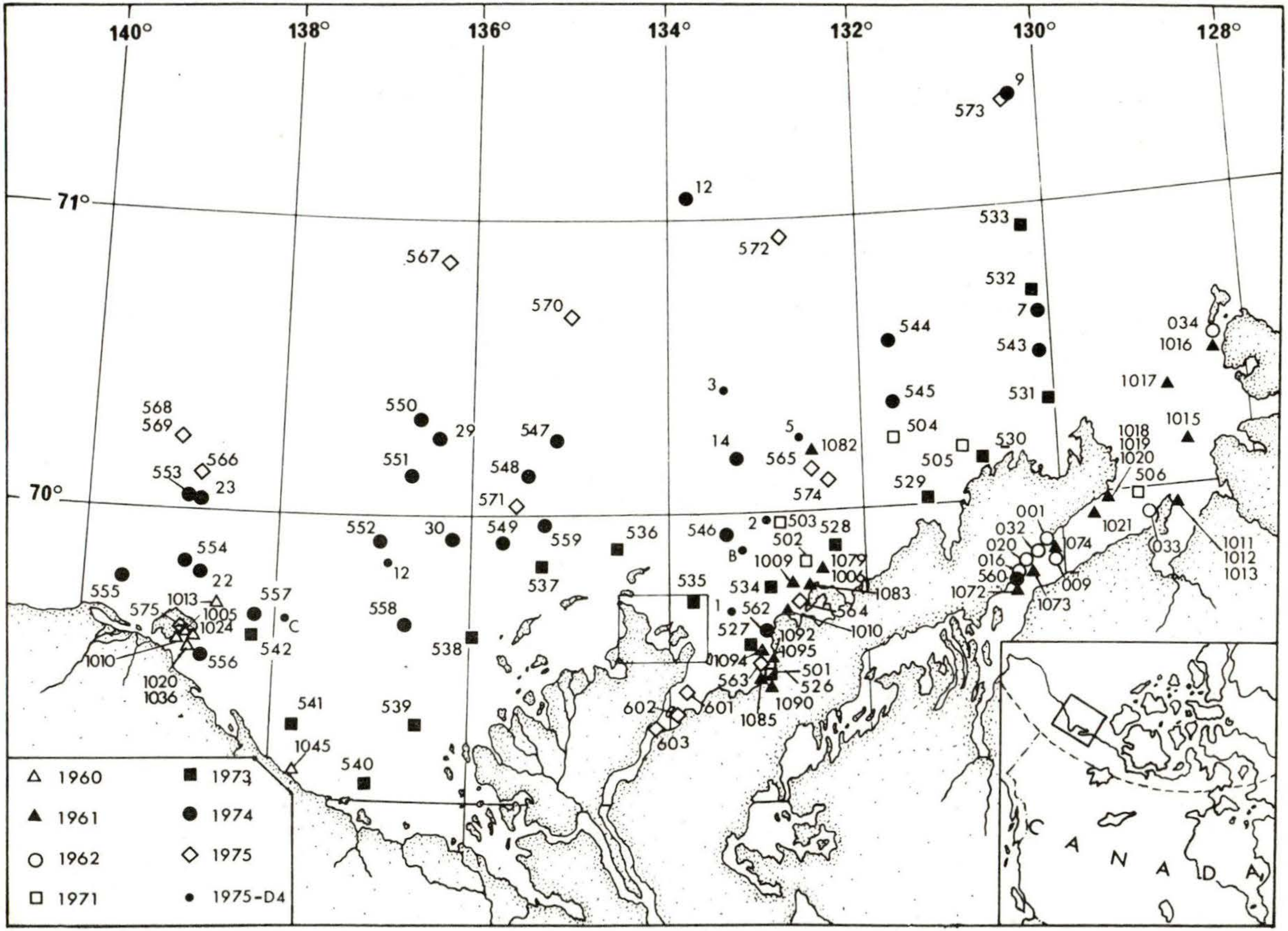

Figure 1. Stations which provided physical and chemical data.

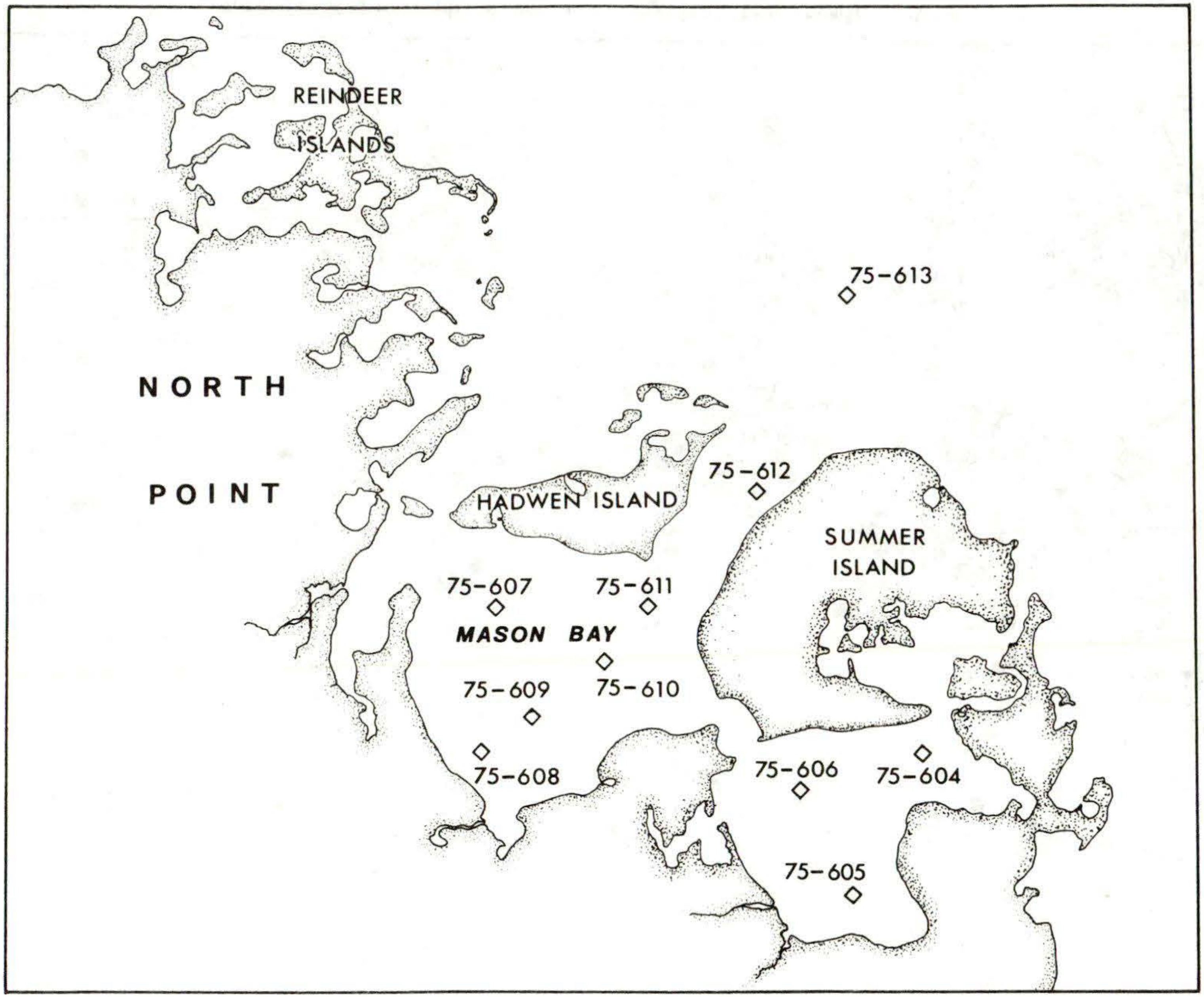

Figure 2. Mason Bay stations. Area shown in Figure 1.

The data on which this study is based may be found in two data reports, one of them on physical and chemical oceanography (Grainger and Lovrity 1975), the other on zooplankton (Grainger and Grohe 1975).

3. CURRENT STATE OF KNOWLEDGE

Before the initiation of studies in the early 1970's, the state of knowledge of the southeastern Beaufort Sea ecosystem was distressingly ill developed. Clearly this sea, bordering on both Canada and the United States and the route of whalers for a hundred years, had been almost totally ignored by oceanographers of all kinds. The first oceanographic paper on the region appears to be Tully's (1951) in which data collected on H. A. Larsen's historic first return journey through the northwest passage on the R.C.M.P. vessel St. Roche were given. Tully showed that relatively cold (0.2-5.5°C) and brackish (3-9‰) water existed between Point Barrow and Liverpool Bay, with warmer and much saltier water (to 31.6‰) to the west, and similarly cold but again more saline water (to 30.7‰) to the east. The relatively brackish water in the middle region was of course related to the outflow of the Mackenzie River. Cameron (1953), following two cruises by the Cancolim II in the Beaufort Sea, described the net circulation in the south Beaufort as anticlockwise, with low salinity (Mackenzie) water moving eastward along the coast, and higher salinity water following in behind it from the northwest to mix with river water in Mackenzie Bay. Wind was given as the primary factor in influencing the distribution of low-salinity (Mackenzie) water in the south Beaufort Sea. Coastal salinities relevant to the Mackenzie outflow were offered by Henoch (1969). Detailed inshore oceanography, mainly confined to Tuktoyaktuk harbour, was discussed by Barber (1968). A number of temperature and salinity measurements in shallow, inshore waters immediately adjacent to the Mackenzie delta were given by Brunskill, Rosenberg, Snow, Vascotto and Wagemann (1973), and a fairly detailed discussion of mainly offshore physical oceanography was contributed by O'Rourke (1974).

No account of inorganic nutrients in any part of the south Beaufort Sea preceded the symposium on Beaufort Sea coast and shelf research held in San Francisco early in 1974. From this there appeared accounts of nutrients from the southeast Beaufort Sea (Grainger 1974) and from the Colville River and its estuary off northern Alaska (Hufford 1974; Hamilton, Ho and Walker 1974; and Schell 1974). Gudkovich (1955), English (1961) and Kinney, Arhelger and Burrell (1970) had previously given nutrient data from the Arctic Ocean for north of the Beaufort Sea, and their information may be compared with the present study. Mackenzie River nutrient information has come from Reeder, Hitchon and Levinson (1972).

Available works on phytoplankton of the region appear to be limited to Mann's (1925) report on diatoms of the Canadian Arctic Expedition of 1913-18. Later, Bursa (1963) discussed general phytoplankton of north Alaska, to give the only ecological data on these plants in the Beaufort Sea region. Benthic plants (algae) were considered by Collins (1927), and the paucity of data, especially in the western Canadian arctic, was brought out quite recently by Lee (1973). Grainger (1974) described chlorophyll distribution in the vicinity of the Mackenzie delta. For benthic animals a few scattered collections were made along the north coast of Alaska and closer to the Mackenzie before MacGinitie's (1955) excellent account of the marine invertebrates of north Alaska. The most notable among the earlier works were several papers arising from the Canadian Arctic Expedition, in which a few collections of several taxonomic groups originating in the area of interest here were described. Almost no quantitative data were assembled on the benthic fauna, however, and no information was available for the assessment of stocks or production rates until the reports by Wacasey (1974) and Carey, Ruff, Costillo and Dickinson (1974). Zooplankton was somewhat better covered, and as many as 27 papers pertaining to the Beaufort Sea were reported by Shih, Figueira and Grainger (1971). Zooplankton from the vicinity of the Mackenzie delta was described by Grainger (1974a).

The reports from 1974 were the first biological contributions which had real relevance to the objectives of the present study. The basic pattern of animal distribution and dependence upon the estuarine system off the delta, and the features of the regime which control plant production were indicated at that time. Subsequent work has tended to confirm and refine the earlier conclusions.

4. STUDY AREA

4.1 The south Beaufort Sea

The central part of the south Beaufort Sea is characterized by fairly warm and low-salinity water inshore, and cooler, more saline water offshore. It is in many ways typical of sea areas off large river mouths everywhere, having river-contributed features spreading seaward over deeper oceanic influences below. River flow is dominant in giving the south Beaufort Sea its identity. River flow and varying winds are probably most important in bringing about variations in the distribution of offshore features of the Beaufort Sea in the region of the Mackenzie delta. It is an arctic marine region, and it is ice-bound during much of the year. This means light penetration and vertical mixing are restricted and that production is limited to a fairly brief period of the year.

Place names are shown in Figure 3.

4.2 Mason Bay

This is a specialized inshore area largely separated both on horizontal and vertical planes from the main body of the Beaufort Sea, and combining coastal and offshore Beaufort Sea features with locally developed qualities associated with land drainage from northeastern Richards Island. Located between the eastern and western mouths of the Mackenzie, Mason Bay, opening to the north, probably misses the main thrust of the outflowing Mackenzie River under most wind conditions. Only strong and fairly prolonged northerly winds would be expected to transport significant quantities of outside water into the bay. The deepest parts of Mason Bay are separated from the main body of the Beaufort Sea by a sill at the entrance to the bay. It is necessary to travel 25 miles north from the bay in order to find water depths in the Beaufort Sea as great as the deepest parts of Mason Bay, or (in summer) to find salinity as high as is found in Mason Bay.

4.3 Liverpool Bay

Much larger but also shallower than Mason Bay, Liverpool Bay receives river-diluted surface water from the Beaufort Sea, but little of the colder, more saline water which is found in the deeper parts of Mason Bay. Liverpool Bay receives relatively less local freshwater influence than Mason Bay, even though it includes output from the adjacent Eskimo Lakes system. Liverpool Bay is therefore more saline at the surface and less saline at the bottom than Mason Bay.

4.4 Eskimo Lakes

This region, the subject of a long study by the Arctic Biological Station, is referred to only briefly in this report. Conditions at the Liverpool end of the system are similar to those in adjacent Liverpool Bay, and temperature tends to increase and salinity to decrease towards the upper or southern end of the system. Deeper water is found within the lakes than outside in Liverpool Bay, more than 100 miles distant from depths as great in the Beaufort Sea. Those depths however do not show salinity as high as is found in the bottom waters of Mason Bay, or any greater than is found in the much shallower bottom water of Liverpool Bay.

5. METHODS

5.1 Field techniques

5.1.1 Ships more or less equipped for oceanography

Four vessels in this category were used in carrying out this study. Most effective was the North Star of Herschel Island, used in late July of 1973 to occupy 18 stations, most of them fairly close to shore between Herschel Island and Cape Dalhousie. In 1974, the Theta and in 1975 the Pandora were used for brief voyages, mainly in the offshore, western part of the Beaufort region covered by this study. Most of the remaining open-water observations were made from the Salvelinus, research vessel of the Arctic Biological Station. These included the planned programme in 1975 which was part of the Beaufort Sea Project study of that year and earlier collecting done in various years as parts of the continuing fisheries study of the Arctic Station. Collections obtained from a fifth vessel, which was not in any way part of the Beaufort Sea Project study, are included here. This is the Cancolim II, operated in 1951 by the Defence Research Board in an oceanographic operation which yielded some zooplankton reported here for the first time.

5.1.2 Helicopters

Eleven stations were occupied from the sea ice surface, using helicopters. This was shown to be a highly successful technique when carried out with suitable working equipment and by experienced and willing people. Collecting by this means was of course limited to vertically moved gear which meant that horizontal plankton net hauling, and benthos dredging and trawling were not possible.

5.1.3 Shore stations

This approach was used mainly in the Eskimo Lakes, where stations close to shore were visited either by small boat (summer) or by snowmobile (winter). All standard light gear could be used from the small boat, whereas only vertical sampling was possible from the ice surface in winter.

5.1.4 Collecting methods

Water samples from below the surface were collected with non-metallic 5-litre Van Dorn bottles or 1.7-litre Niskin bottles. Surface sampling was done with a plastic bucket. Light penetration was measured with a Secchi disc.

Most water temperatures were determined using calibrated reversing thermometers. A few water temperatures and salinities were measured in situ using a YSI model 33 S-C-T meter. Standard plankton nets were used for zooplankton. Most collections were made with nets of 30 cm diameter opening and mesh of 73μ, hauled vertically. Other meshes were used as well (see Grainger and Grohe 1975).

5.2 Laboratory methods

Most salinity determinations were done using a Bissett Berman model 6230 laboratory salinometer. Dissolved oxygen samples were usually analysed by the Winkler titration method; a few were determined using a YSI model 54 oxygen meter. Water samples for chlorophyll were filtered immediately after their collection through HA Millipore filters, which were kept frozen and dark over silica gel until later extraction and analysis of chlorophylls. The remaining water for chemical determinations was kept frozen until later analysis. Chlorophyll a, phosphate-phosphorus, nitrate-nitrogen, nitrite-nitrogen, silicate-silicon and particulate organic carbon were determined according to the methods of Strickland and Parsons (1968). The slower and far more laborious tasks of plant and animal identifications and counts were conducted (and are still being carried out) under standard laboratory conditions.

6. RESULTS

6.1 Sea ice cover

Variations in the extent of the sea ice cover during biological collecting periods in recent years are shown in Figure 3. In 1973, perhaps something like a "normal" ice year, fully open water reached to about 25 miles off Tuktoyaktuk Peninsula and the outer edge of Herschel Island off Mackenzie Bay in late July. During August, the ice edge moved farther from shore. In 1974, known far and wide by now as an especially severe ice year, the extent of open water was somewhat less in late August than it had been a month earlier in 1973. The ice edge had been much closer to shore earlier in 1974 and was in the process of moving seaward in late August. In 1975, there was evidently a notably early appearance of open water conditions off the delta, Mackenzie Bay and Tuktoyaktuk Peninsula. By early August, the ice edge was far outside the positions shown in Figure 3 for the two earlier years. In fact, the ice moved shoreward again while the biological collecting was under way in 1975; it was however a year of extensive open water during the early and middle parts of the summer.

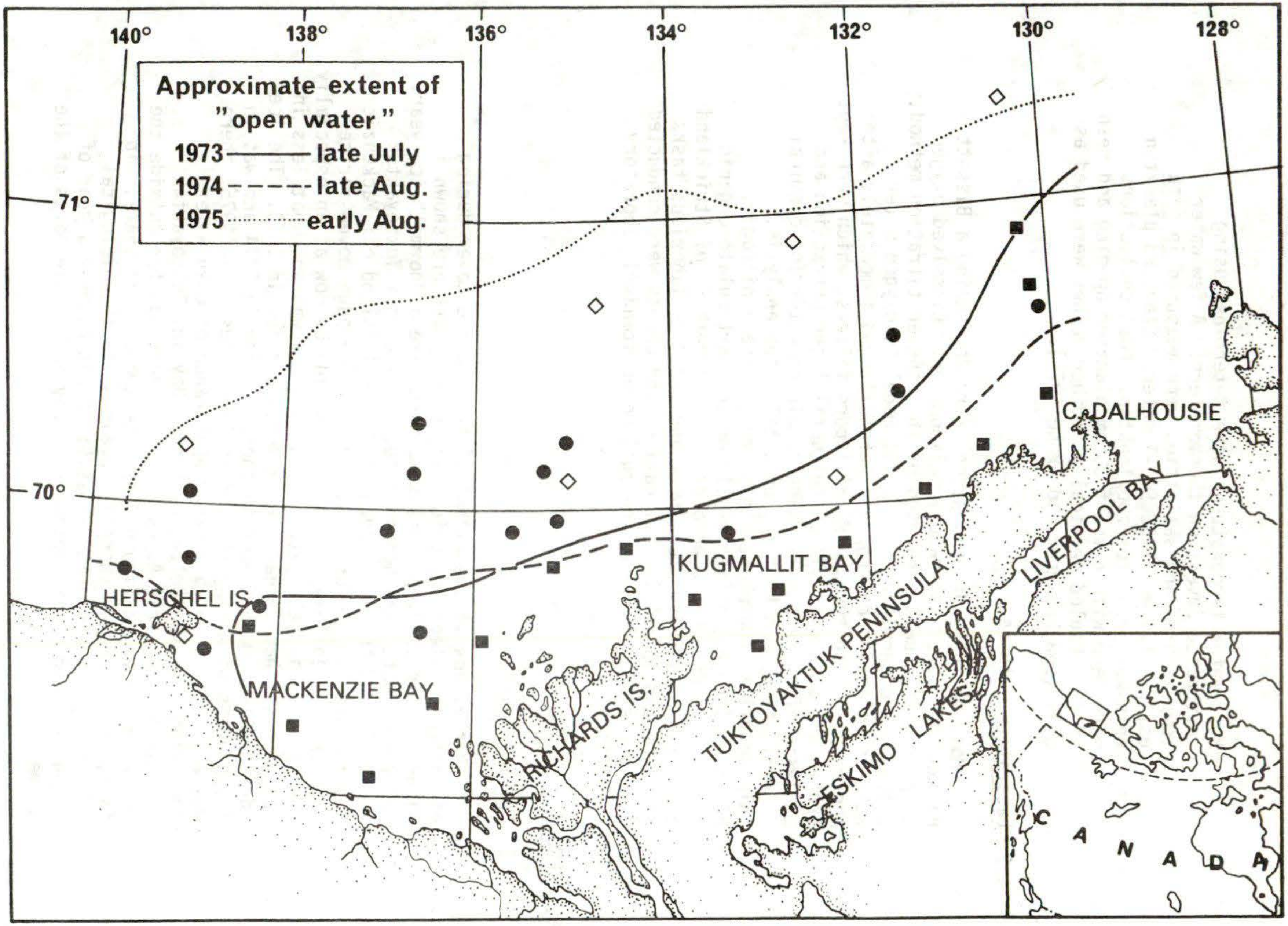

Figure 3. Positions of the ice edge during 3 years of investigation.

The biology is discussed in section 6.9 below.

6.2 Light

Secchi disc readings were made at many of the stations occupied in open water, and results, as depth of 1% of surface light calculated from the Secchi disc readings, are shown in Figure 4. Penetration of 1% of surface light as deep as 60 metres is shown at the stations located farthest from the delta. Cruise stations situated farthest from the delta showed 1% of surface light down to 40 metres. In general, a pattern of least light penetration closest to Mackenzie River discharge points (1% of surface light reaching to less than 1 metre below the surface) and greatest light penetration farthest from the sources of river water is shown in Figure 4.

The Secchi disc measurements made would appear to indicate two causes of inhibited light passage, one the sedimentary load of the waters near the delta, indicating direct Mackenzie River contribution to the sea, the other organic particulate matter, probably mainly plant cells. These features are not necessarily clearly differentiated in Figure 4. Most of the near-shore turbidity (1% of surface light penetrating to 1 metre or less) is indicative of river transported sediments. The deep light penetration of the northeastern part of the study area shows clear waters with minimal quantities of particulate matter of all kinds. The shallower penetration of the northwest sector may be a result mainly of plant cells in the surface waters.

6.3 Temperature and salinity

During the open water periods the warmest waters, with surface temperature more than 10°C, were found adjacent to the Mackenzie delta, the coldest, with surface temperature close to 0°C, farther off shore. A pattern was also revealed in the salinity distribution, with the lowest surface values (less than 2‰) being found in Mackenzie and Kugmallit Bays and close to the north shore of Richards Island, and the highest surface records coming generally from the open-water stations farthest from the Mackenzie River outlets.

Temperature profiles in Figure 5 show the high values prevailing from surface to bottom in the shallow stations close to shore. Close to Tuktoyaktuk Peninsula, station 73-530 showed largely uniform high temperatures from surface to bottom and nearby station 71-505 similar surface conditions but a bottom temperature 6° colder. An offshore station (73-533) was

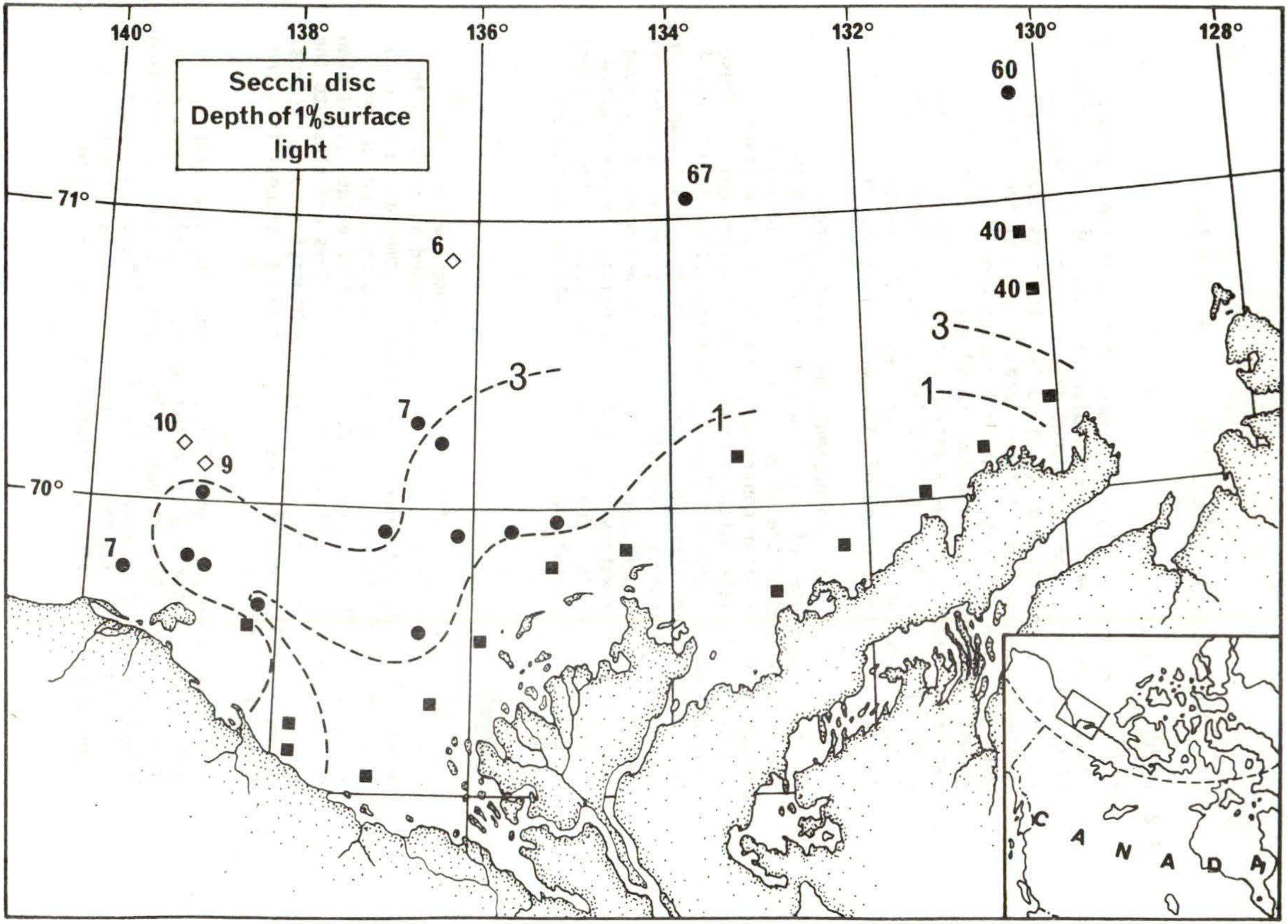

Figure 4. Depths of light penetration beneath the surface of the sea.

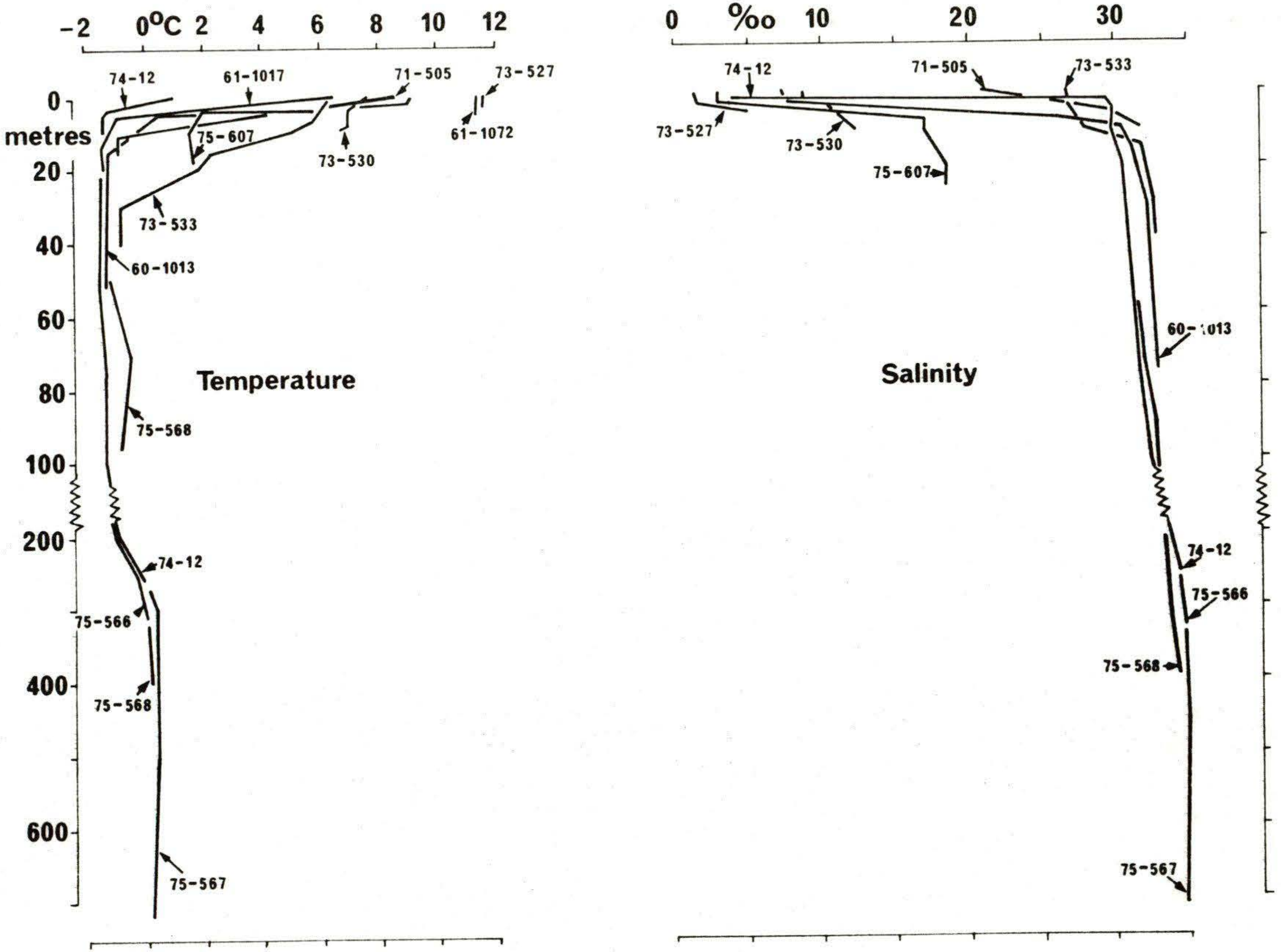

Figure 5. Curves of temperature (left) and salinity (right).

considerably warmer at the surface than an offshore station occupied from the floating sea ice (74-12). The Mason Bay station 75-607, warm at the surface, was less than 2° below about 5 metres. Nearly all waters between 50 and 200 metres were below 0°C, and all the deep stations showed warming to more than zero between 200 and 300 metres (the Atlantic water layer of the arctic basin). Station 75-567 showed slight cooling below about 500 metres. Stations close to shore and in coastal bays showed the lowest surface salinity (73-527, 75-607), but values were only a little less than surface readings taken during sea ice melting at the stations farthest from shore (74-12). Stations occupied far from shore in open water tended to show the highest surface salinity (73-533). All stations with sufficient depth showed salinity greater than 34‰ below between 200 and 300 metres (the Atlantic water layer, also indicated by temperature curves in the same figure).

The overall temperature-salinity features of the waters sampled in this study are shown in a temperature-salinity diagram (Figure 6). Surface waters from Mackenzie Bay to just off Tuktoyaktuk Peninsula are represented by the upper left part of the figure, with inshore waters tending towards higher temperature and lower salinity, and offshore waters towards lower temperature and higher salinity. Liverpool Bay surface water is indicated by the upper central part of the figure and waters from off Cape Dalhousie by the upper right section of the figure, with the surface of the latter showing higher temperature and lower salinity, and intermediate water of the latter showing lower temperature and higher salinity. Surface water near melting ice is represented by the lower left corner of the figure, intermediate depths in Mackenzie Bay and towards Herschel Island by the lower central part, the latter a little warmer than intermediate water depths under the ice. All "deep" water (about 50 metres and below) is indicated by the lower, right corner of the figure.

The same waters, distinguished above on temperature and salinity grounds, can be separated into virtually the same categories on the basis of animals contained, as is shown in a later section of this report. Salinity and temperature, and especially the former, are obviously the principal environmental features controlling the distribution of species of plankton in this region.

6.4 Nitrate

Nitrate-nitrogen showed a pattern of distribution in which the highest values in the surface waters occurred in the vicinity of the Mackenzie River outlets, and the lowest quantities in

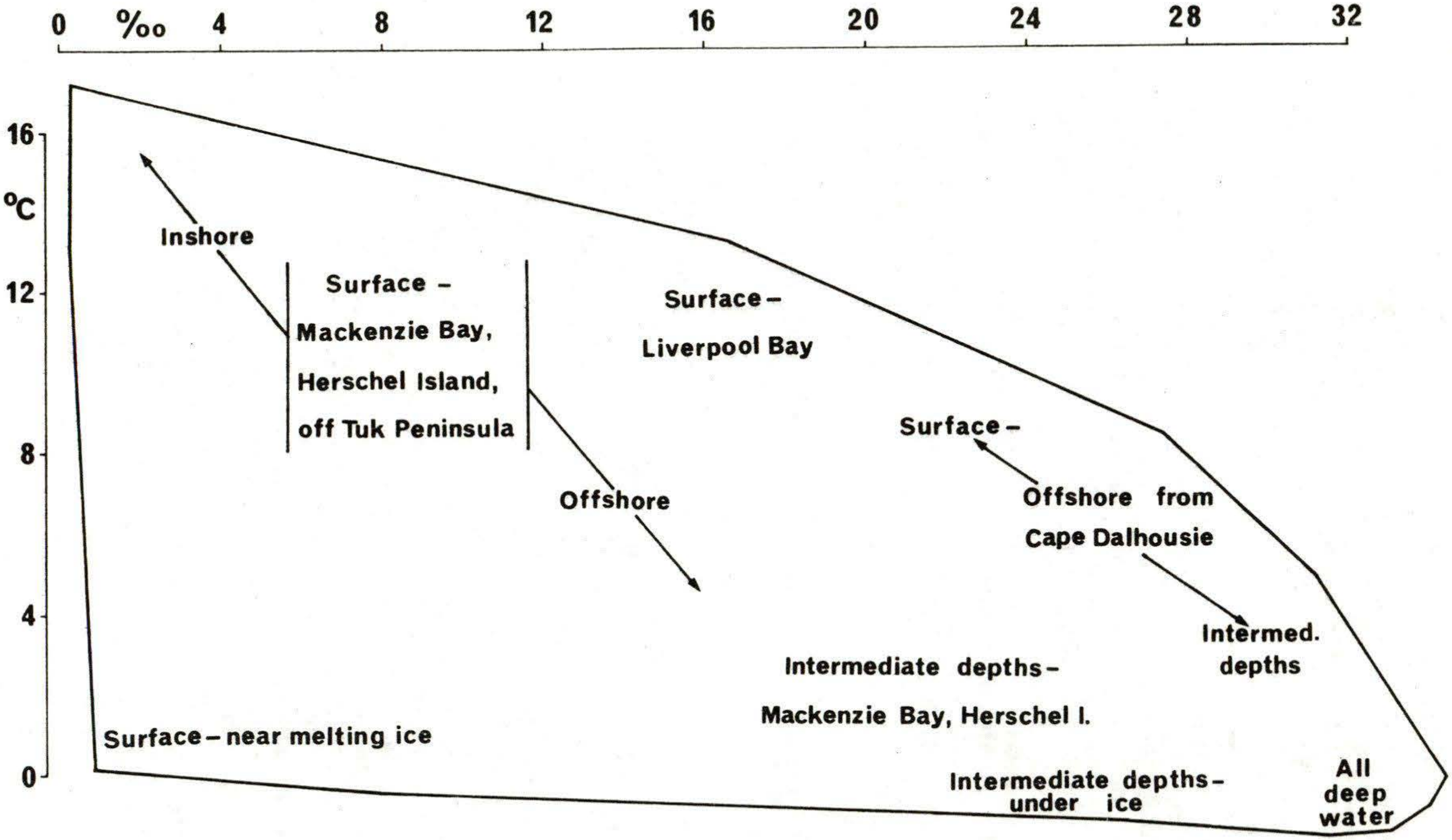

Figure 6. Temperature salinity diagram of all waters of the study area.

surface waters existed at stations farthest from the river mouths (Figure 7). The pattern evident in Figure 7 is fairly regular in spite of the differences in time of observations in the various years except for the April-May sampling of 1975. Quantities measured during that period are shown as underlined numbers in the figure, and most do not conform to the pattern shown by the other values. They were higher than all the other numbers in the figure, at least partly because they were a consequence of winter _in situ_ replenishment which took place during a period of virtually no depletion, that is, of no utilization by plants. Observations made just off Tuktoyaktuk Peninsula in very shallow water a little later in May, and not included in the figure, showed nitrate levels as high as the Kugmallit Bay samples from April-May, and both of these showed larger quantities than were indicated by the April-May samples from farther off shore. These observations indicate that the high winter nitrates were supplemented by Mackenzie River contributions which were shown by the highest levels of the entire study (above 30 metres) being found in the upper few metres at the stations closest to the outflowing Mackenzie River.

Five lines of stations are shown in Figure 8. From left to right in the figure they are: (1) from Mackenzie Bay to Herschel Island; (2) from Herschel Island northward; (3) from Richards Island northward; (4) from Kugmallit Bay towards Cape Dalhousie, off the Tuktoyaktuk Peninsula coast; and (5) from near Cape Dalhousie northward. In sections 1, 3 and 4, surface values are shown to fall along lines leading seaward from river mouths. Section 4, most of which represents river-influenced waters, shows most clearly the outflow of nitrate at the surface, overlying deeper, nitrate-poor water. Farther off shore, the deepest stations show the highest nitrate values of all towards the bottom.

Some of these features are shown again in single station depth curves in Figures 9 and 10. Increase in nitrate with depth is the main trend apparent in Figure 9, at least in most of the open-water stations. In the upper right corner of the figure, December and April-May observations in and near Kugmallit Bay show the high surface values associated at least partly with Mackenzie River outflow. It is interesting that stations 3 and C in the same figure, both sampled also in the April-May period, and both evidently outside the main influence of the Mackenzie River outflow to the sea, had much lower nitrates near the surface than the other early spring stations. They probably illustrate close to maximum nitrate levels resulting from _in situ_ replenishment over winter. Deeper

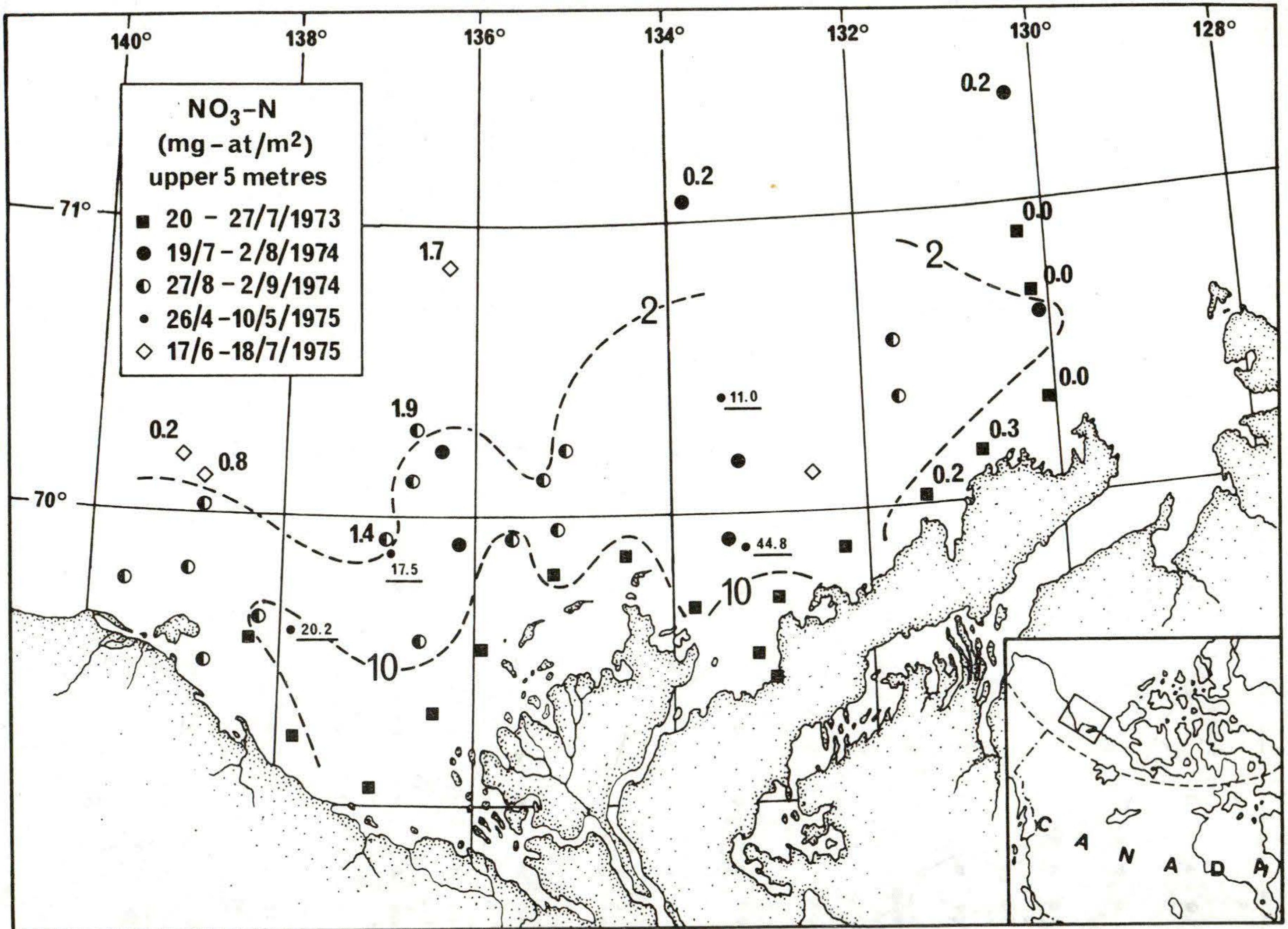

Figure 7. Nitrate in the upper 5 metres. Underlined numbers, early spring values, do not conform to the pattern shown by isometric lines.

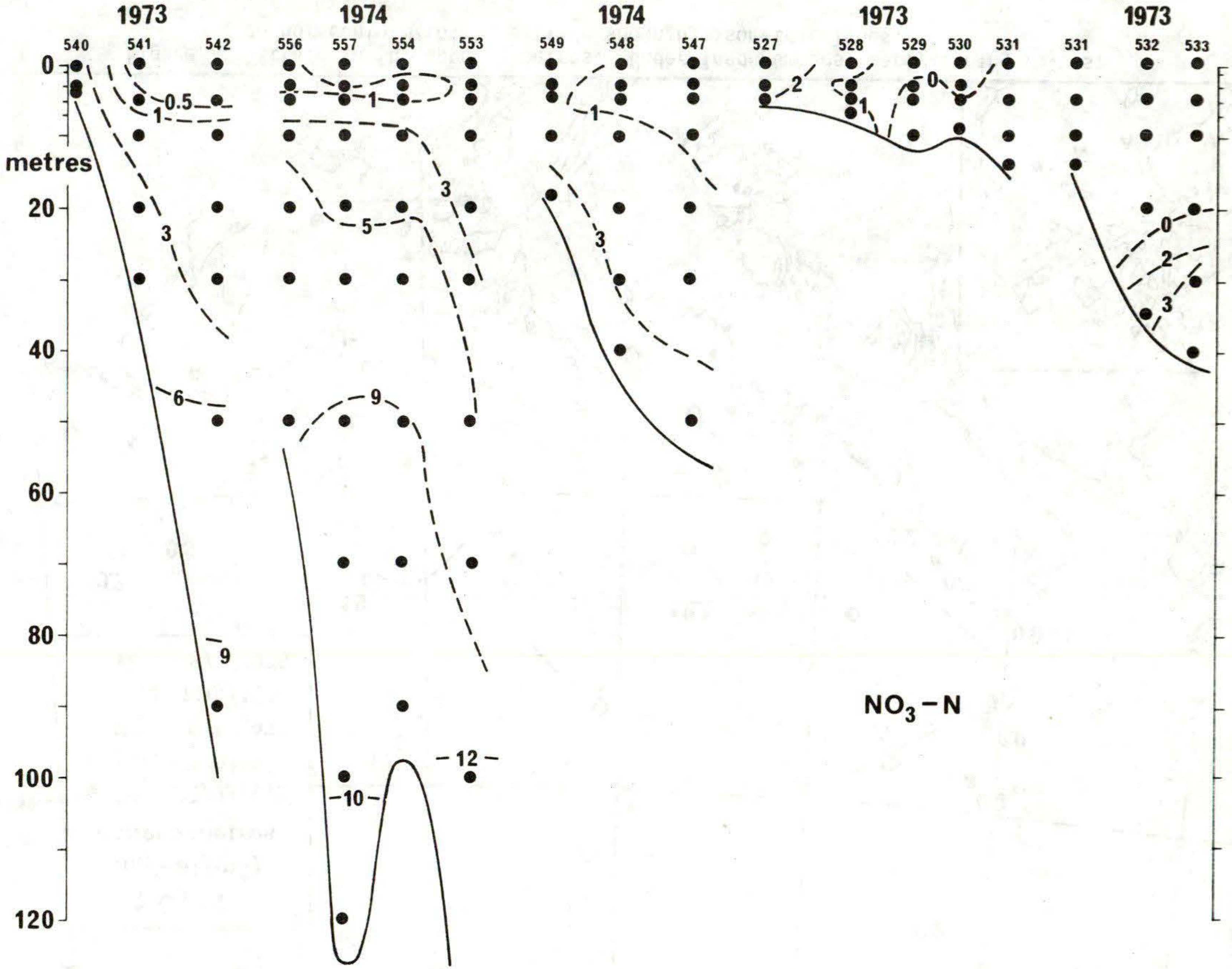

Figure 8. Nitrate profiles along 5 lines of stations.

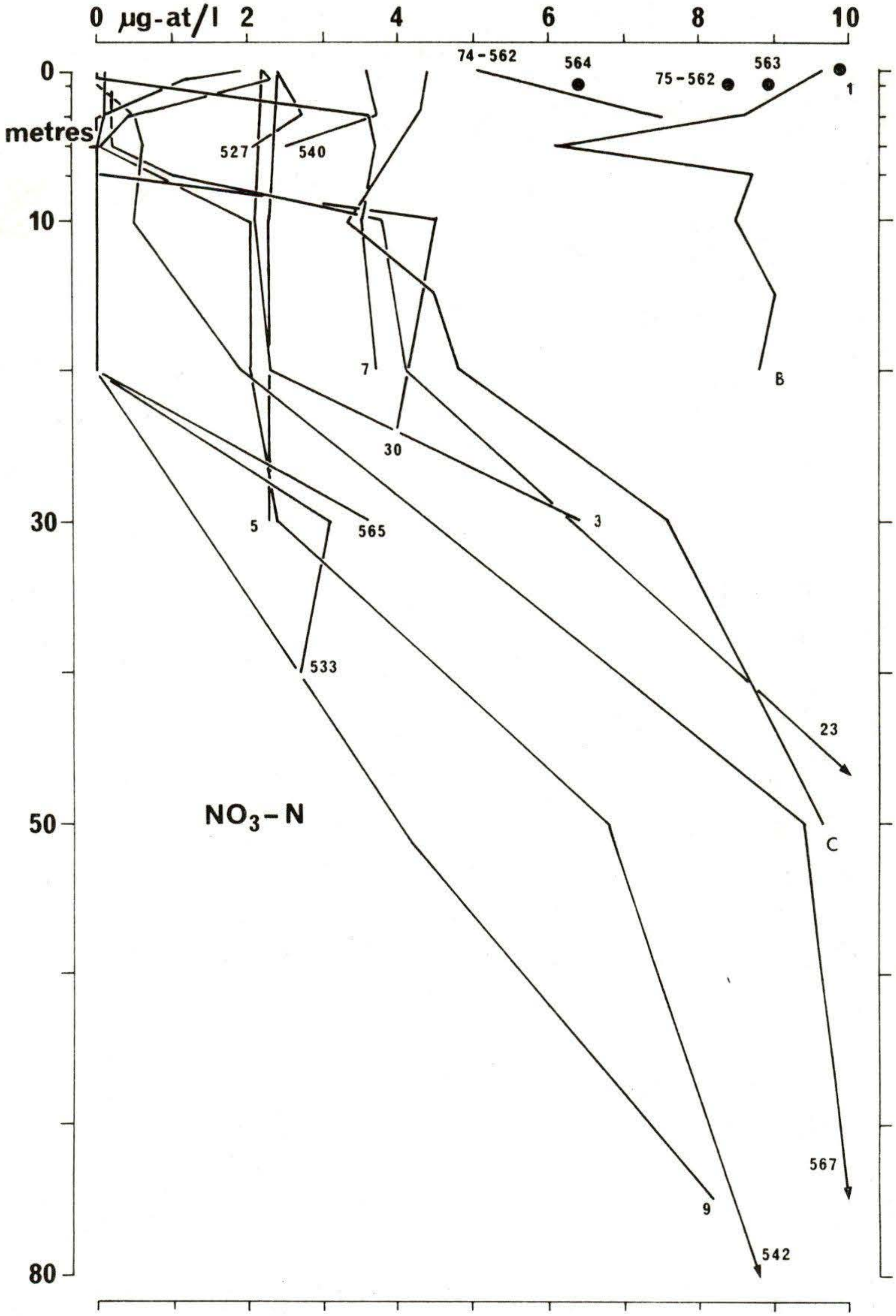

Figure 9. Nitrate curves, shallow stations.

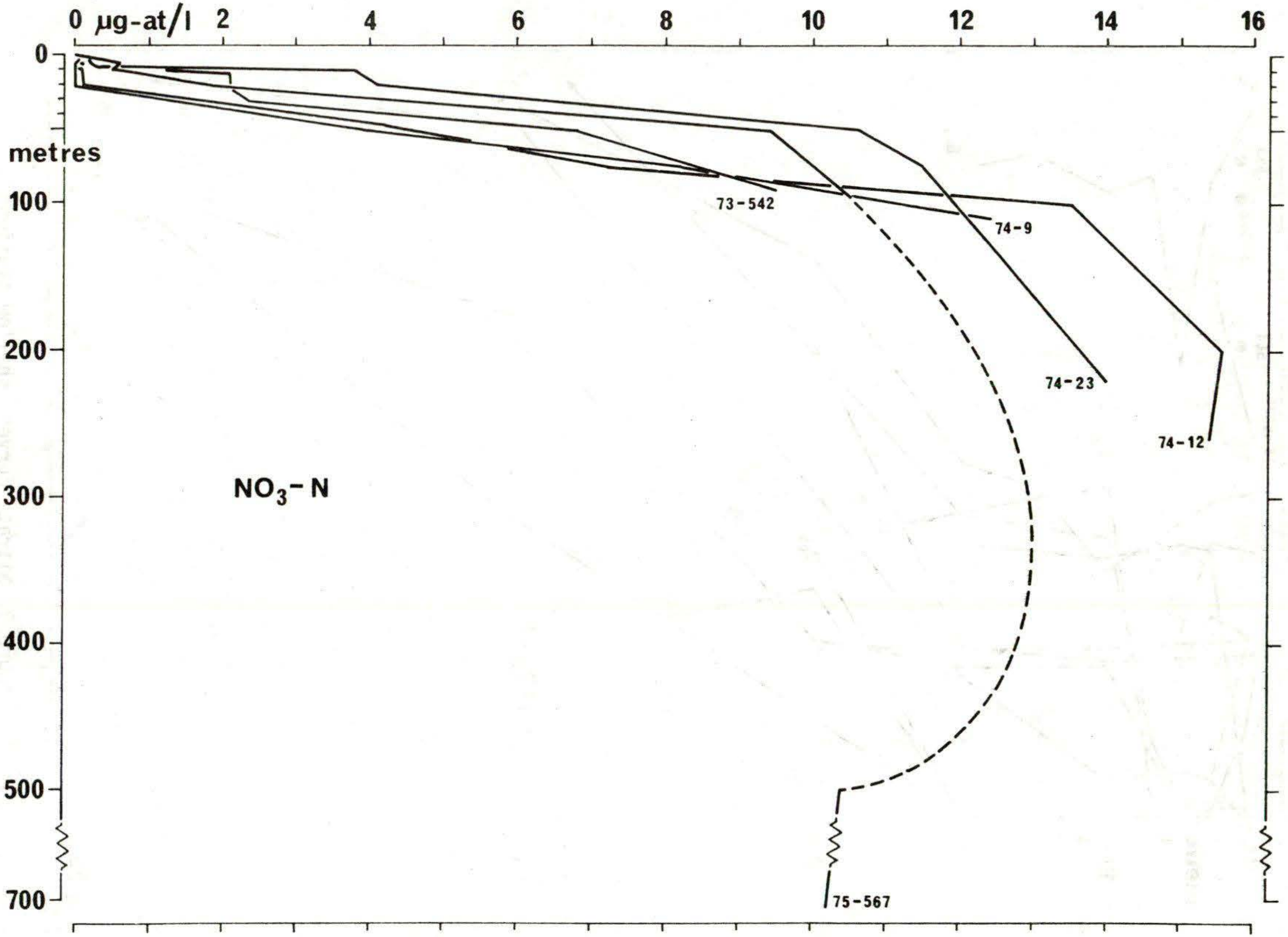

Figure 10. Nitrate curves, deep stations.

waters (Figure 10) show nitrate reaching to near 16 ug-at/l. Maximum levels seem to occur between 100 and 200 metres, with lower levels being found in still greater depths.

6.5 Phosphate

The horizontal distribution of phosphate is less satisfactorily explained than that of nitrate, above. There is evidence of a pattern (Figure 11) showing highest surface values closest to the river outlets during the open-water period. At the same time, stations farthest from the shore also showed high levels near the surface, while nearly all stations in between had less surface phosphate, many of them without any measureable quantity at all. River contributions are indicated at least in July and August. However, in April and early May, at stations near Tuktoyaktuk, phosphate in very shallow coastal water was low in every station measured suggesting that river-contributed phosphate was scarce. At that time, river flow was probably at its minimum for the year, or at about 10% of maximum flow which develops fairly quickly in late May. However, at the same time, phosphate near the surface at stations farther from shore was relatively high (see Figure 11, underlined numbers). Most of those stations were effectively outside the area of readily detectable Mackenzie River influence at that time, and must therefore have gained phosphate in the upper layers mainly as a result of replenishment within the sea.

Profiles of lines of stations (arranged as in Figure 8) are shown in Figure 12. In this there is nothing like as clear an indication of river-contributed nutrients as there was for nitrate at the same stations. Rather, the main effect of the figure is to show fairly regular increase in phosphate with depth. This figure and the next two illustrate the far smaller range of phosphate found here (mean high values around 4 or 5 times the mean low values) than of nitrate values in the same waters (a comparable ratio of more than 10 to 1).

In Figure 13, the winter and near-shore spring stations are shown in the upper left corner, the area of low phosphate. So are observations from the surface of the April-May stations taken just outside Kugmallit Bay (stations B and 2). Other April-May stations from farther from shore show much higher surface levels (stations 3 and C). Deep stations show (Figure 14) maximum values of about 1.6 ug-at/l between 100 and 200 metres, and a decline to about one half that quantity at 500 to 700 metres.

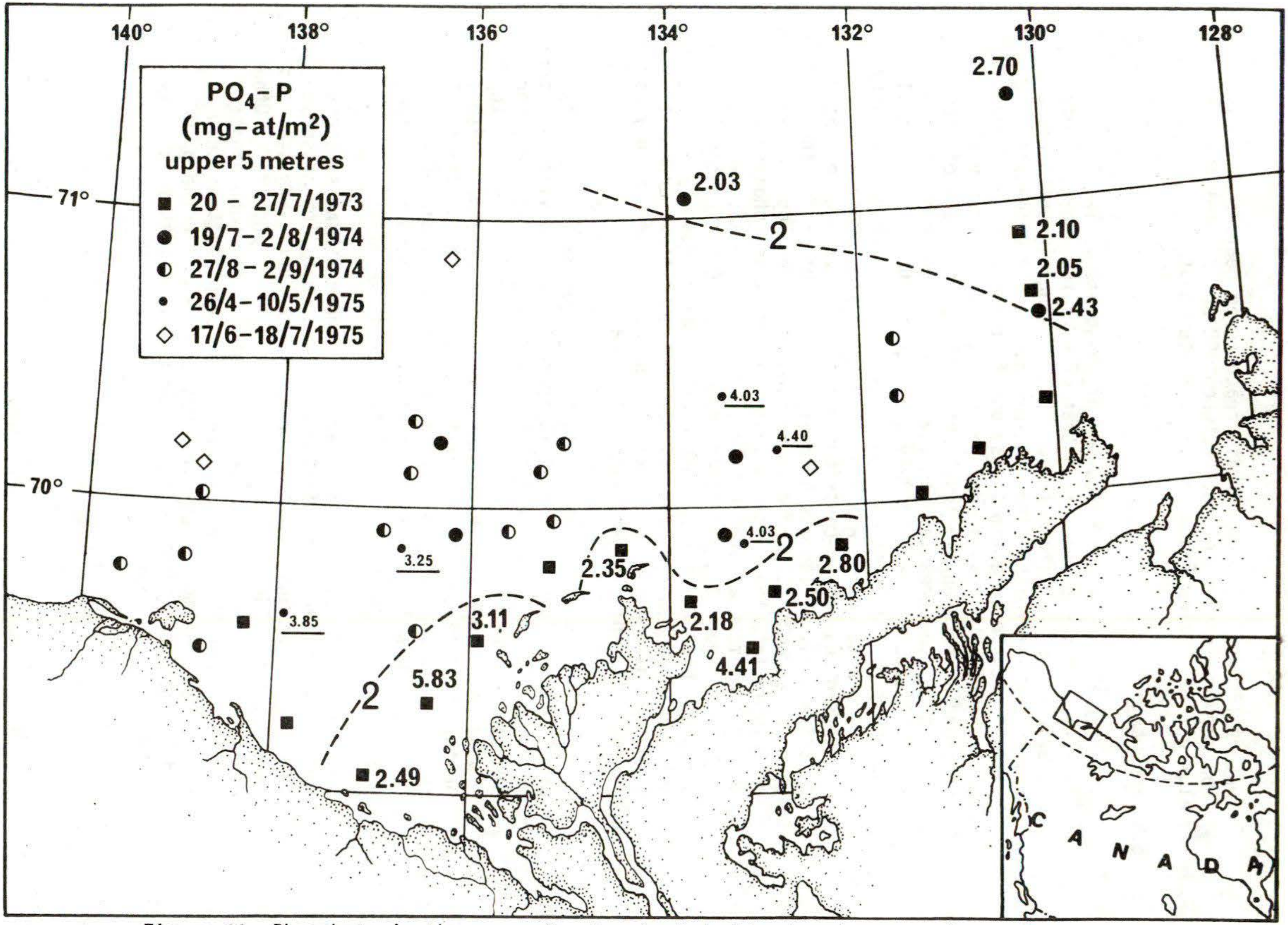

Figure 11. Phosphate in the upper 5 metres. Underlined numbers, early spring values, do not conform to the pattern shown by isometric lines.

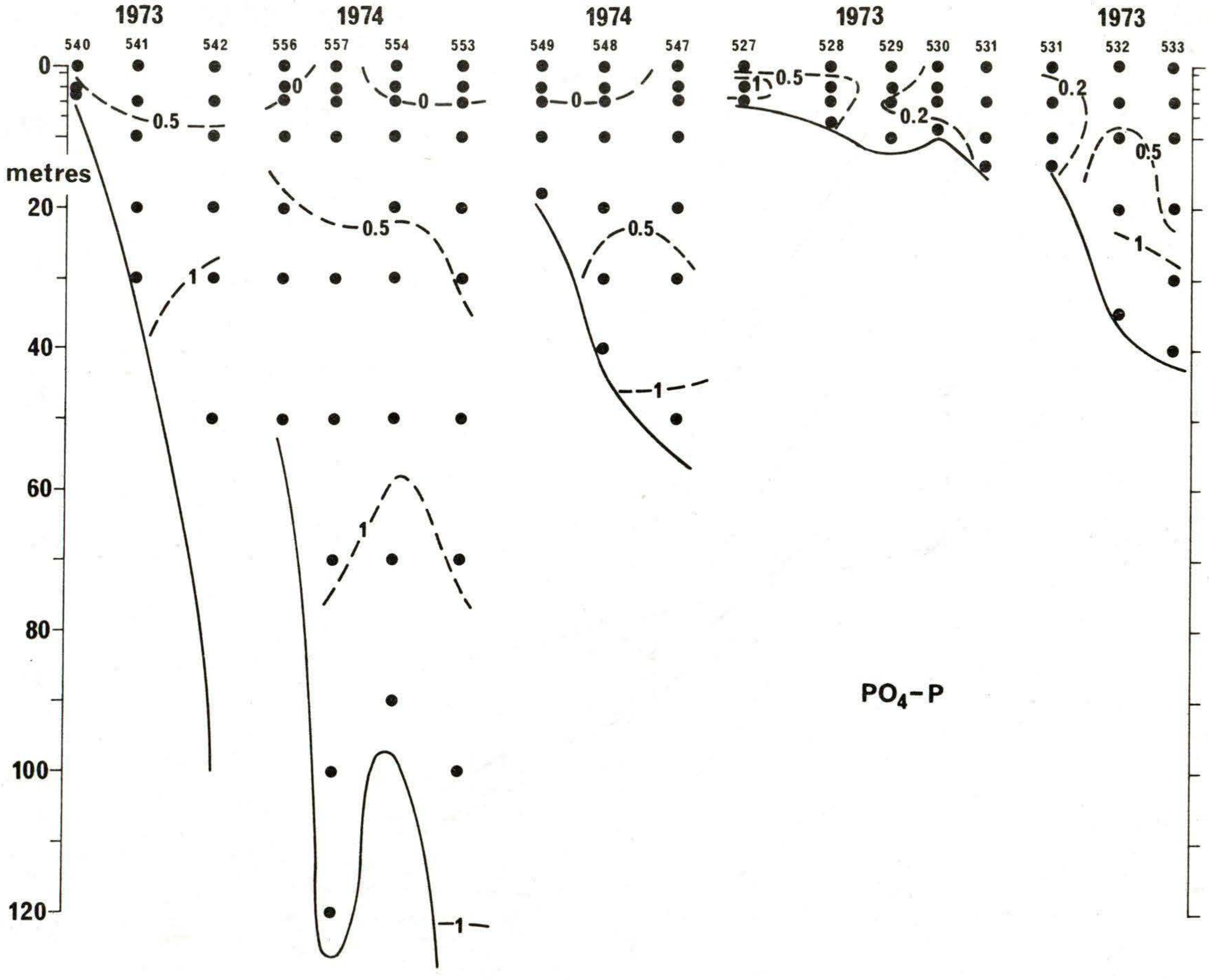

Figure 12. Phosphate profiles along 5 lines of stations.

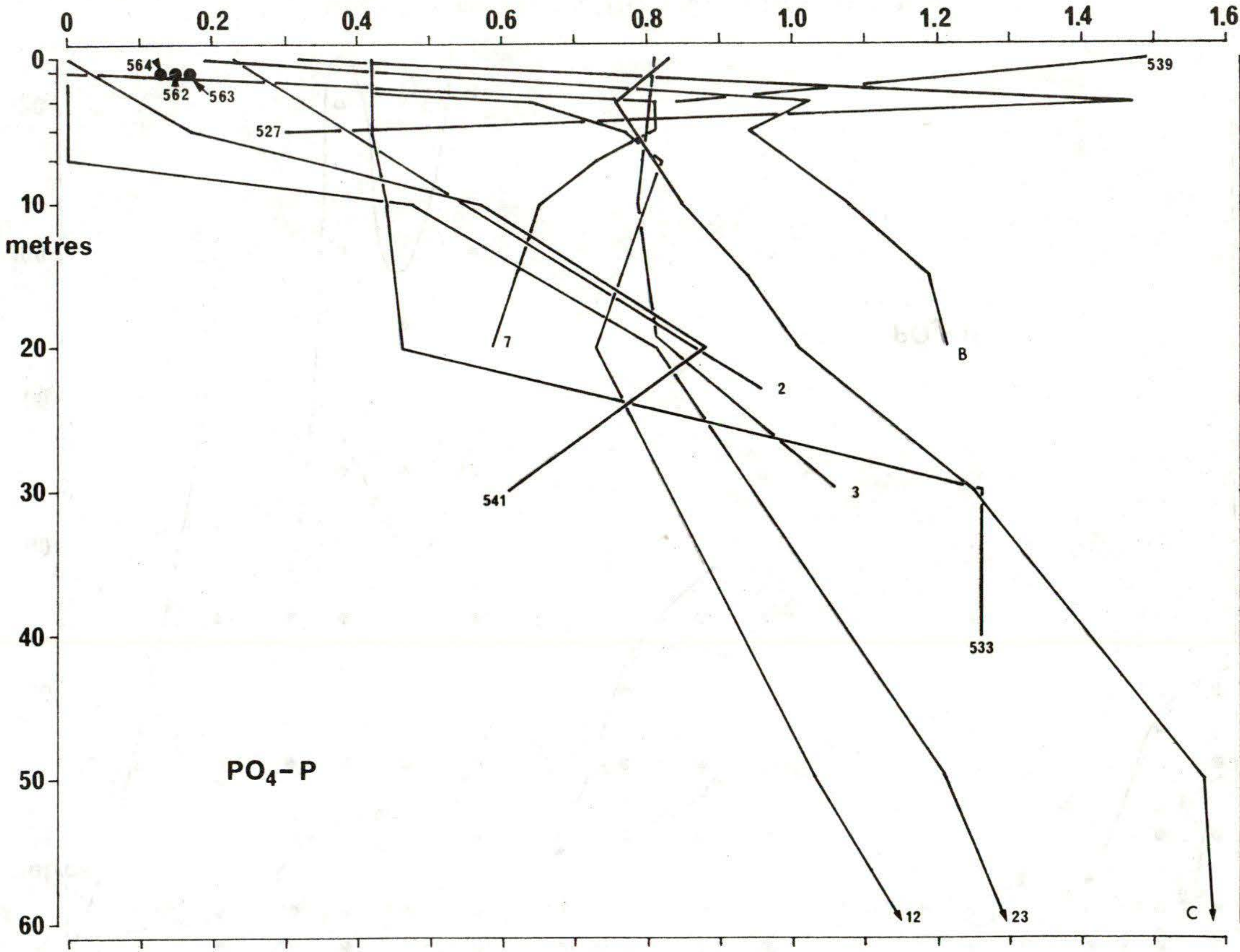

Figure 13. Phosphate curves, shallow stations.

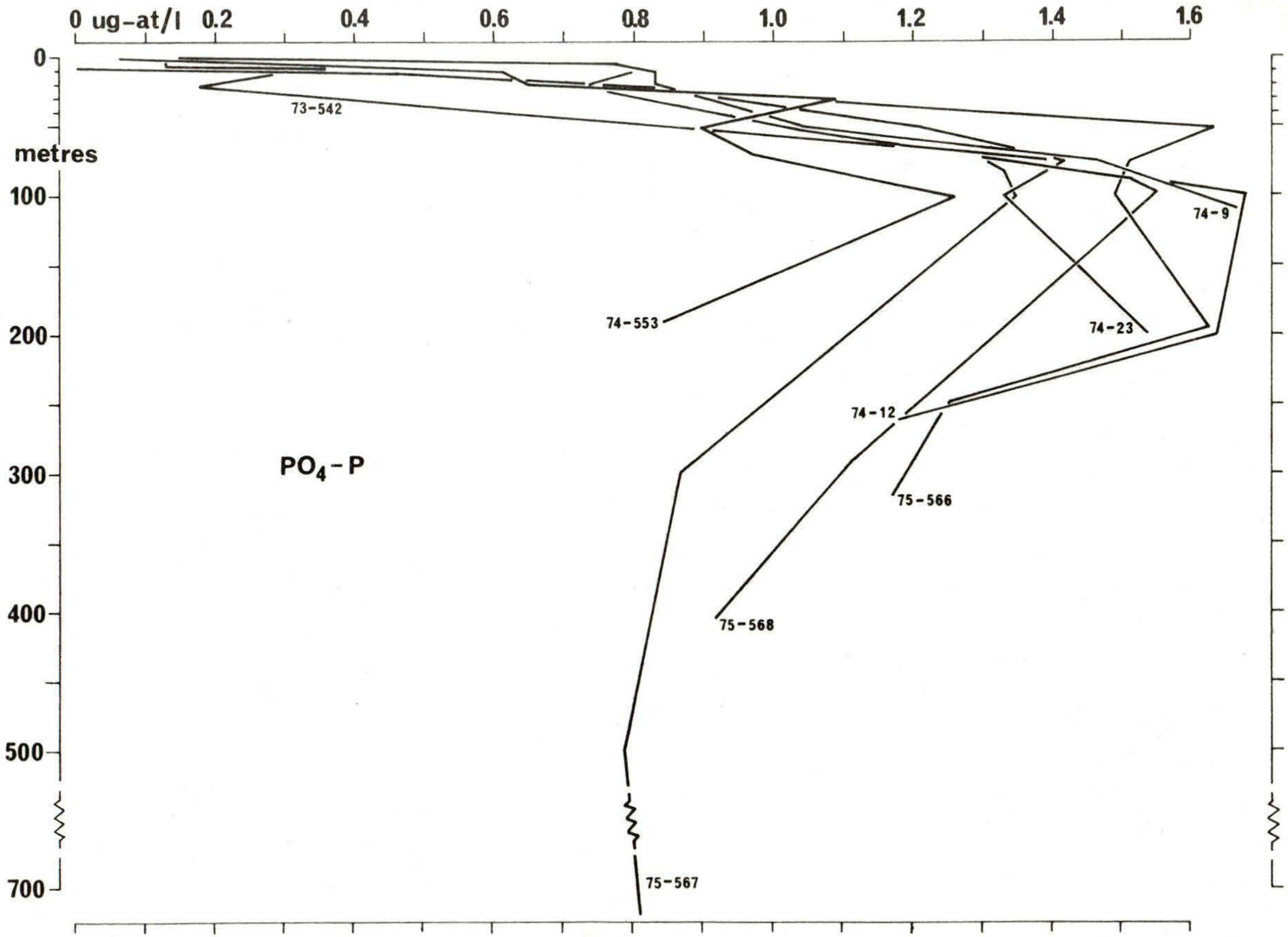

Figure 14. Phosphate curves, deep stations.

6.6 Silicate

A very clear pattern is shown in the horizontal distribution of silicate found near the surface of the south Beaufort Sea (Figure 15). Highest values are probably associated with Mackenzie River flow, lowest with offshore waters outside the area of primary river influence. It is certainly significant that while the other nutrients measured, especially nitrate, were conspicuously more abundant in the waters near the surface in April and early May than they were in similar depths at other times of the year, silicate increased only slightly at that time (underlined numbers in Figure 15).

Evidence of river-contributed silicate to the surface is strongly shown in Figure 16, especially in sections 1 and 4. As was shown for nitrate and phosphate, there was a layer of minimal values below the surface, below which quantities increased towards the bottom. Unlike what was found for both the other nutrients, however, quantities in deep water were not greater than the maximum amounts found near the surface. They were in fact considerably less. This is shown in Figures 17 and 18. In Figure 17, late winter values near shore were high, higher than at stations taken progressively farther from the river mouths (stations B and 3), which showed little difference from open-water values of summer. Maximum values beneath the surface (Figure 18) of about 40 ug-at/l occurred between 100 and 200 metres and were less than the highest surface figures obtained. Below 200 metres, levels declined to about 10 ug-at/l at 700 metres.

6.7 Oxygen

Dissolved oxygen in the south Beaufort Sea (Figure 19) showed a pattern of distribution in which the lowest values appeared adjacent to the Mackenzie delta, and the highest farthest from shore in the upper 5 metres. A range of oxygen values of 6.7 to 7.8 ml/l in the upper 5 metres of the waters adjacent to the Mackenzie delta in late July indicated low levels for the time of year. At the same time, saturation values were low, all less than 100%. In the offshore waters, average quantities in the upper 5 metres exceeded 9 ml/l and 117% saturation. This rather tidy picture was disrupted somewhat by the data obtained in 1975 (collected and measured by the Marine Sciences Directorate, Victoria, B.C., and not included in Figure 19). Oxygen levels taken at stations north of 70° in early August, only a very little later by the calendar than those measured in 1974, were found to be much lower. Average values for the upper 5 metres ranged from 7.4

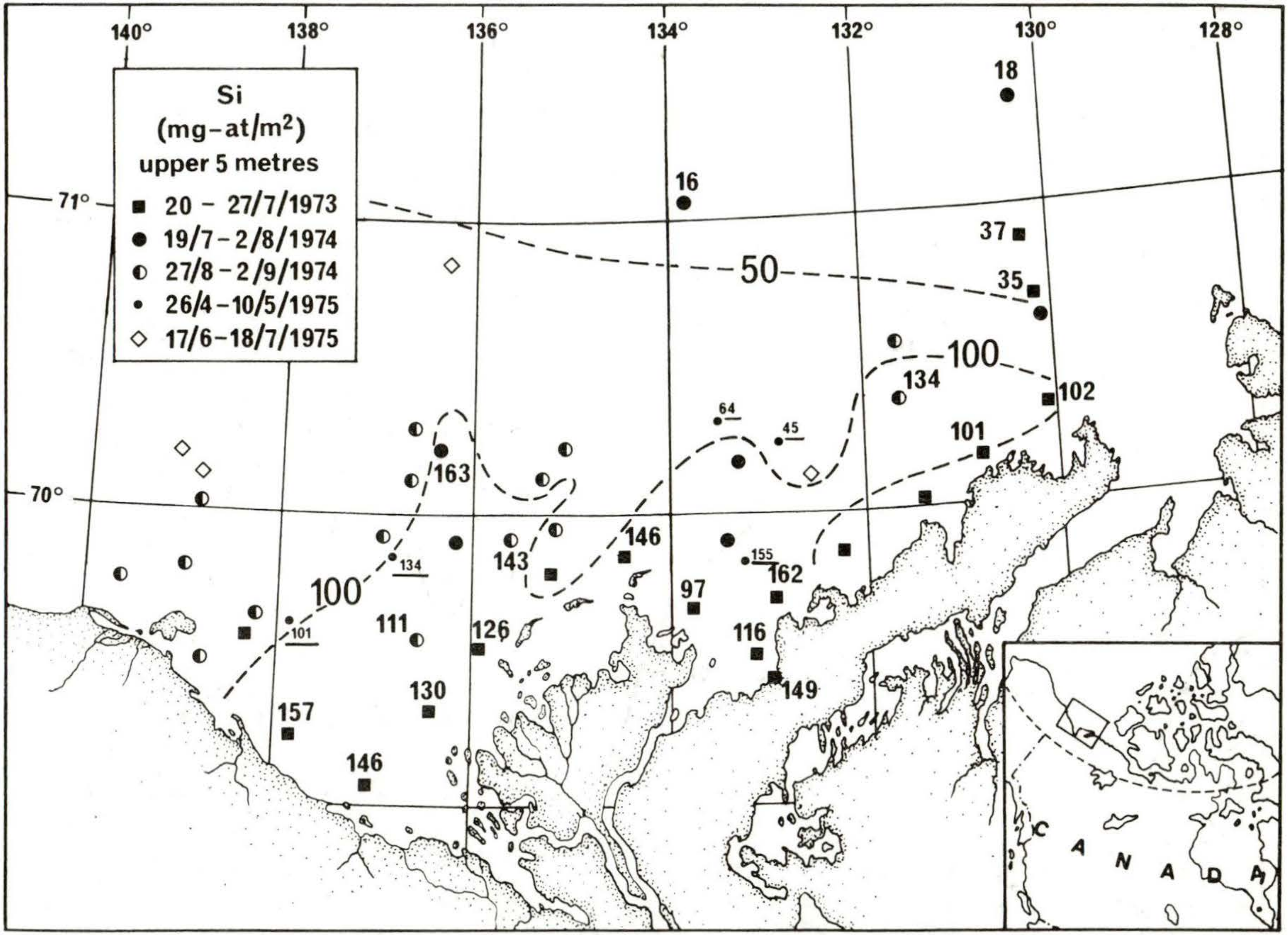

Figure 15. Silicate in the upper 5 metres. Underlined numbers show early spring values.

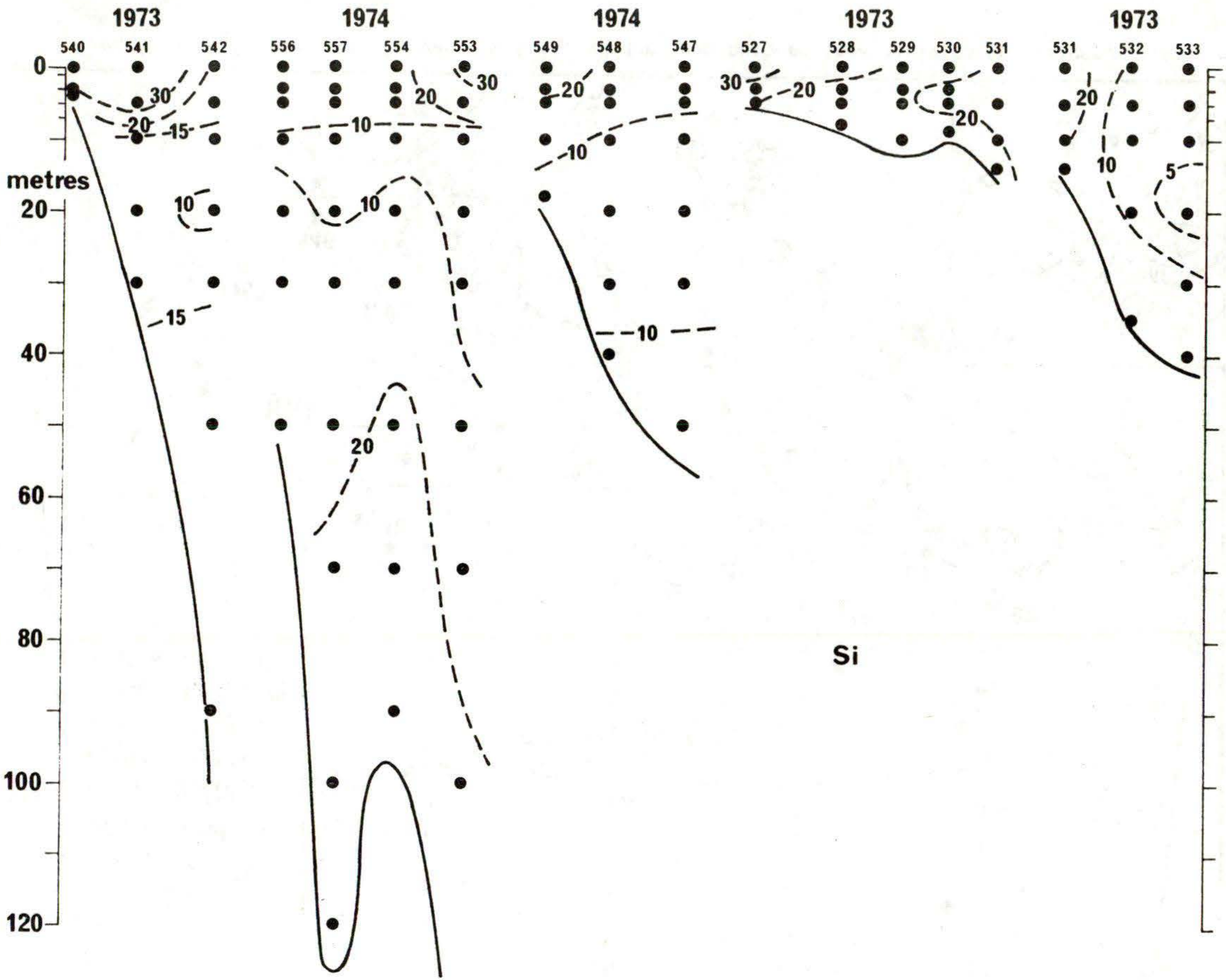

Figure 16. Silicate profiles along 5 lines of stations.

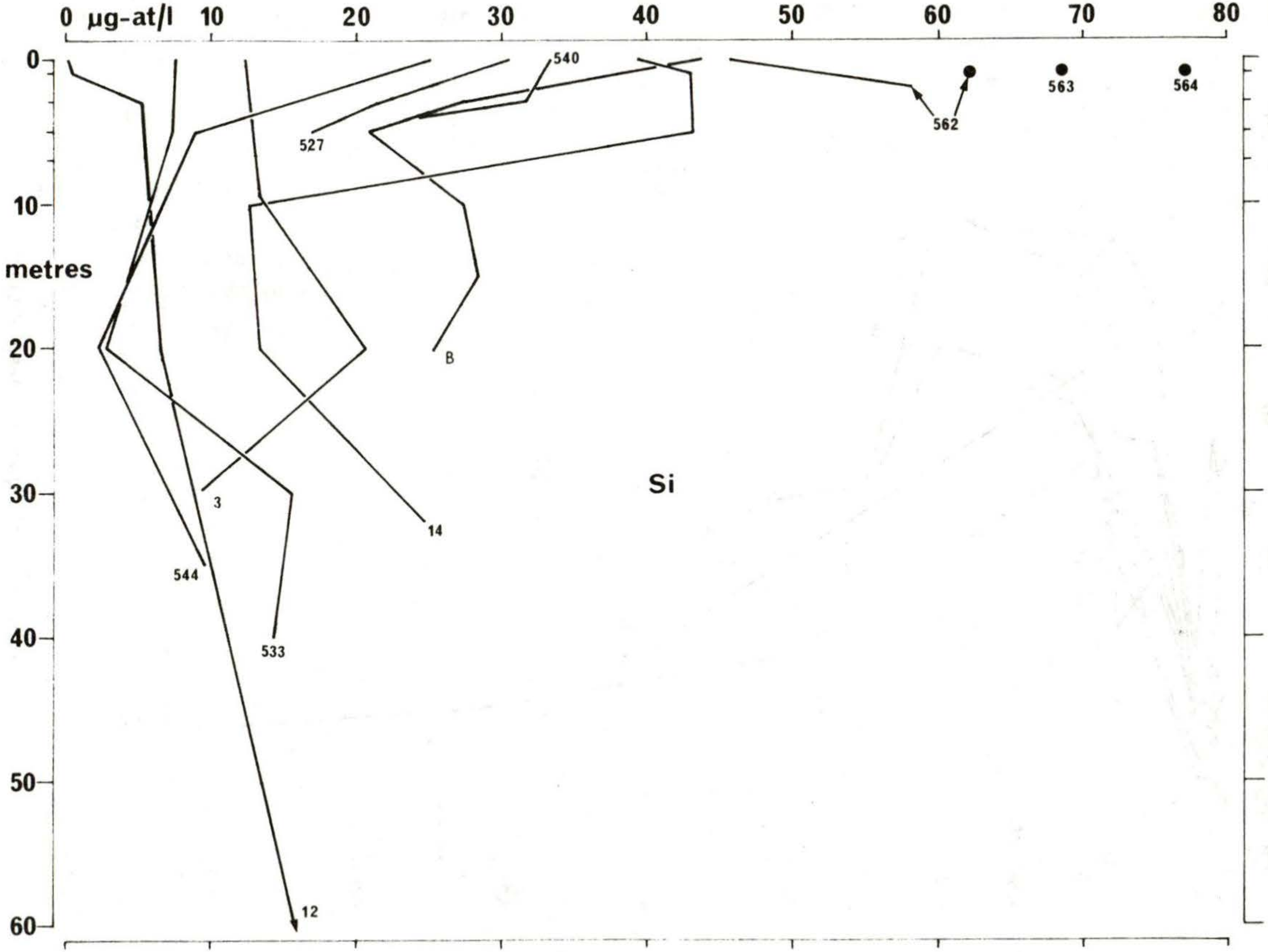

Figure 17. Silicate curves, shallow stations.

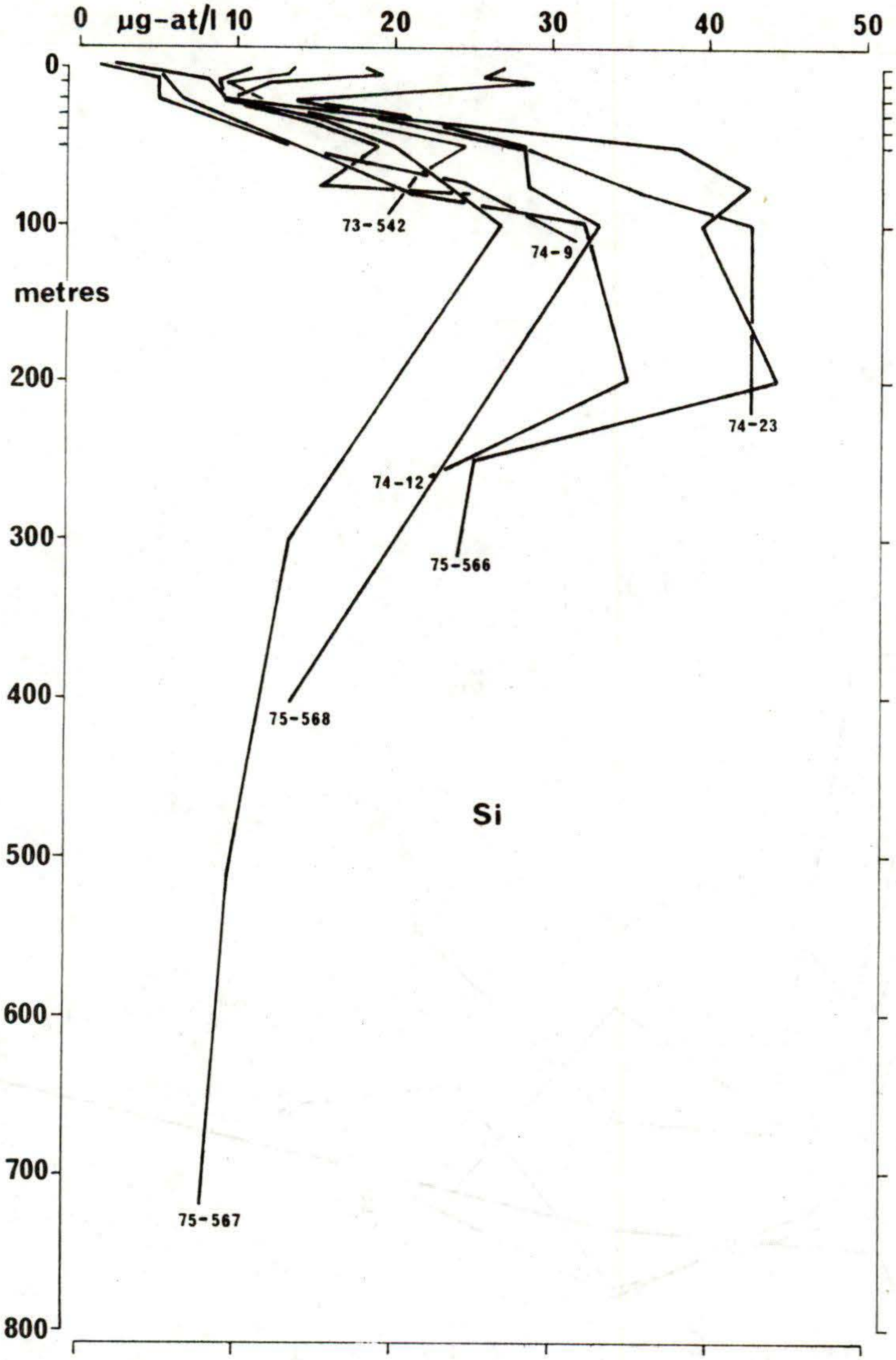

Figure 18. Silicate curves, deep stations.

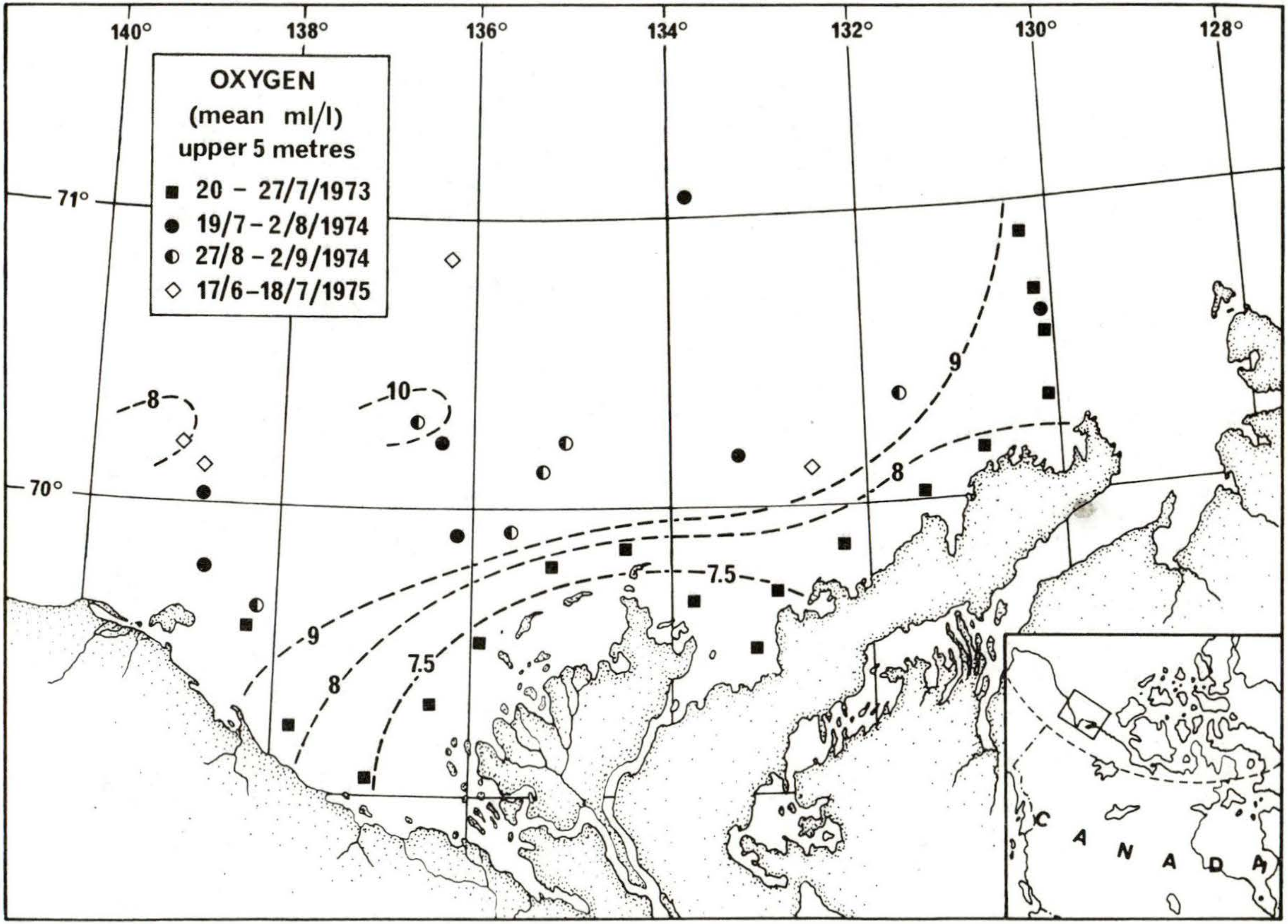

Figure 19. Oxygen in the upper 5 metres.

to about 8.5 ml/l, all less than the 9+ values found the year before and only a month or so previously in the same year. Quite apparently these figures reflect the ice cover effects of the two summers and the differences in timing of oxygen production in the same two years.

Vertical profiles of individual stations (Figures 20 and 21) show generally depressed surface quantities and increase in oxygen with depth to 10 or 20 metres (to 10 ml/l and more), below which oxygen declines. This diminishing trend continues downward to between 200 and 300 metres, and to between 6 and 7 ml/l. In deeper waters, values rise once again.

6.8 Chlorophyll

Highest chlorophyll a levels were found in Mackenzie and Kugmallit Bays, lowest in the northeast sector of the study area, in the upper 5 metres (Figure 22). The highest values at single stations were usually found in the upper 5 metres, rarely deeper than 10 metres. At 50 metres and deeper, levels were usually less than 0.1 mg/m^3. Values at all depths were low by northern coastal marine standards, and would seem to denote low standing stocks of phytoplankton (see Beaufort Sea Project Technical Report #12b).

6.9 Sea ice biology

The constituents of the sea ice cover of the Beaufort Sea were not examined, but some work of this kind was done as part of a long-term study in the nearby Eskimo Lakes, and some of the Eskimo Lakes findings are presented here. A fundamental difference between the ice cover of the Eskimo Lakes and much of the cover over the south Beaufort Sea concerns their ages and thicknesses. The Eskimo Lakes generally become totally free of ice during summer. The ice cover therefore during most winters is first-year growth, fairly evenly developed and with a relatively smooth surface. This covers almost the entire area of the Eskimo Lakes. In contrast, the Beaufort Sea, especially as seen in 1975, does not necessarily lose all its ice in summer. The ice pack, from the previous winter and before, may drift southward reaching fairly close to the coast during autumn when new ice is forming. If the initial winter surface forms in this way, the ice cover may be comprised to a significant degree of old ice, rafted, overturned and thicker by far than the ice of the year. In no way can measurements of features in and on the lower surface of annual ice be extrapolated to areas of old and thick ice of unknown history, about the biology of which we know almost nothing. The Eskimo

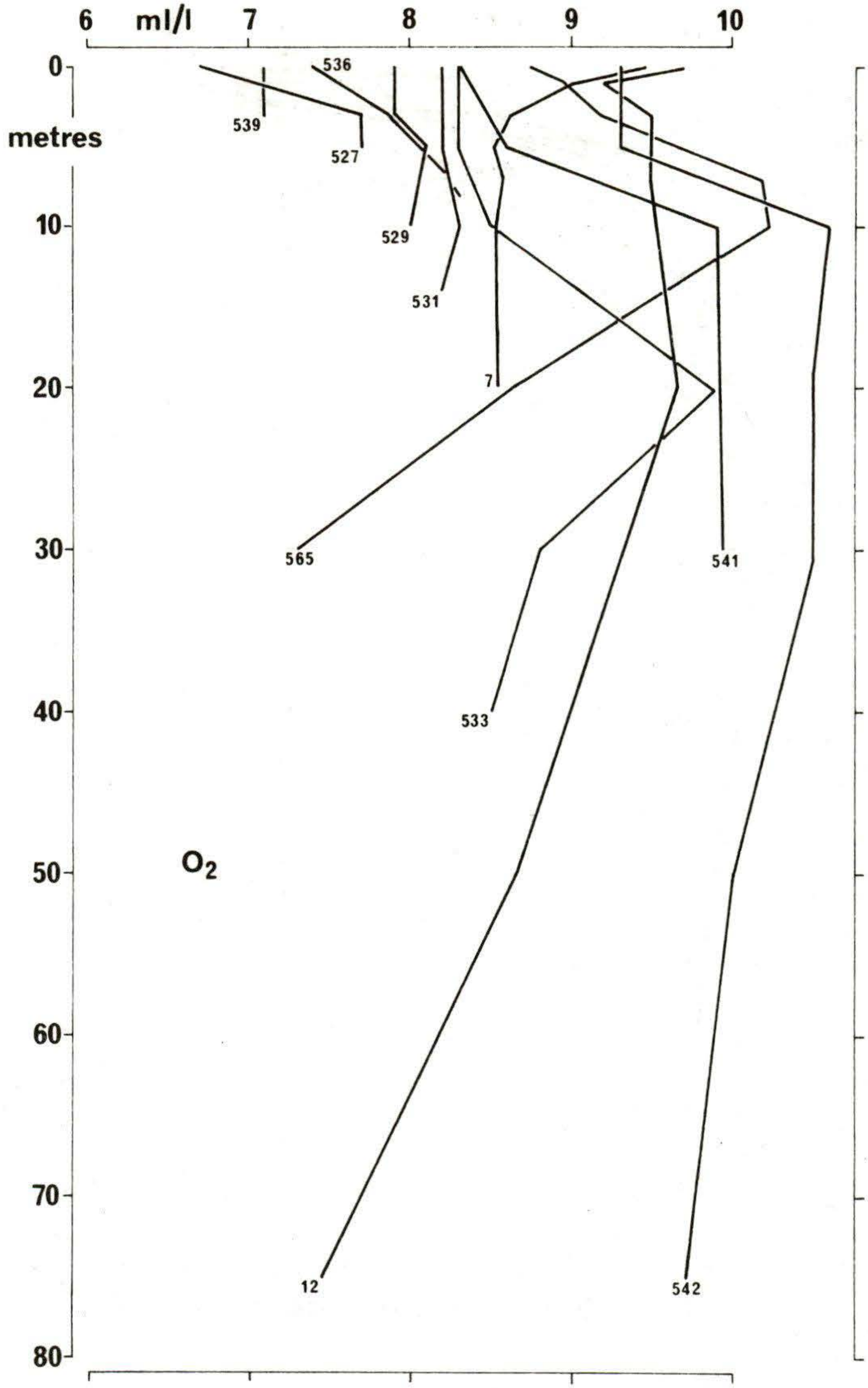

Figure 20. Oxygen curves, shallow stations.

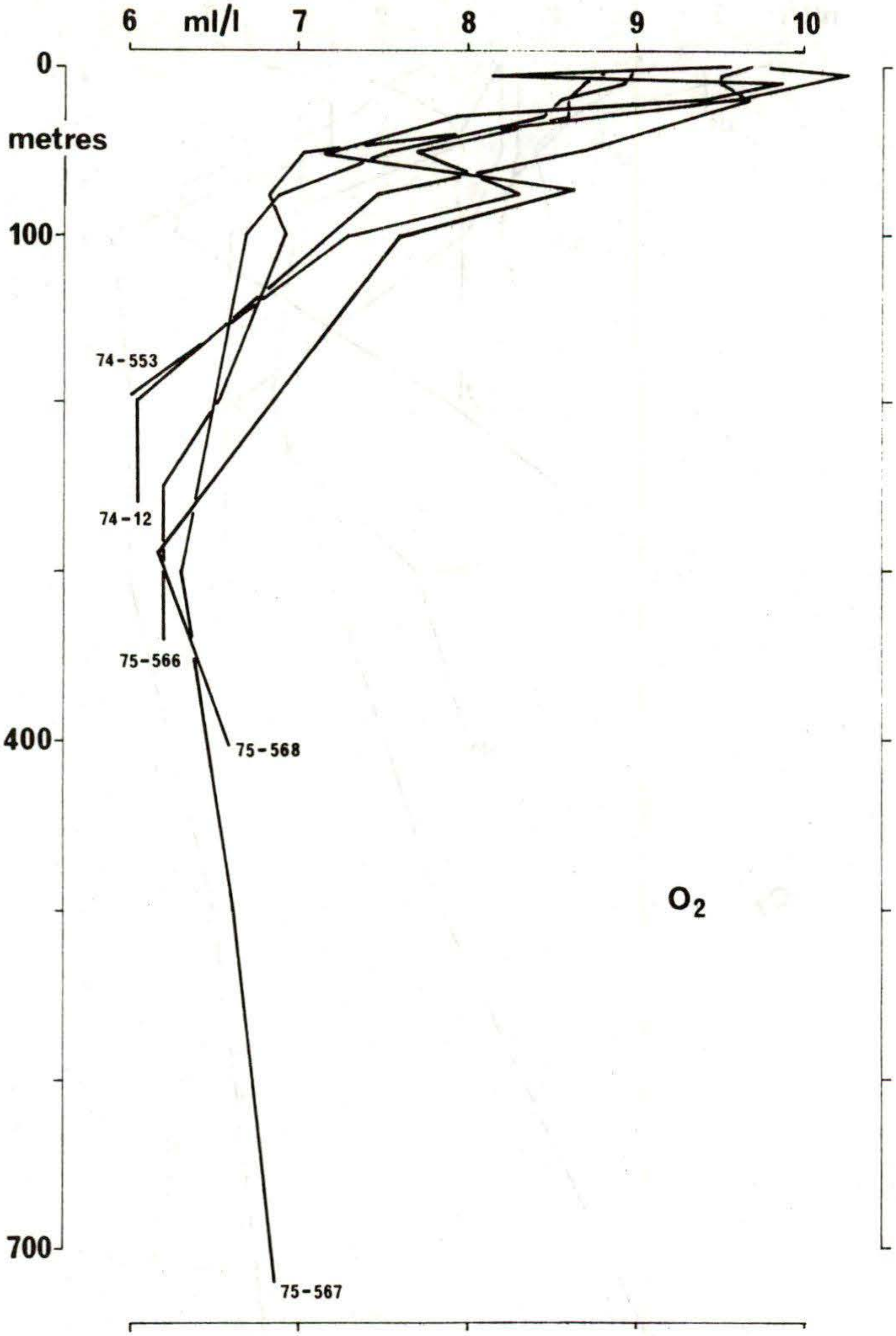

Figure 21. Oxygen curves, deep stations.

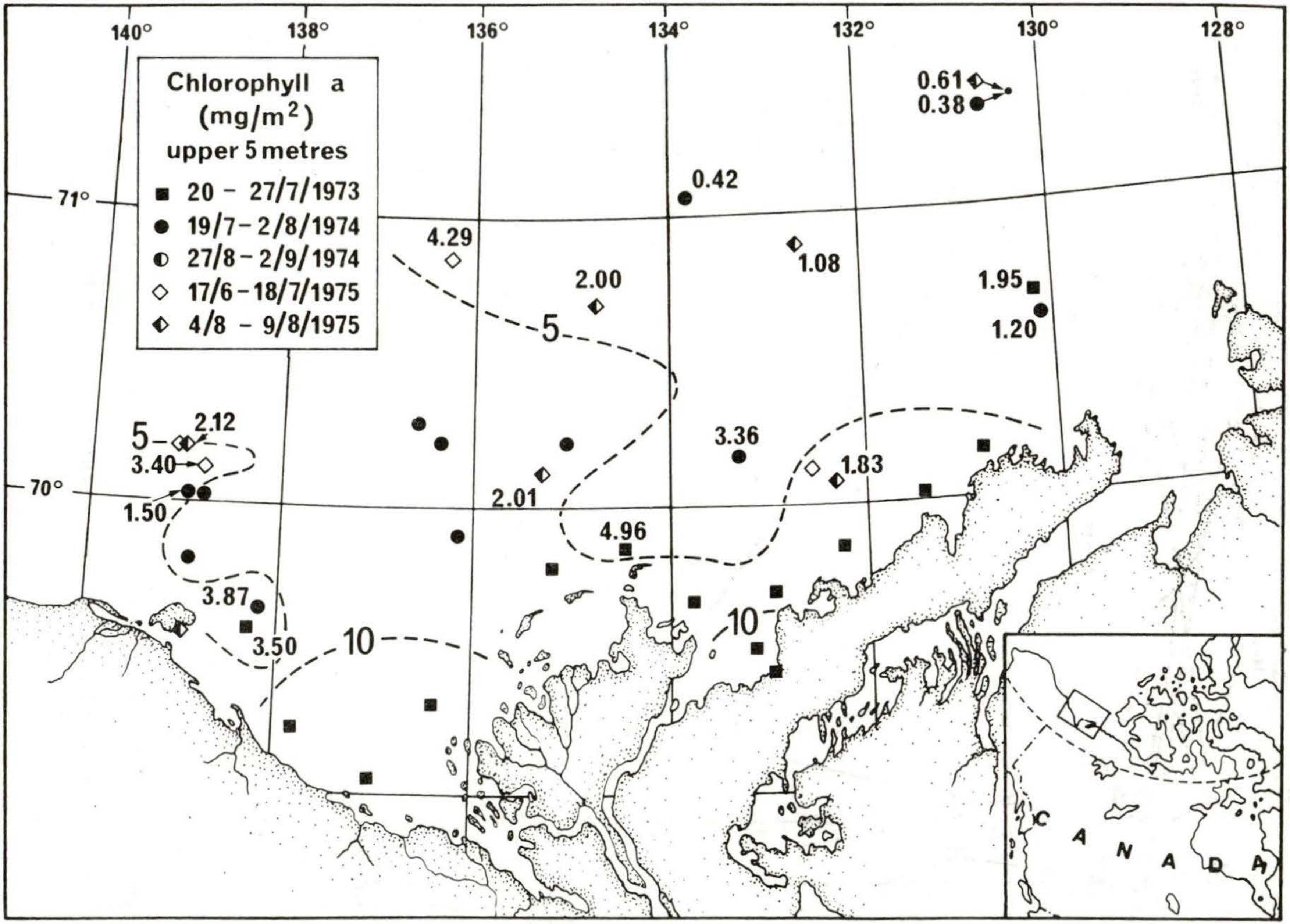

Figure 22. Chlorophyll a in the upper 5 metres.

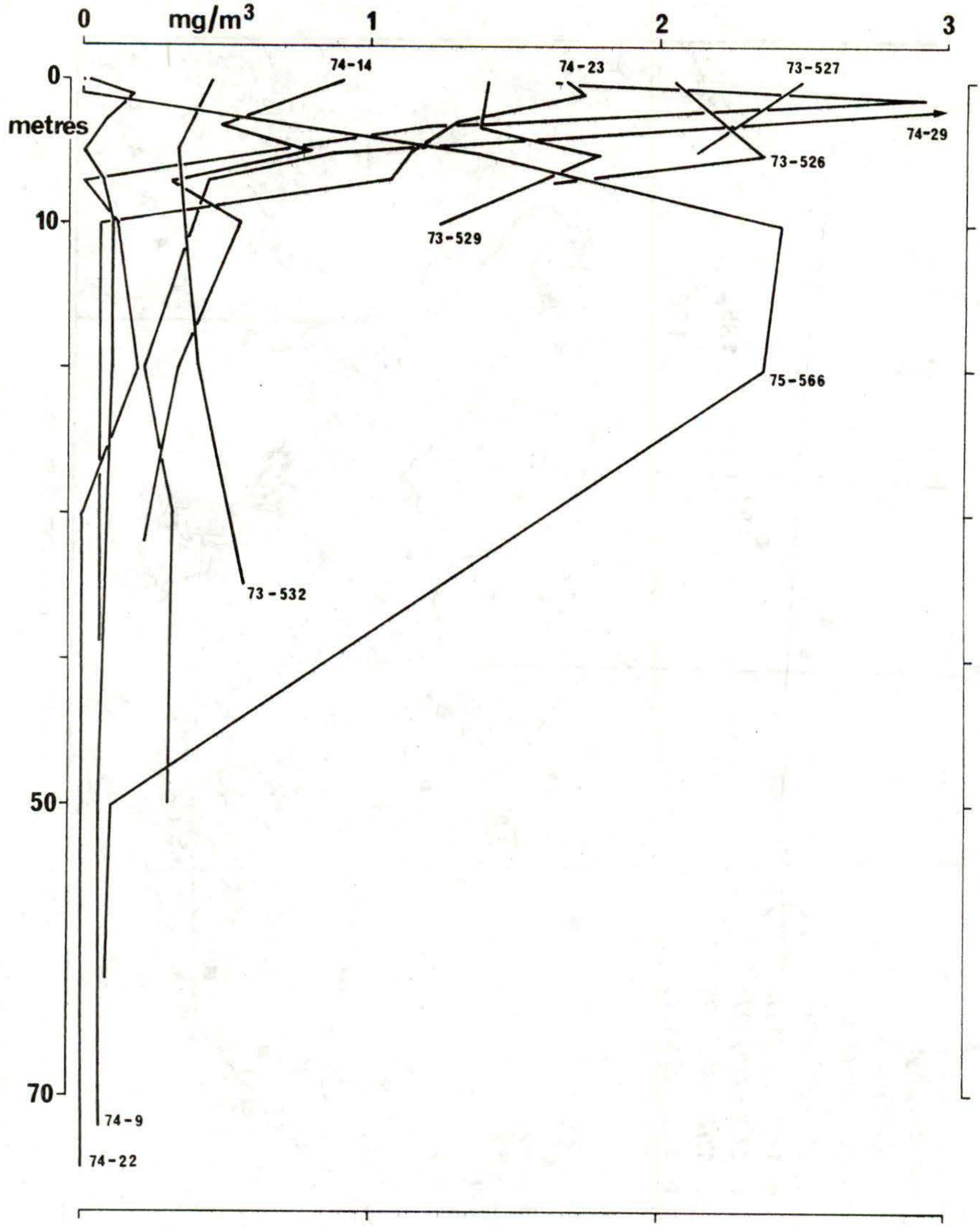

Figure 23. Chlorophyll a curves, selected stations.

Lakes ice study therefore cannot stand in place of a thorough Beaufort Sea ice study. It may give us some indication however of conditions found in the new, first-year Beaufort Sea ice, formed and remaining in a fairly stable position, say, along the outer edge of Mackenzie Bay or a few miles off Tuktoyaktuk Peninsula.

In the spring of 1973, Eskimo Lakes sea ice reached a thickness of about 170 cm, beneath a snow cover which probably did not exceed 15 cm all winter. The snow disappeared from the ice surface at about the end of the first week of June, and the ice cover had gone from the Lakes by about the beginning of the last week of June. It was a fairly early breakup. Chlorophyll a was measured in the ice on 24 November, 23 February and 19 May (Figure 24), and on the three dates was found as 0.30, 0.73 and 4.47 mg/m^2 of ice surface. On the last date of sampling, horizontal stratification had developed strongly, and a concentration equivalent to more than 50 mg/m^3 was found in the lower 10 cm of ice, at the same time as less than 1 mg/m^3 was found at the top of the ice. During the period, chlorophyll a was low in the water beneath the ice, present as only a small fraction of the quantity found in the ice. Measurements of nitrate, phosphate and silicate were also made on the same dates (Figure 24), and they showed ultimate development to 1.1 $mg\text{-}at/m^2$ of nitrate, 0.58 $mg\text{-}at/m^2$ of phosphate and 2.5 $mg\text{-}at/m^2$ of silicate in the ice. Nitrate and silicate were increasing during that time in the water from which the growing ice formed, and quantities of both can be more than accounted for as having been frozen into the ice as it grew. Phosphate, however, was far less plentiful in the water than the ice levels would suggest it should be, and the build-up of phosphate in the sea ice cannot be readily explained at the present time.

These figures show a development of chlorophyll in the ice within an environment containing nutrients and, concluded from the ice and snow cover thickness at the time of the May sampling, sufficient light for plant photosynthesis. At the time, in the Eskimo Lakes, there was no apparent planktonic plant production underway beneath the ice; that came later, after the release of the ice-bound plants to the water column as the ice melted. We do not have sufficient data from the Beaufort Sea at that time of year; it seems likely however, at least in the first-year ice, that plant production occurs within the ice, hence that the sea ice supports a vital flora which, as shown elsewhere, sustains an under-ice fauna and enters the sea as ice melting takes place in late spring or early summer.

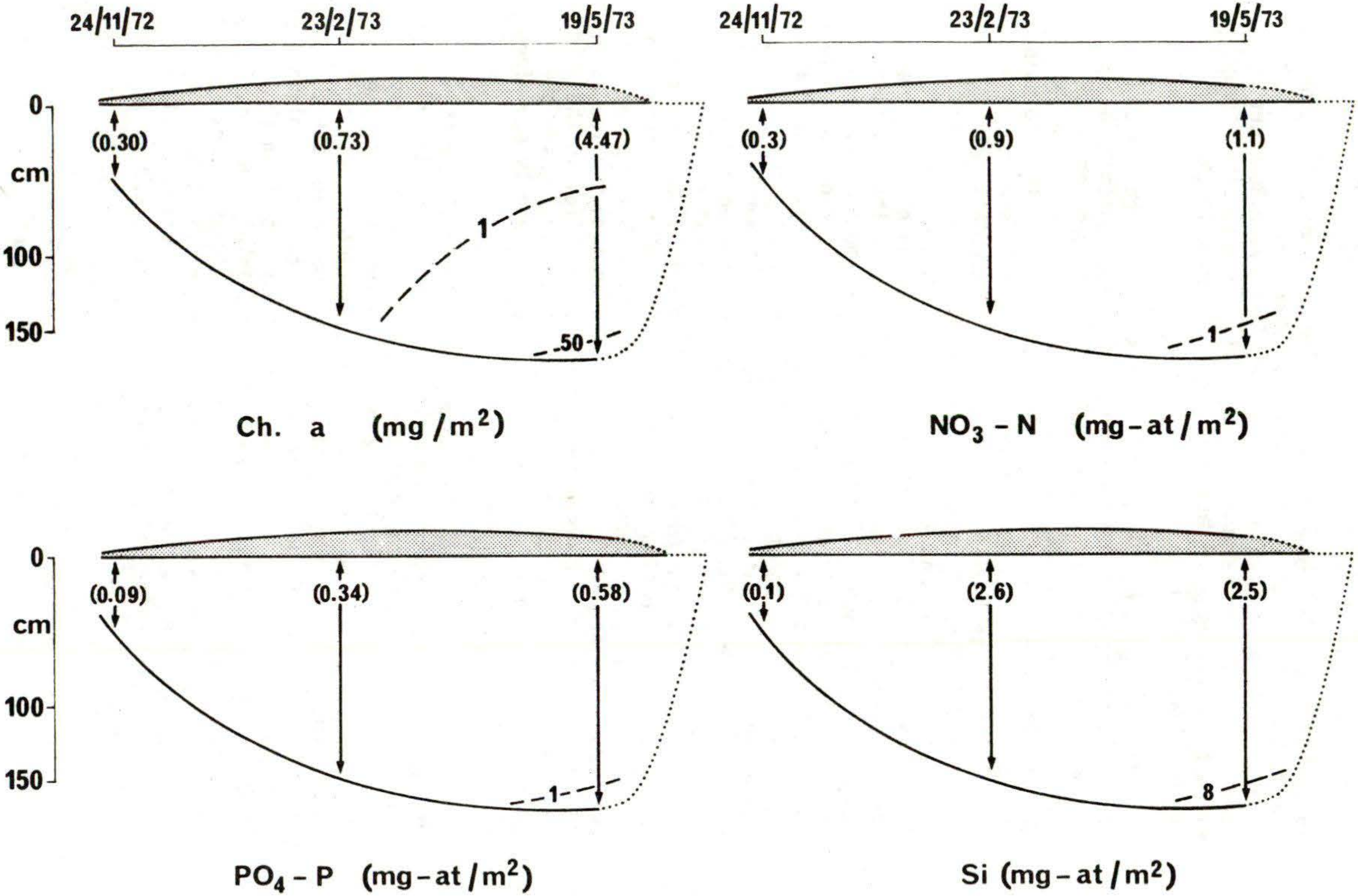

Figure 24. Diagrammatic sections of the ice and snow cover, Eskimo Lakes, showing chlorophyll and nutrients as total quantities in the ice (bracketed numbers) and as mg/m^3 (unbracketed numbers).

6.10 Zooplankton

Collections of zooplankton reported here originated at nearly 100 stations shown in Figures 25 to 26. At least 92 species are included in these collections, and they are listed in Table 1. For zooplankton data, see Grainger and Grohe (1975).

Numbers of species taken at single collection stations are shown in Figure 27. The smallest numbers (3 and fewer) were found in the east channel mouth of the Mackenzie River, in Kugmallit Bay, and just north of Richards Island. Slightly larger numbers were found in Mackenzie Bay and Liverpool Bay. Intermediate numbers were found in the centre and the largest numbers (14 species and more) near the western and northwestern limits of the study area. There were almost always more species found below 50 metres than above. The high diversity at the stations farthest from shore applies only to the waters below 50 metres at those locations; considering the upper 50 metres only, the offshore stations fall in the same category as the intermediate ones on the grounds of species numbers.

Expressed as number of copepodite specimens per cubic metre of water sampled, the results show a somewhat different picture. In this presentation (Figure 28), stations farthest from shore and those closest to the Mackenzie River showed the fewest organisms per unit of water sampled. Highest numbers were found off Tuktoyaktuk Peninsula (more than 1000 organisms per cubic metre) in Mason and Liverpool Bays, and intermediate numbers in the middle latitudes.

Combining the information in these two figures shows that the very shallow stations closest to the Mackenzie had the smallest standing stocks and the smallest species diversity. Deep stations farthest from shore also had small stocks (relative to water quantity sampled) but they showed the greatest species diversity, entirely below 50 metres. Stations in Liverpool Bay and Mason Bay and off Tuktoyaktuk Peninsula showed the largest standing stocks and rather variable diversity, ranging from low to medium (fewer than 3 to at least 10 species). Generally, stations in the centre of the study area were intermediate in both quantities. Stations in deep water farthest from the shore and the Mackenzie River influence supported the greatest number of species. Stations in intermediate depths between the innermost and outermost stations supported the largest number of specimens, and probably the largest biomass per unit of water sampled.

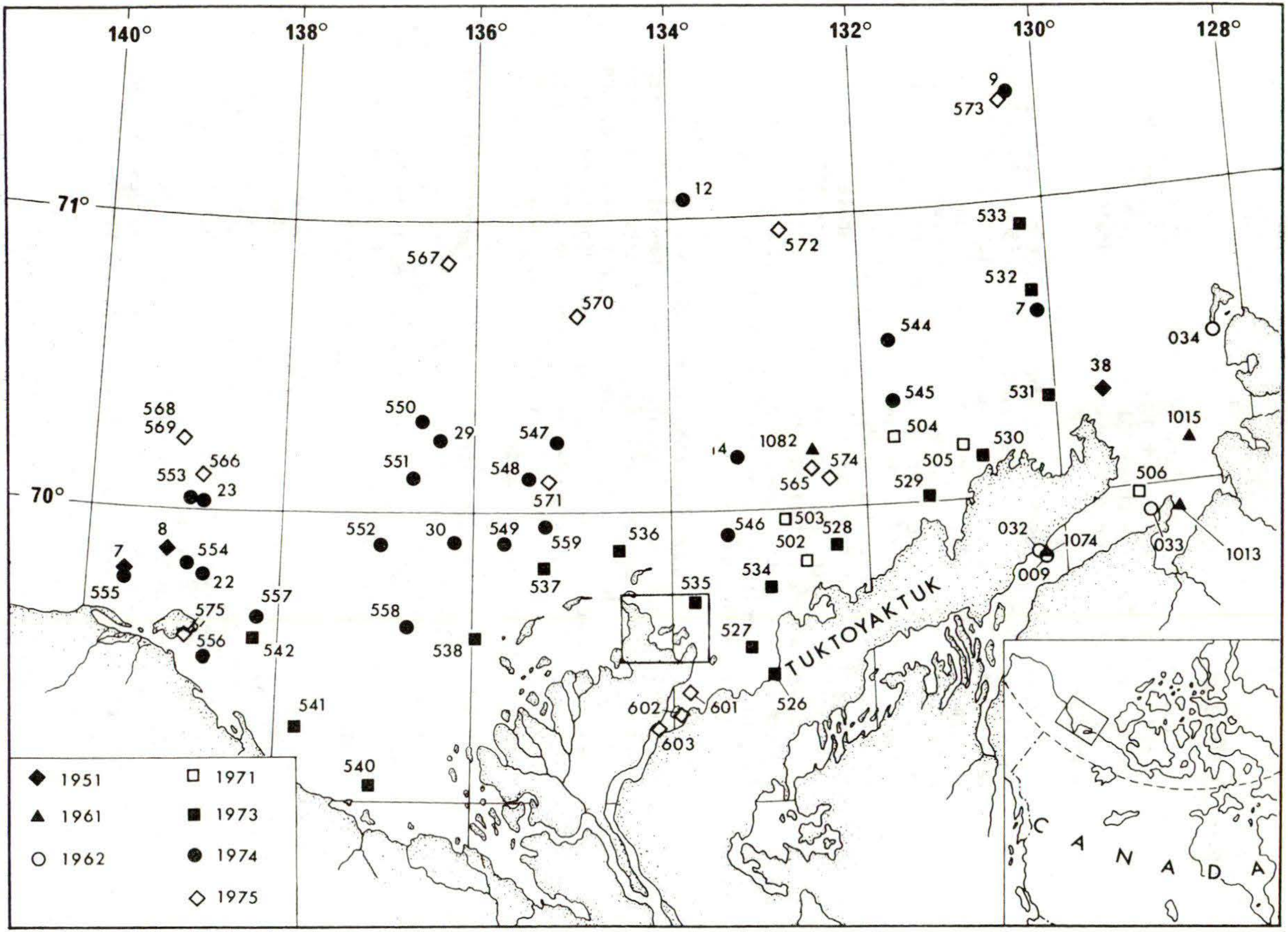

Figure 25. Stations which provided zooplankton data.

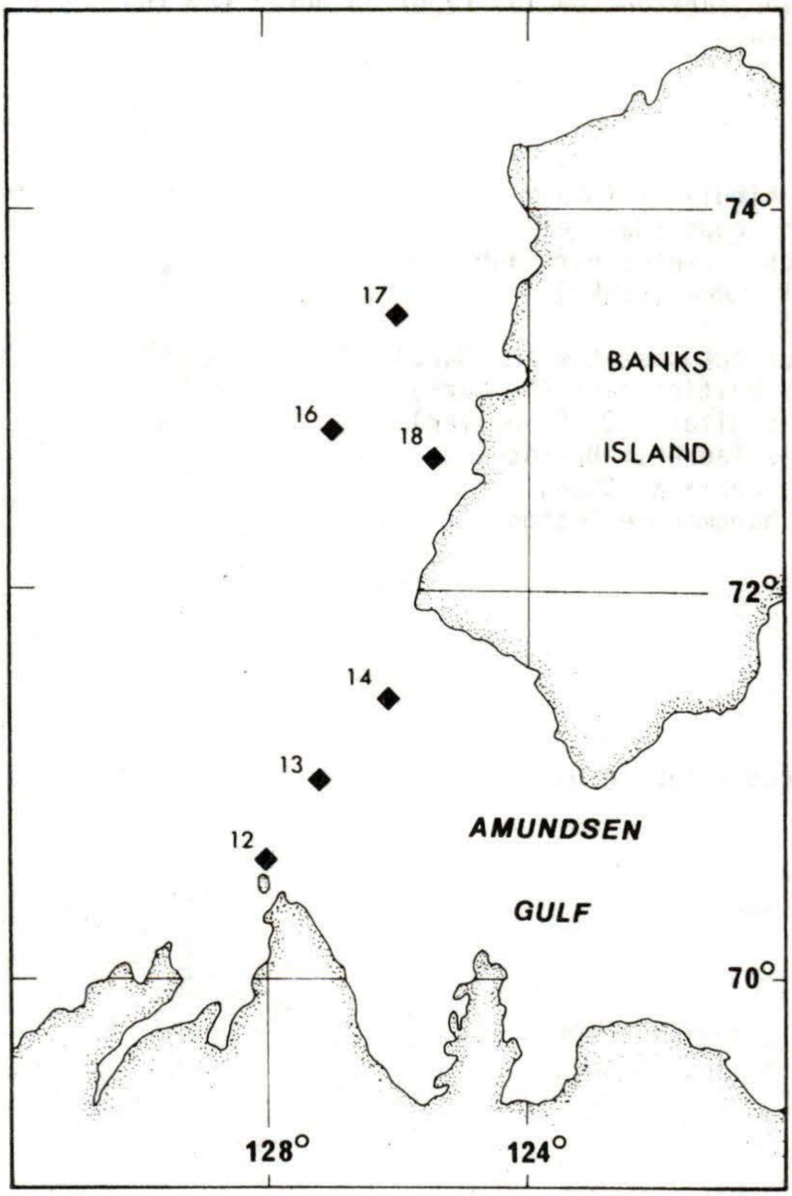

Figure 26. Stations which provided zooplankton data.

Table 1. Zooplankton species reported here from the south Beaufort Sea.

HYDROZOA

Eumedusa birulai (Linko)
Sarsia princeps (Haeckel)
Halitholus cirratus Hartlaub
Euphysa flammea (Linko)
Obelia sp.
Melicertum octocostatum (M. Sars)
Tiaropsis multicirrata (M. Sars)
Aglantha digitale (O. F. Müller)
Aeginopsis laurenti Brandt
Dimophyes arctica (Chun)
Muggiaea bargmannae Totton

ANTHOZOA

Larvae

CTENOPHORA

Beroe cucumis Fabricius

NEMATODA

Unidentified

MOLLUSCA

Spiratella helicina (Phipps)
Clione limacina (Phipps)

ANNELIDA

Pelagobia sp.
Polychaete larvae

BRANCHIOPODA

Daphnia sp.
Podon leuckarti G. O. Sars
Bosmina sp.

OSTRACODA

Conchoecia borealis maxima Brady & Norman

Table 1. (Continued)

COPEPODA

Acartia clausi Giesbrecht
Acartia longiremis (Lilljeborg)
Chiridius obtusifrons G. O. Sars
Derjuginia tolli (Linko)
Gaidius tenuispinus (G. O. Sars)
Calanus cristatus Krøyer
Calanus glacialis Yaschnov
Calanus hyperboreus Krøyer
Limnocalanus macrurus G. O. Sars
Diaptomus sp.
Eucalanus bungii bungii Johnson
Euchaeta glacialis Hansen
Heterorhabdus norvegicus (Boeck)
Metridia longa (Lubbock)
Metridia pacifica Brodsky
Drepanopus bungei G. O. Sars
Microcalanus pygmaeus (G. O. Sars)
Pseudocalanus minutus (Krøyer)
Spinocalanus longicornis G. O. Sars
Scaphocalanus brevicornis G. O. Sars
Scaphocalanus magnus (Scott)
Scolecithricella minor (Brady)
Epischura sp.
Eurytemora herdmani Thompson & Scott
Temorites brevis G. O. Sars
Ectinosoma neglectum G. O. Sars
Microsetella sp.
Pseudobradya minor (T. and A. Scott)
Harpacticus superflexus Willey
Danielssenia stefanssoni Willey
Tachidius sp.
Tisbe furcata (Baird)
Cyclops sp.
Cyclopina schneideri Scott
Mormonilla polaris G. O. Sars
Oithona similis Claus
Oncaea borealis G. O. Sars
Oncaea minuta Giesbrecht
Oncaea notopus Giesbrecht
Monstrilla sp.

CIRRIPEDIA

Nauplii
Cypris larvae

MYSIDACEA

Mysis litoralis (Banner)

Table 1. (Continued)

CUMACEA

Diastylis rathkei (Krøyer)

ISOPODA

Unidentified

AMPHIPODA

Apherusa glacialis (Hansen)
Halirages megalops (Bucholtz)
Gammaracanthus loricatus (Sabine)
Pseudalibrotus glacialis G. O. Sars
Monoculodes sp.
Pontoporeia affinis Lindström
Aceroides latipes (G. O. Sars)
Acanthostepheia malmgreni (Goës)
Acanthostepheia behringiensis (Lockington)
Pontogeneia inermis (Krøyer)
Metopa sp.
Hyperia galba (Montagu)
Hyperia medusarum (Müller)
Parathemisto abyssorum Boeck
Parathemisto libellula (Lichtenstein)

EUPHAUSIACEA

Thysanoessa inermis (Krøyer)
Thysanoessa raschi (M. Sars)
Thysanoessa longipes Brandt

DECAPODA

Sabinea septemcarinata (Sabine)
Pandalus sp.

CHAETOGNATHA

Eukrohnia hamata (Möbius)
Sagitta elegans Verrill
Sagitta maxima (Conant)

COPELATA

Fritillaria borealis Lohmann
Oilopleura vanhoeffeni Lohmann

ASCIDIACEA

Larvae

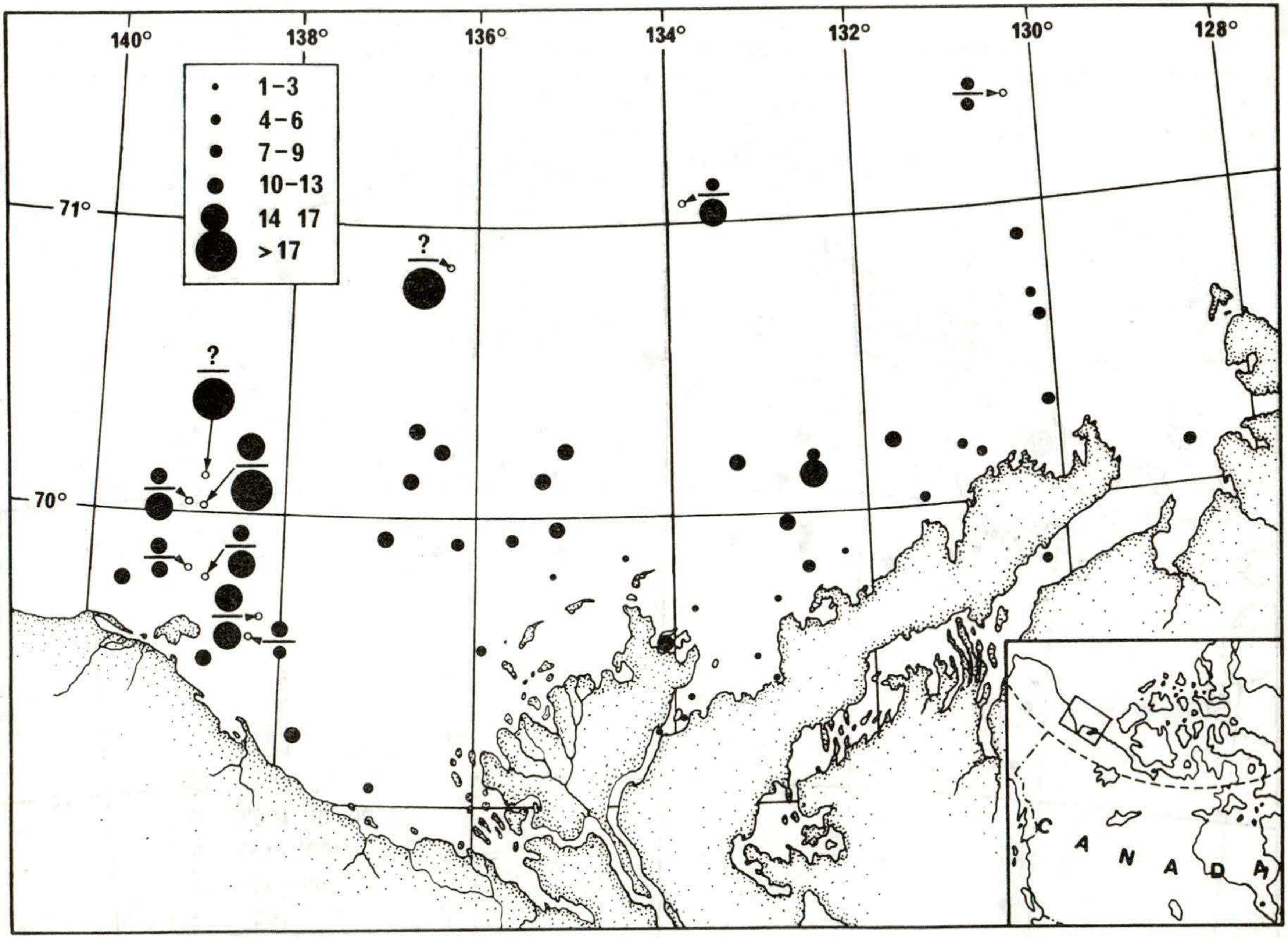

Figure 27. Number of species of zooplankton at each station. Paired circles show numbers above and below 50 metres depth.

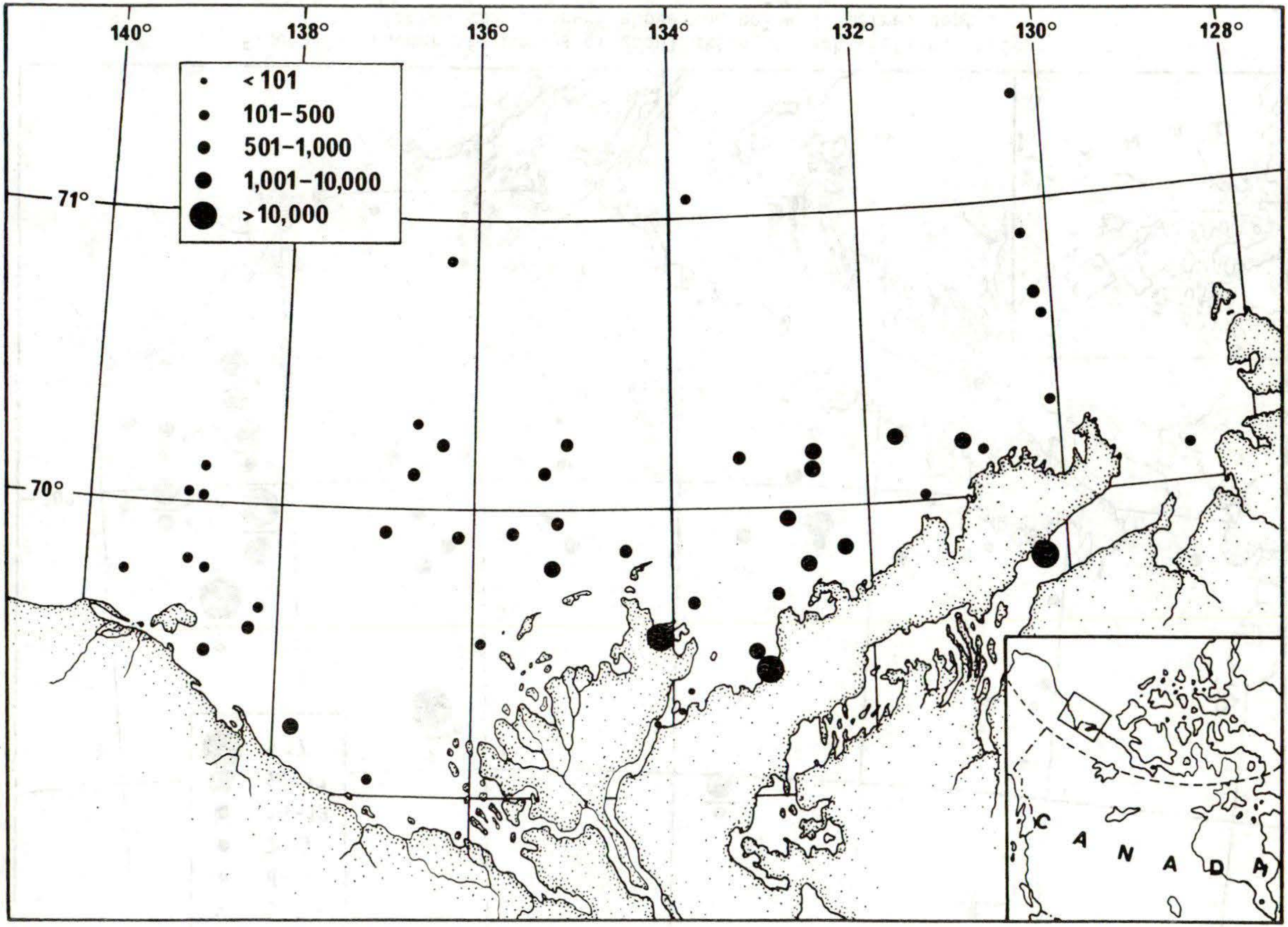

Figure 28. Numbers of zooplankton individuals per cubic metre.

One group of zooplankters consisted of essentially freshwater forms of the genera *Daphnia*, *Diaptomus*, *Epischura* and *Bosmina*. They were found within the east channel of the Mackenzie River and just off the delta (Figure 29), in water which was virtually fresh. These are all animals of freshwater origin which had entered the sea with outflowing river water. *Cyclops* is a genus of fresh and estuarine waters. It was found here over a fairly large area up to several miles from shore (Figure 30) in salinity at least as high as 12‰ (few animals) to less than 1‰ (many). These organisms were likely discharged to the sea in outflowing fresh water. *Mysis* (Figure 31) was found under similar circumstances, nearly all in salinity less than 12‰, the largest collection in less than 6‰. *Eurytemora herdmani* was another with another range, with the larger collections coming from salinity of about 2 to 15‰. With perhaps a little higher salinity tolerance than the others mentioned above, *E. herdmani* has reached into Liverpool Bay and the Eskimo Lakes, where it occurs in large number.

Two species which are characteristically found in marine waters of low salinity, but evidently in a higher minimum salinity than the species above, are *Acartia clausi* and *Halitholus cirratus* (Figure 33), found in as low a concentration as about 7‰ and as high at least as 20‰, and for *H. cirratus* at least perhaps sometimes considerably higher.

A very abundant species is *Limnocalanus macrurus*, another species found characteristically in low salinity, but with a generally wider range than the species above, occurring in salinity as high as 25‰ (Figure 34). This species and *Derjuginia tolli* (Figure 35) outline apparently quite well the Mackenzie river plume. *D. tolli* is slightly less tolerant than *L. macrurus* of especially low salinity, so is absent from innermost Mackenzie and Kugmallit Bays; both however extend to about the same salinity maximum.

Several species are characteristic of so-called Arctic Surface water, that is water which originates at the surface of the Arctic Ocean, where it occupies the upper 200 to 300 metres, and which extends arctic marine influence southward by flowing among the islands of the Canadian Arctic Archipelago and down the east coasts of Greenland and mainland North America. These species, illustrated here by *Aglantha digitale* and *Calanus glacialis* (Figures 36 and 37), range from the outermost stations towards shore. They are seldom if ever found in bays or in any other location with salinity less than a little below 20‰. While all the species of low salinity referred to above are found in shallow and surface waters, these arctic surface species are present near the surface in offshore arctic waters, but they

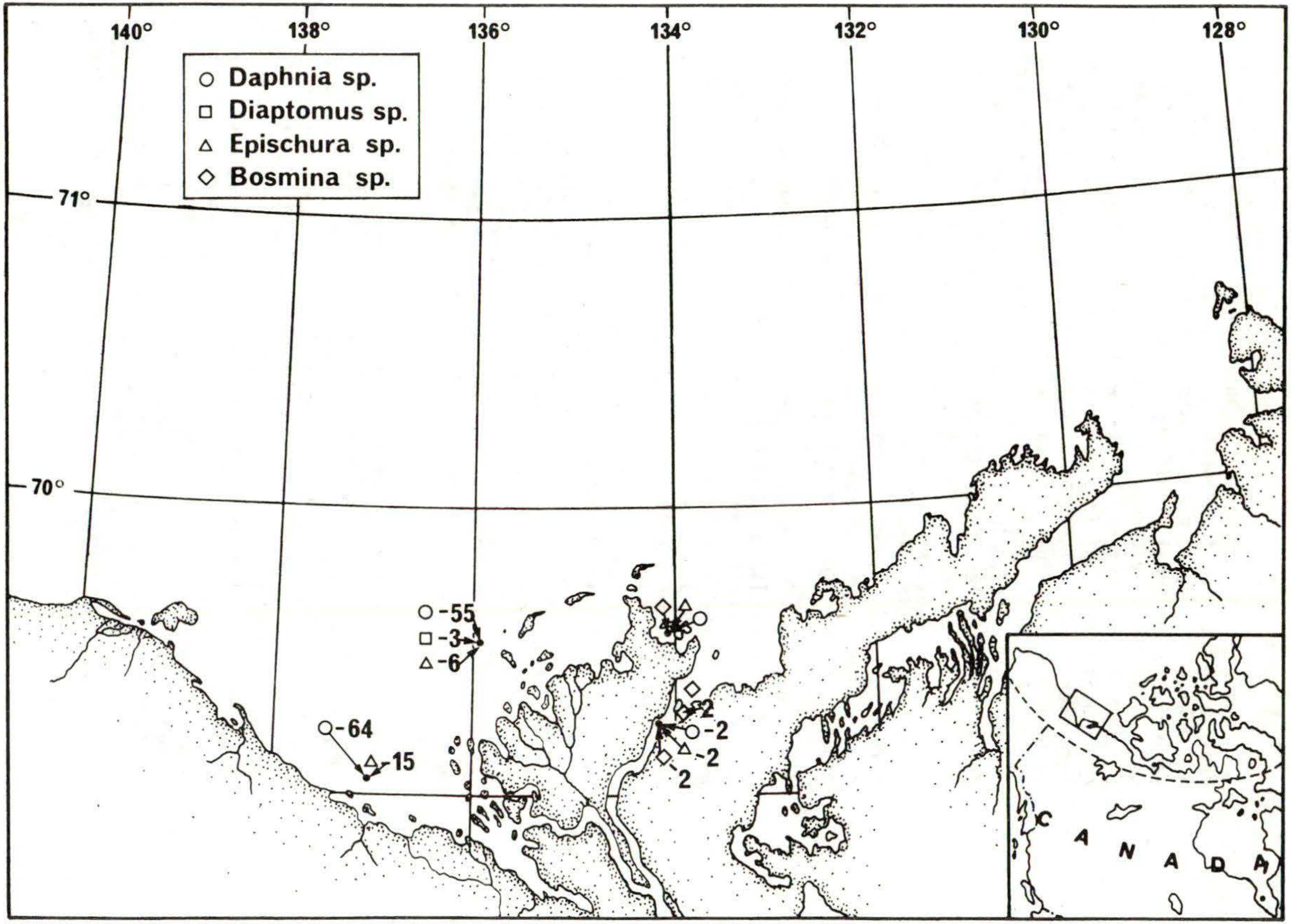

Figure 29. Freshwater zooplankton in the Beaufort Sea.

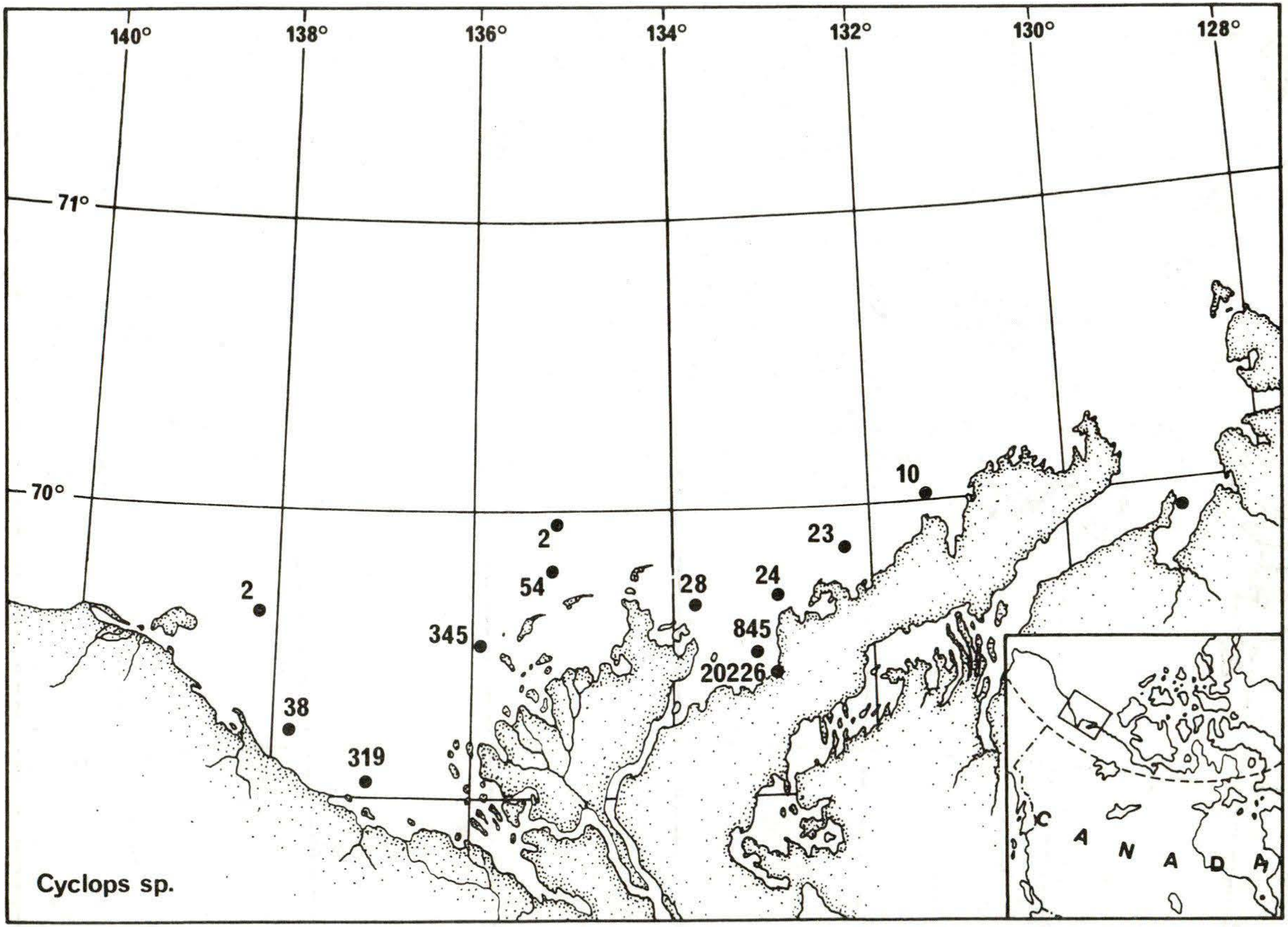

Figure 30. The distribution of *Cyclops*.

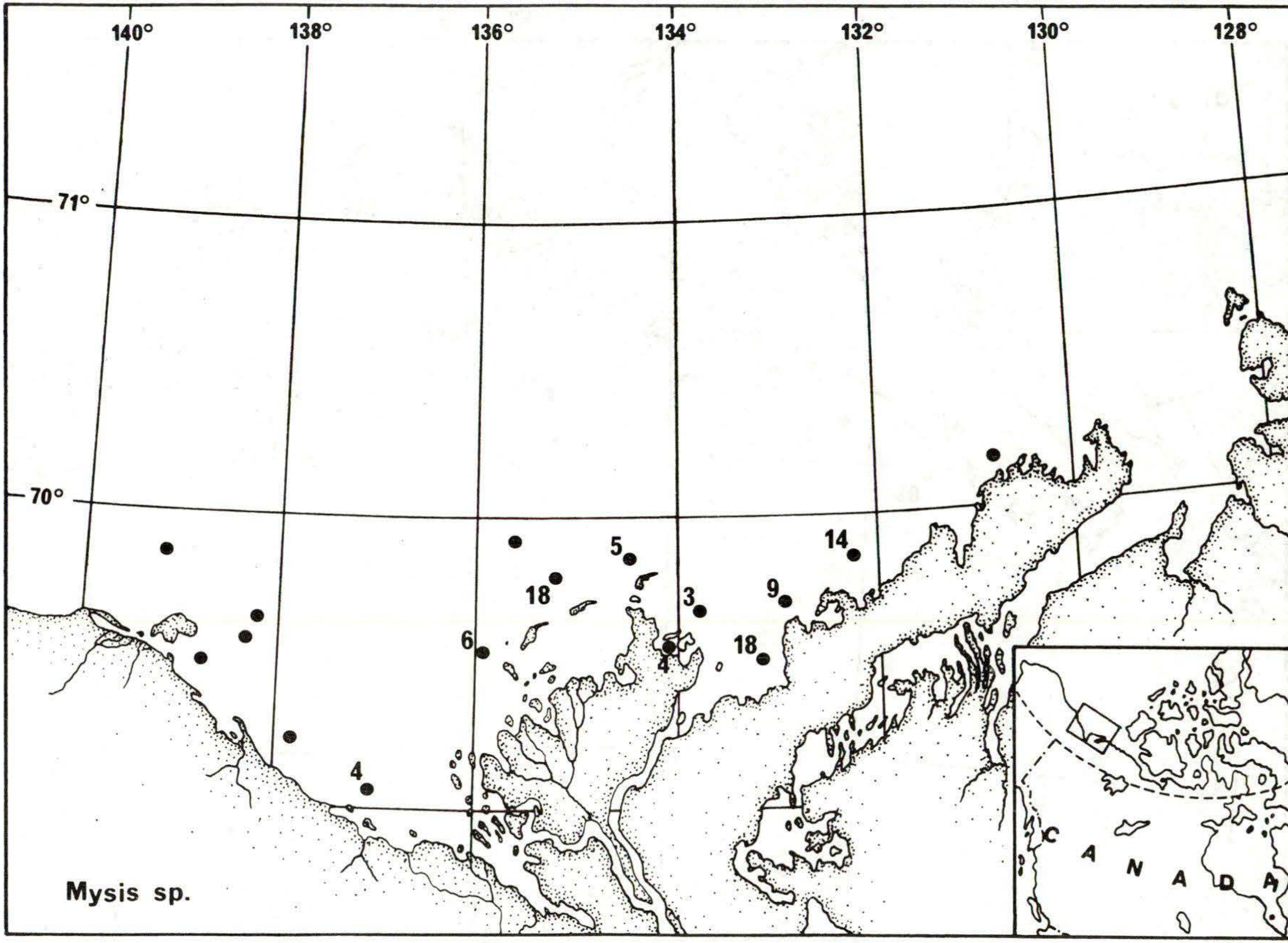

Figure 31. The distribution of *Mysis*.

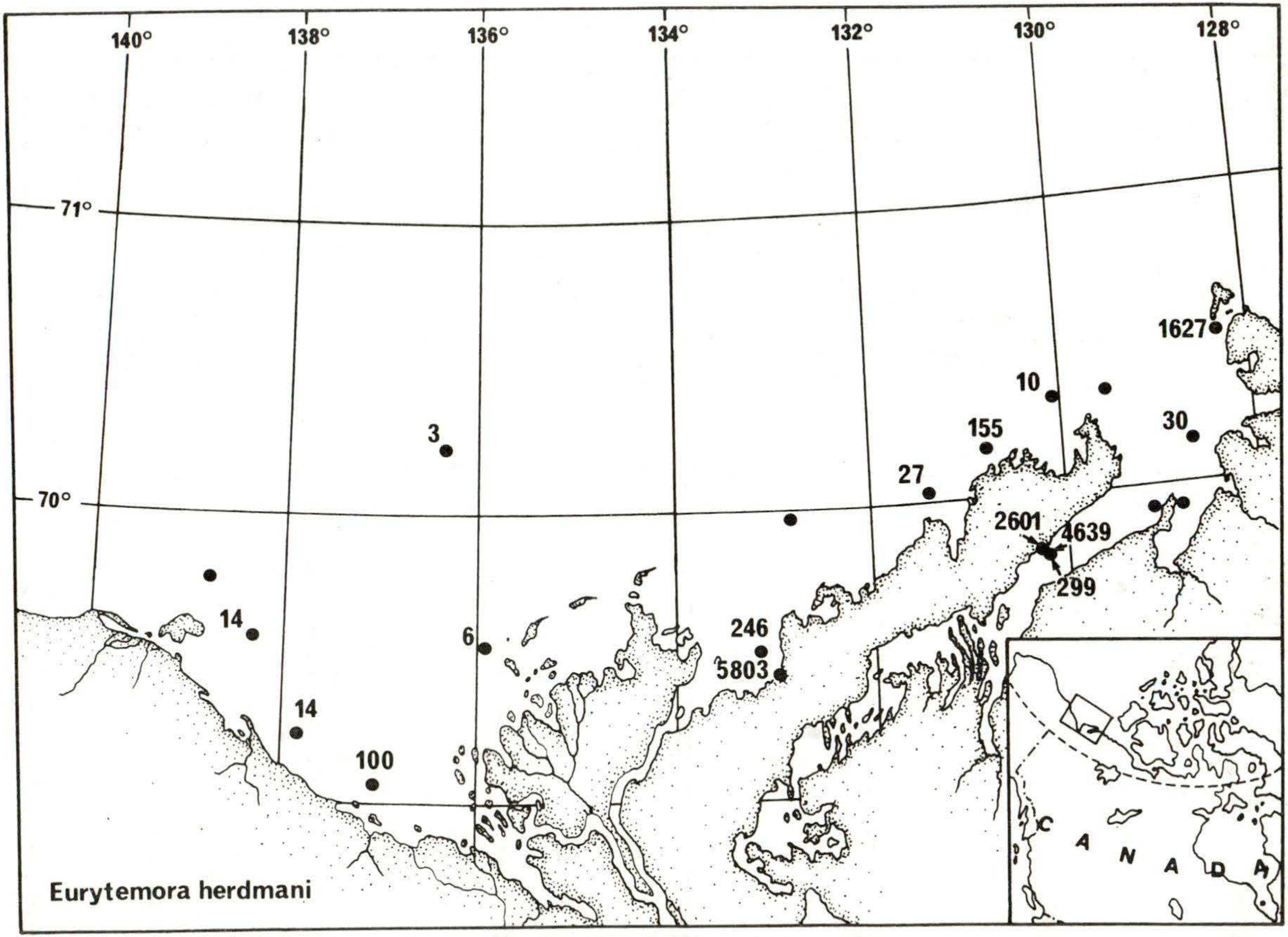

Figure 32. The distribution of *Eurytemora*.

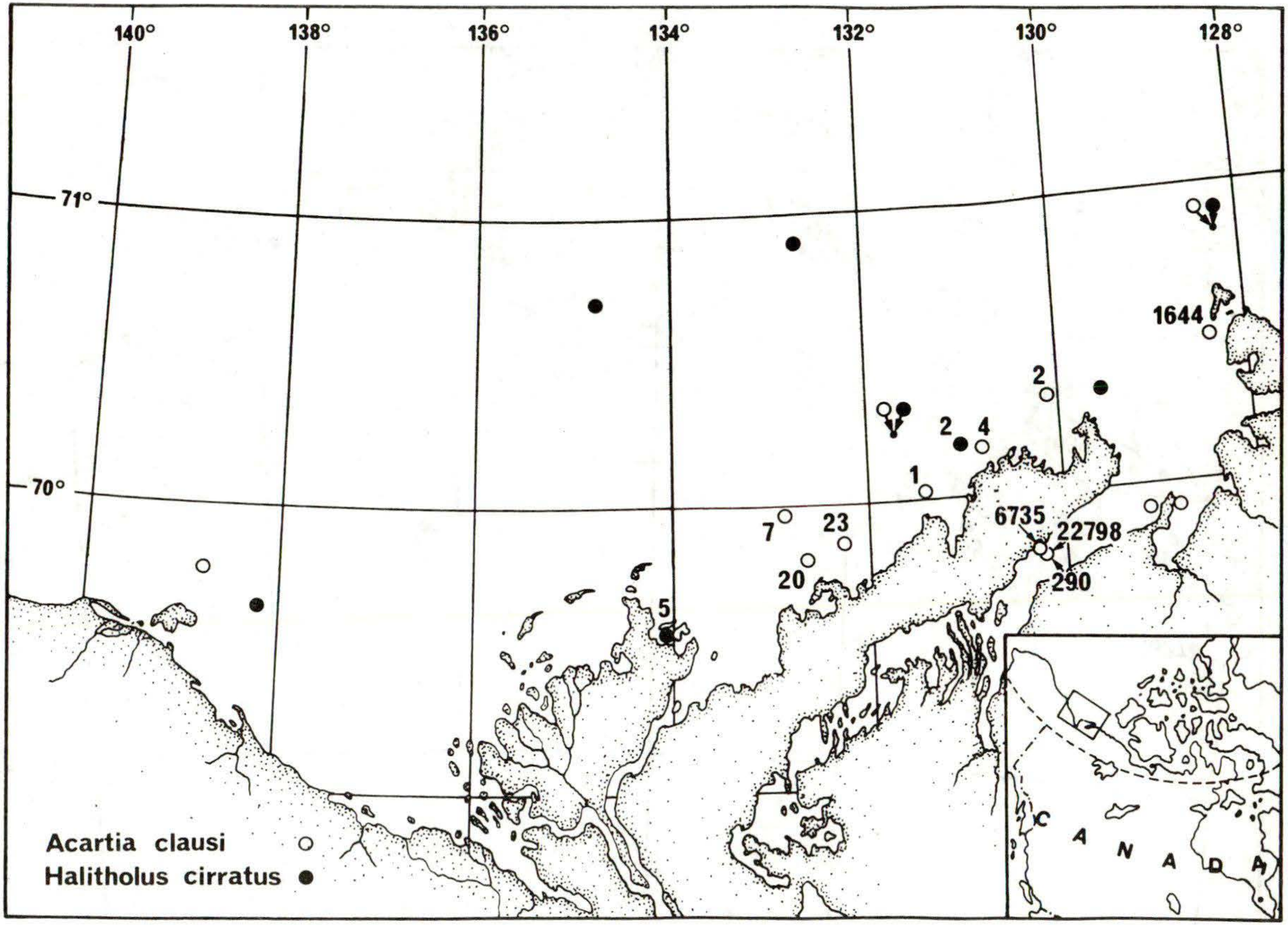

Figure 33. The distribution of *Acartia* and *Halitholus*.

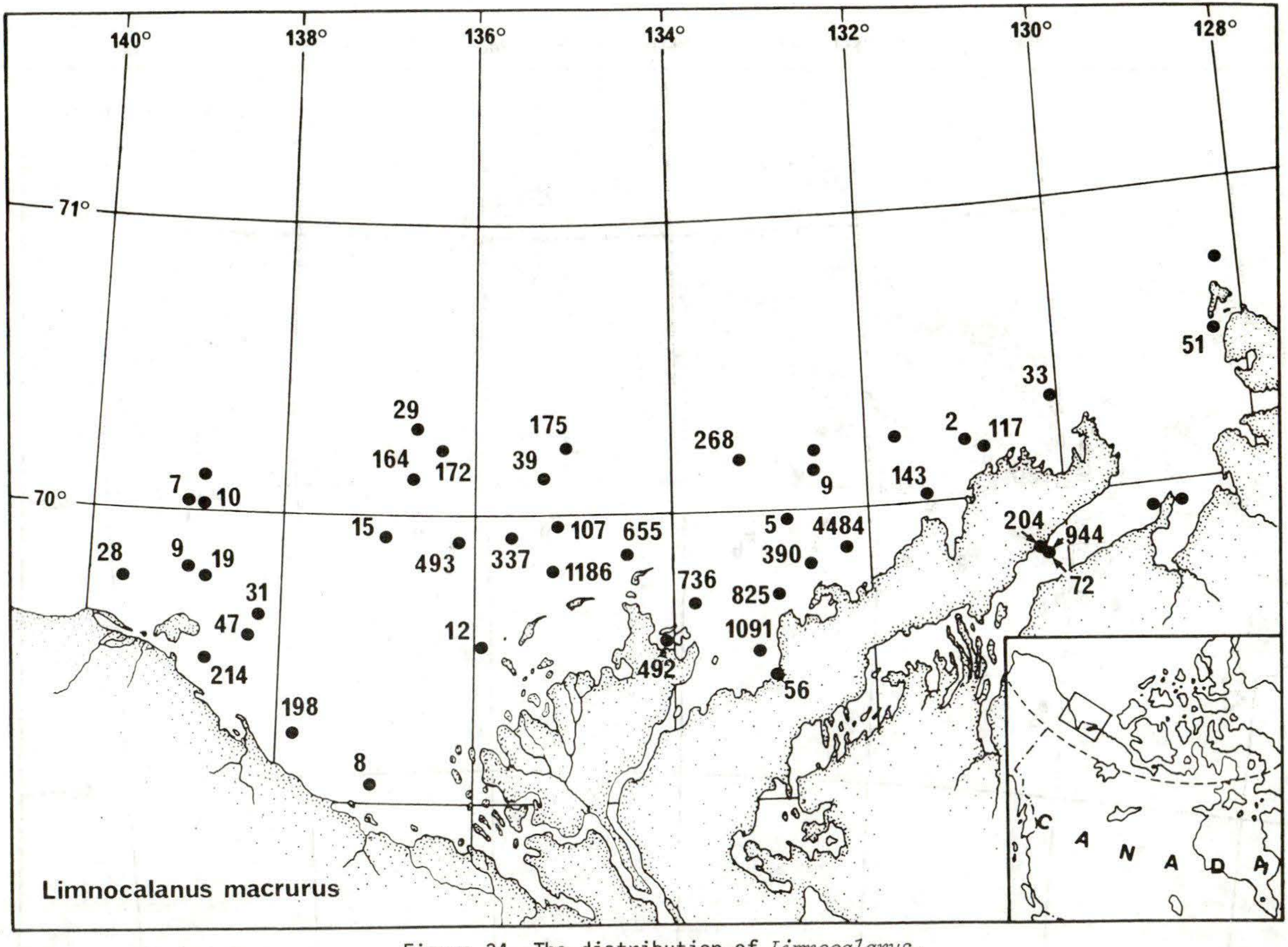

Figure 34. The distribution of *Limnocalanus*.

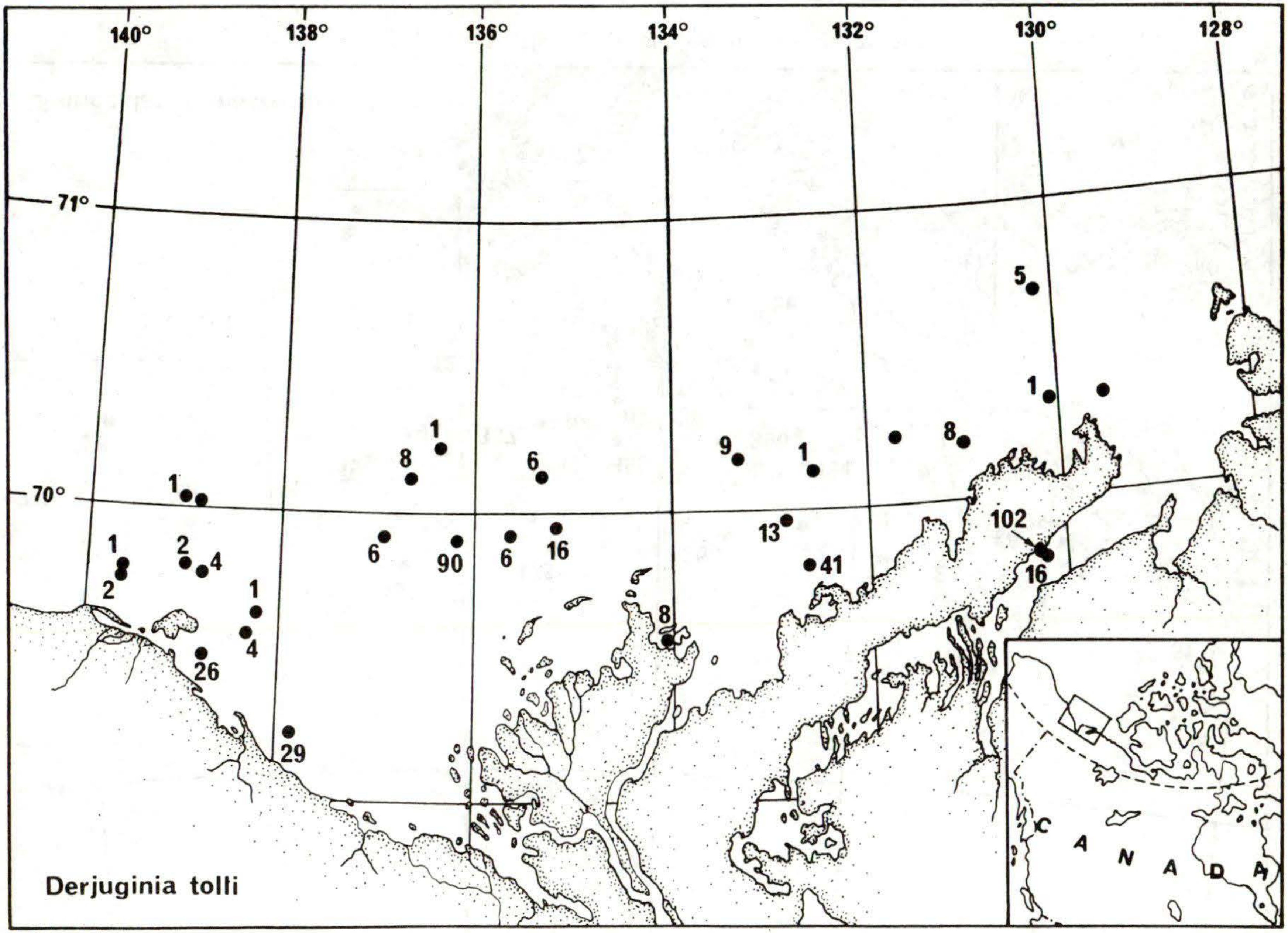

Figure 35. The distribution of *Derjuginia*.

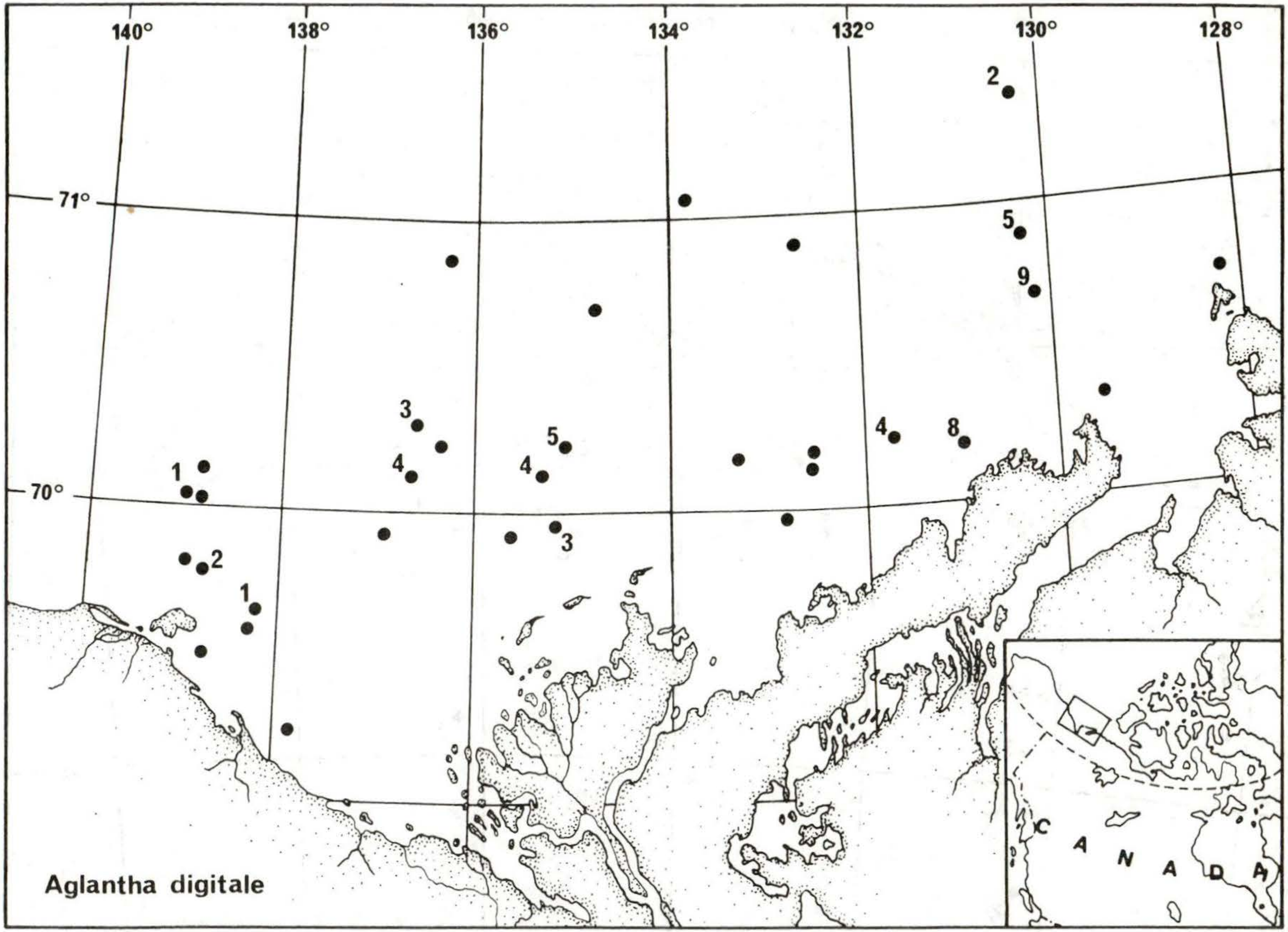

Figure 36. The distribution of *Aglantha*.

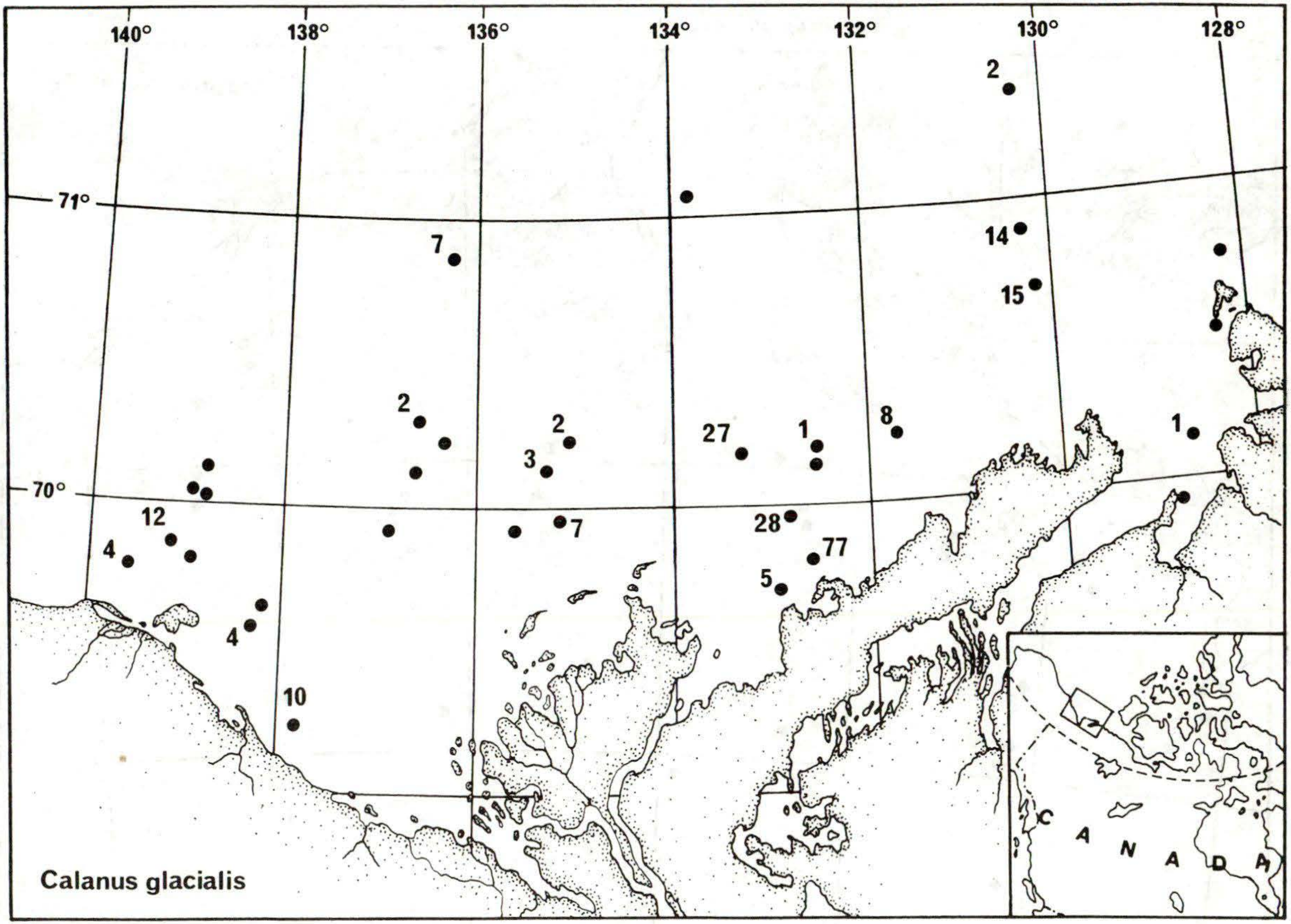

Figure 37. The distribution of *Calanus*.

are found deeper beneath waters of low salinity or high temperature (above 8 to 10°C).

Another group of species is characteristic of deeper Arctic Ocean water, the Atlantic layer which lies beneath the Arctic Surface layer, extending from 200 or 300 metres to around 900 metres. These species of course are not frequently found in coastal waters, although isolated individuals do rise above the Atlantic layer. The species of this group identified in this study include *Chiridius obtusifrons*, *Gaidius tenuispinus*, *Heterorhabdus norvegicus* (Figure 38), *Spinocalanus* sp., *Scaphocalanus magnus* and *Scolecithricella minor* (Figure 39). All were taken in small numbers only.

The final group includes Pacific species, which are described as entering the Arctic Ocean through Bering Strait from the Pacific. They occur in the Chukchi Sea and eastward in the Beaufort Sea as far as the locations shown here (Figure 40). Included are *Calanus cristatus*, *Eucalanus bungii* and *Metridia pacifica*. They too, occurred only in small numbers.

7. DISCUSSION

The coastal waters of the south Beaufort Sea show what is in many ways the typical river mouth structure of water of low salinity and of river origin overlying water of higher salinity of offshore, oceanic origin. The river water is contributed by the Mackenzie, and the underlying oceanic water by the Arctic Ocean. The variable balance between these factors determines much of the basic biological character of the south Beaufort Sea.

One of the characteristic features of arctic waters is the presence of a sea ice cover during a large part of the year. Ice cover conditions in the Beaufort Sea are notably variable, and especially well illustrated by conditions prevailing at various times of the normal open-water season during the last 3 years. The importance of the sea ice cover on the biology of the system is associated with the establishment of a 3-dimensional substratum on and within which a number of events of biological significance occur, culminating in the development of an ice flora. It is also, when snow-covered, a barrier to the entry of light to waters beneath the ice, hence often an inhibitor of pelagic plant growth. It is obvious therefore that the extent of sea ice cover both in space and time and the nature of its snow cover are highly important features of a far northern marine environment, from the point of view of the biology of the system. It would appear to be no less important in the Beaufort Sea than elsewhere.

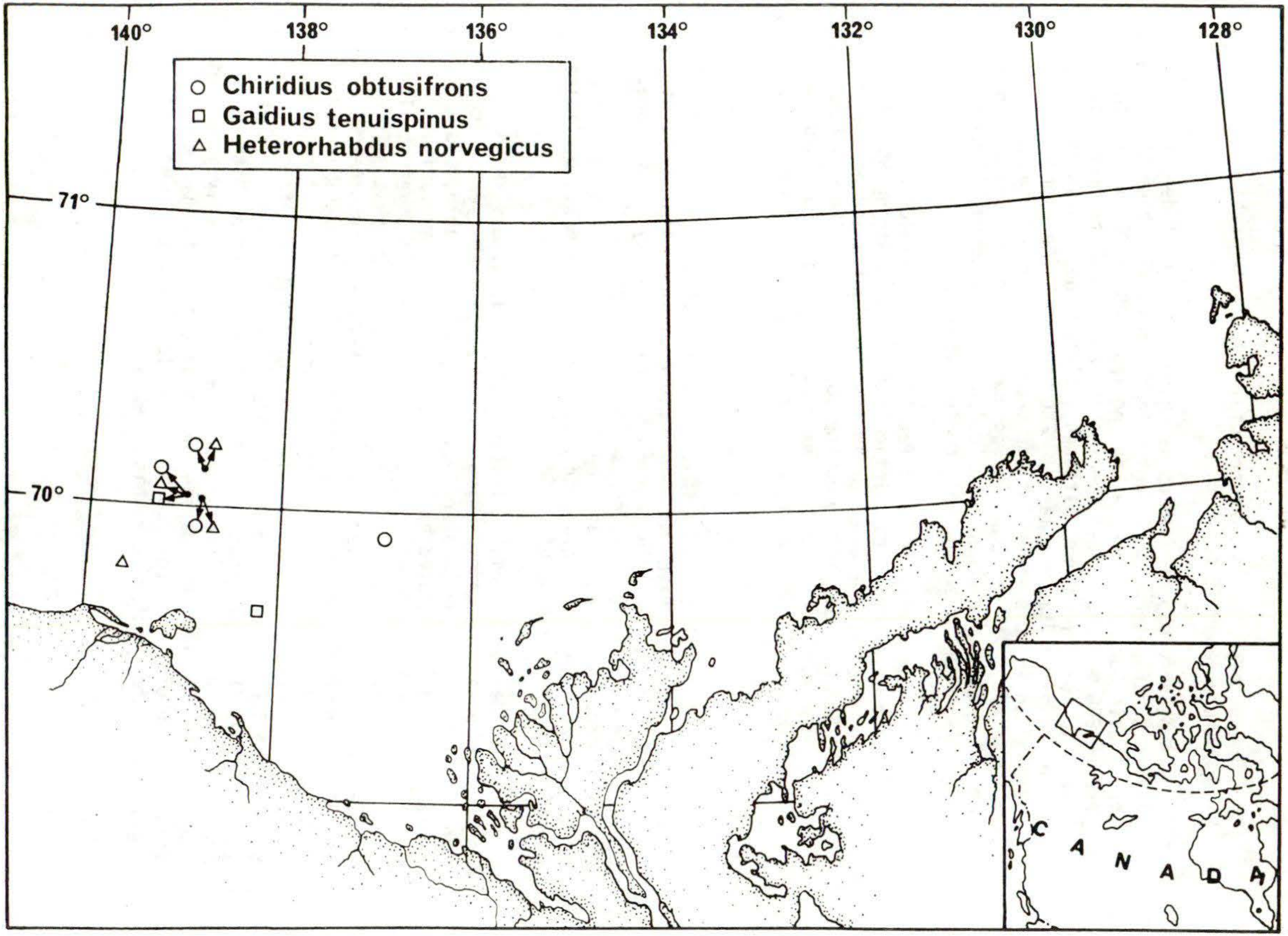

Figure 38. The distribution of Atlantic zooplankton species.

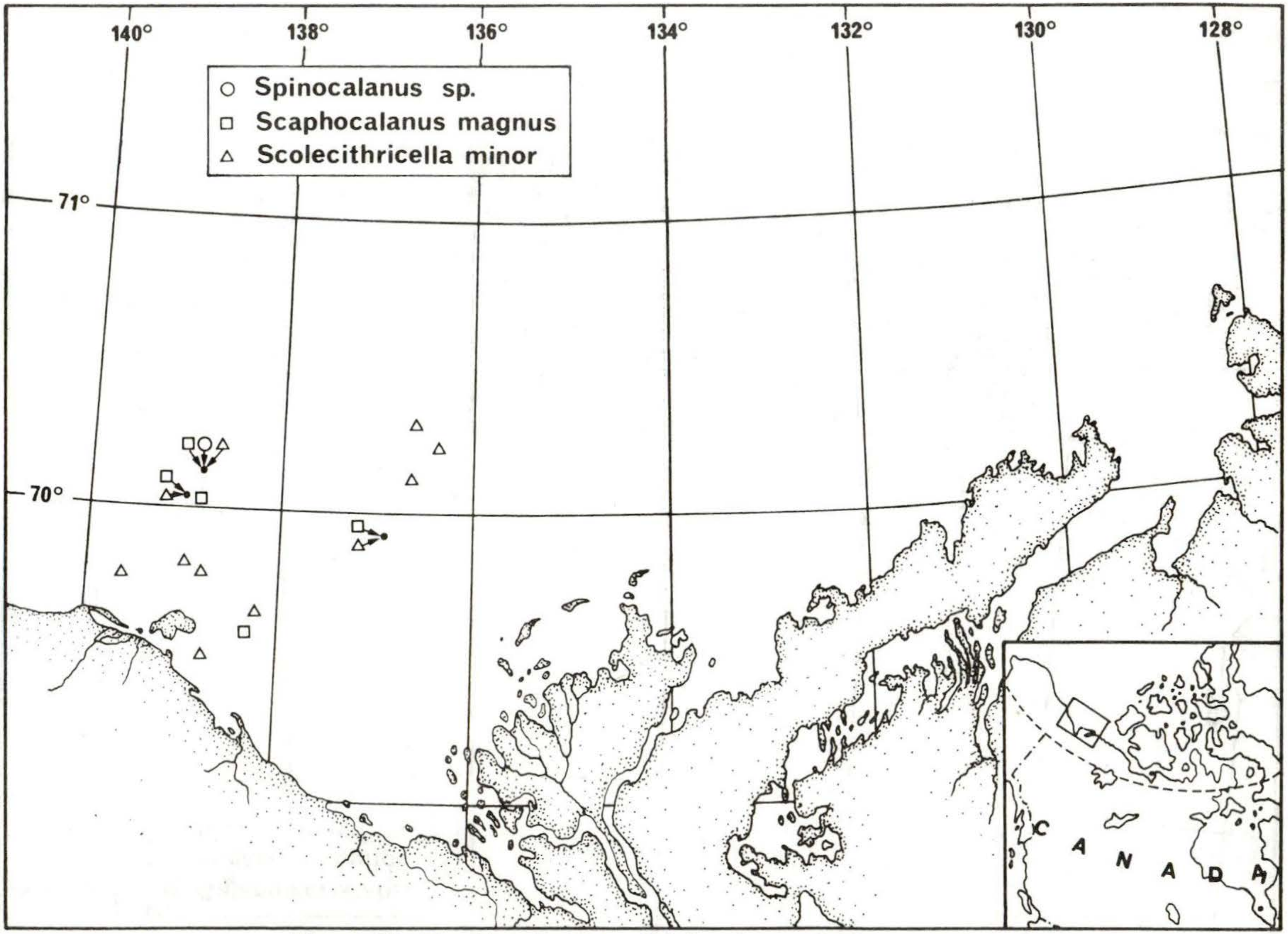

Figure 39. The distribution of Atlantic zooplankton species.

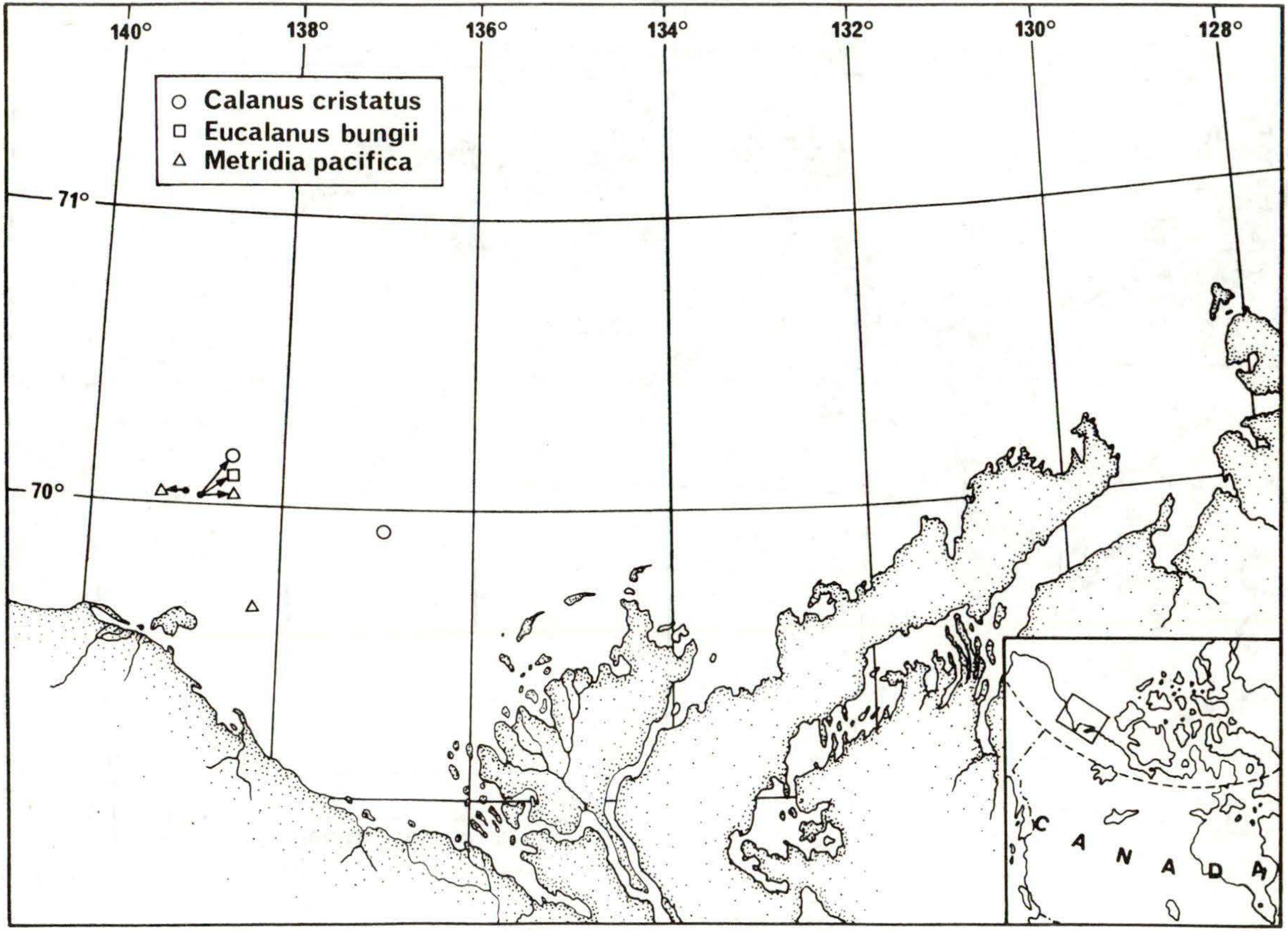

Figure 40. The distribution of Pacific zooplankton species.

The timing of cyclical events and the magnitude of activity of the biological component of arctic seas is largely controlled by the availability of light and nutrients. Light may be prevented from penetrating the sea surface by a cover of ice and snow, variations in the duration of which, within limits, may alter light supply sufficiently to modify underwater biological activity rates. It is also apparent that the plants of arctic seas are adapted to the oscillating light which the normal annual cycle under ice-covered seas provides. The ice flora appears to be adapted to an exceptionally low quantity of light (Bunt 1964; Apollonio 1965). The first phytoplankton to appear in spring, often under the ice, is adapted too, to low light intensity, but to higher levels than the ice flora (Steeman Nielsen and Hansen 1959; Bursa 1961). These steps in the appearance of the annual plant bloom represent a succession of plant forms adapted to different light ranges. Progression through this series is essential for the completion of a normal arctic summer plankton production sequence. The winter sea ice cover which gradually breaks up and disappears by summer plays a dominant role in this succession. Adaptation to variations in the conditions of the ice cover can be made by the plants to at least the degree of variation brought about by natural annual fluctuations. Obviously there are more extreme fluctuations possible to which the plants could not adapt.

Another factor which affects the penetration of light below the water surface is the suspended particulate matter, evidently originating mainly from the Mackenzie River and occurring in the river plume in the south Beaufort Sea. This is a conspicuous feature of the region, when seen either from an aircraft or from the deck of a ship. The sea is conspicuously brownish in colour, and visibility through it is severely limited. Secchi disc readings permit calculation of light penetration beneath the sea surface in terms of percentage of light reaching the surface. It is indicated by these that under conditions of neutral wind effect, that is with the river plume extending out from the delta and veering, as a result of forces other than the wind, to the east along Tuktoyaktuk Peninsula, a light intensity as high as 100 lux seldom reaches to as deep as 1 metre below the surface within 20 to 40 miles of the delta and Tuktoyaktuk Peninsula coasts.

Most of the observed phytoplankton photosynthesis in Frobisher Bay, in the eastern Canadian arctic, was shown to take place at about 1000 lux and higher (Grainger, in press). The very minimum light requirement for photosynthesis in the sea ice was shown to be 66 lux by Clasby, Horner and Alexander (1971). The indication from these values is that the inhibiting effect of low light on potential photosynthesis, regardless of the level of plant populations in the plume waters, is very great, and that active photosynthesis is expected to be restricted to the top few centimetres of the water column at least in the innermost parts of the plume.

Light penetration was shown to increase gradually with increasing distance from the Mackenzie River mouths (Figure 4). A fairly abrupt increase is seen in the figure however about 50 miles from the river mouths, beyond which distance light penetration was much greater than nearer to shore. Only near those stations farthest from shore was subsurface light at all similar to what was found rather routinely in the eastern arctic in Frobisher Bay (Grainger 1971) where the depth of penetration of 1% of surface light between late June and early September (which includes the period of the phytoplankton bloom) was from about 15 to 25 metres.

The pattern of nitrate distribution in the waters near the surface (Figure 7) points to a contribution of the nutrient from the Mackenzie River. Reeder, Hitchon and Levinson (1972) showed a range of values over the Mackenzie drainage area of less than 0.2 to 12.4 ug-at/l, and in the Mackenzie where it enters the delta of 4.5 ug-at/l NO_3-N. These are fairly high levels, as high as the highest individual measurements made in the inner part of the plume in summer. They are interestingly higher than any measurements made in the drainage area of the Eskimo Lakes in late July (0 to 0.7 ug-at/l) and in the Eskimo Lakes themselves in summer (from unpublished data). Higher nitrate levels were found in May near the surface in and near Kugmallit Bay, where they reached 9.9 ug-at/l. These were collected near the end of the period of nutrient replenishment over winter, a period when there was little or no use by plants. They probably reflect a combination of replenishment within the sea and contribution from the Mackenzie River. Other May values, also large but not as great as those above, were taken farther from shore, and probably showed reduced Mackenzie River influence. The highest nitrate quantities of all were found in deep waters and reached almost to 16 ug-at/l. These were typical of deep quantities reported farther north in the Arctic Ocean (Gudkovich 1955; English 1961; Kinney, Arhelger and Burrell 1970). Quantities near the surface in the south Beaufort Sea were higher however than surface levels found at the Arctic Ocean stations. The general distribution of nitrate as shown here in the south Beaufort Sea is much like what was shown off Siberian river mouths by Codispoti and Richards (1968). River-contributed nitrate also was shown on the north Alaska slope (Hufford 1974).

Figures 7 and 9 show lowest surface nitrate values at the stations farthest from shore. These stations, which were not sampled at any time early in the year, are rather difficult to interpret. It is suggested however that low to virtually exhausted nitrates in the upper few tens of metres indicate an earlier production of phytoplankton in those depths. The development of density stratification in summer probably effectively prevents the rise of deeper nutrients to the euphotic layers during the remainder of the period of warm water. At such deep stations far from shore, a single period of drain on the nutrients available in the upper layers probably limits the production of the year to that supply of nourishment. At the time of sampling these stations, chlorophyll a was already fairly low, perhaps grazed fairly quickly.

Stations at intermediate distances from shore generally showed more variable surface nitrate values with a greater range than was found farther out and closer to shore. Many of these stations were variably inside and outside the plume. Inside the plume, nutrient enrichment during the open water period may take place directly from the river. Just outside the plume, it is suggested that summertime nutrient replenishment may occur at the surface as a result of deep water entrainment by the outflowing surface water, and the gradual rise of this towards the surface by movement along the underside of the freshwater wedge. Light available beneath the surface of these stations during the open-water period also was variable, depending upon fluctuations in the extent of the plume. It was often low however, and as calculated above for the stations nearer shore, may seldom have exceeded 100 lux below about 3 metres. This is shallow light penetration, and almost certainly severely inhibits primary productivity as far as 50 miles from shore.

Phosphate does not repeat the picture shown for nitrate. The range of values was far less and the pattern of distribution over the south Beaufort Sea nothing like as clearly defined (Figure 11) as it appeared to be for nitrate. Highest surface values were in and near Mackenzie and Kugmallit Bays, but they were only a little higher there than at stations farthest from the river mouths. The range of PO_4-P found in the Mackenzie drainage area by Reeder, Hitchon and Levinson (1972) was less than 0.10 to 0.95 ug-at/l, and at a single Mackenzie River station at the base of the delta the phosphate level was less than 0.10 ug-at/l. The last of these is especially low, and it and the maximum quantity recorded up the river are less than the maximum surface quantities of nearly 1.5 ug-at/l found off the river mouths in the south Beaufort Sea. This is in contrast with nitrate results which showed similar levels in the river and off the mouths of the river in the sea. These figures are not conclusive, but it is possible that the Mackenzie River may be a more important source of nutrient nitrogen than of phosphorus, at least at certain times of the year. This is further indicated by some early May observations from coastal waters in and near Kugmallit Bay which showed phosphate levels of 0.13 to 0.17 ug-at/l only, at a time when nitrate had reached exceptionally high levels. Phosphate measurements made in April and May farther from shore but in the same general area showed higher quantities of phosphate near the surface, levels similar to those found in

Kugmallit Bay considerably later in the season. These data are not easily interpreted, but they allow the suggestion that phosphate replenishment within the marine system may be relatively more important at the same time as the river is relatively less important for phosphate than for nitrate. Additional support comes from Hufford (1974) who showed that river-contributed phosphate was low in summer on the north Alaska slope, while both nitrate and silicate were relatively more abundant.

Phosphate in the surface waters of stations farthest from the river mouths was relatively high, while nitrate at the same time and place was low. There was nevertheless evidence of phosphate depletion in the upper 20 metres from where nitrate was almost totally exhausted. Evidently a residue of unused phosphate remained. At the intermediate stations, phosphate was low, entirely consumed in the upper 5 metres of several of the stations at times when nitrate existed in positive and rather variable quantities. Perhaps nitrate had been replenished at the surface by such means as the entrainment process, suggested above. Evidently phosphate had not, or it had been consumed quickly as it was replaced. Near the delta relatively high values of phosphate in the shallow, almost fresh water probably reflected at least some degree of Mackenzie contribution. Utilization by plants, as with nitrate, was probably very low there because of lack of light in the highly turbid waters.

The vertical structure of phosphate (Figure 14), showing maximum quantities between 100 and 200 metres (reaching to more than 1.6 ug-at/l) and about one half maximum values in deeper water, is similar to conditions shown from farther north in the Arctic Ocean by Gudkovich (1955), English (1961) and Kinney, Arhelger and Burrell (1970). Compared with the data presented by Codispoti and Richards (1968) from off Siberian rivers, the south Beaufort Sea phosphate levels are low, at the surface and below. It is noteworthy that nitrate was found in similar quantities off the Mackenzie and off the Siberian rivers, while phosphate was distinctly less abundant in the south Beaufort Sea.

Silicate-silicon in the surface waters shows a pattern rather more like that of nitrate than of phosphate. Values in the Mackenzie plume were higher than those outside it. Silicate in the Mackenzie drainage area (Reeder, Hitchon and Levinson 1972) ranged from 5 to 127 ug-at/l. In the river, at the base of the delta, a quantity of 58 ug-at/l Si was reported. These are higher than the maximum levels found near the surface in inshore waters in summer, which were around 35 ug-at/l, and they are in fact higher than maximum deep offshore values which reached to little more than 40 ug-at/l.

The vertical structure compares closely with data from the Arctic Ocean (Gudkovich 1955; English 1961; Kinney, Arhelger and Burrell 1970), in all but values near the surface, which were notably higher in the south Beaufort Sea. The Beaufort Sea summer range was similar to what Codispoti and Richards (1968) found in coastal Siberian waters.

Of the three nutrients considered here, nitrate is probably the most important, at least in the waters outside the plume, in limiting plant production in surface waters. When nutrients are depleted in such waters during the summer when vertical density stratification is strongly developed, plant production must cease until by some means replenishment of the required nutrients is brought about. It is likely that in situ regeneration takes place too slowly to have any significant effect during the course of a single open-water period. In the outer reaches of the plume, observations of totally exhausted phosphate in the euphotic zone indicate phosphate as a limiting factor there. This is not however entirely clear. Just off the delta, all nutrients seem to be in sufficient supply at all times of the summer. Surely nutrient deficiency is not a limiting factor there, where light is probably the main factor limiting the primary productivity rate. Silicate evidently is not limiting anywhere in the region.

The pattern of dissolved oxygen distribution in waters near the surface (Figure 19) showed a regular trend of lowest values near the delta and highest levels farthest from the coast. Brunskill, Rosenberg, Snow, Vascotto and Wagemann (1973) gave dissolved oxygen figures for the Mackenzie drainage area and Kugmallit Bay, and showed generally lower levels in the river channels than off the river mouths in the sea. This trend appears to be extended to the offshore waters.

Oxygen in the sea is controlled by plant production, animal consumption and exchange across the air-sea interface. It varies seasonally. This is not brought out clearly by the pattern in Figure 19, but is shown by some of the 1975 data which were not included in the figure. In the offshore area indicated by values higher than 9 ml/l in the figure, observations made in August of 1975 showed levels there reduced to as low as about 7.5 to about 8.5 ml/l. In fact, earlier observations in the offshore waters showed values reflecting conditions early in the summer production period, which was late in 1974. Happening earlier in 1975, in accordance with earlier ice removal, summer production evidently had peaked in the offshore waters by August, and oxygen levels had declined.

The distribution of consumers (zooplankton) would suggest more oxygen consumption outside the 8 ml/l line in Figure 19, that is in the outer portion of the plume and outside it, than nearer the delta. Highest oxygen values in the same region, in spite of probably greater oxygen use there, points to greater oxygen production in those waters than nearer shore. This, of course, follows the expected pattern as shown by available light in sub-surface waters.

The vertical structure of dissolved oxygen (Figure 21) shows very close similarity to the curves from farther north in the Arctic Ocean in Kinney, Arhelger and Burrell (1970). The main divergences from the pattern are the inshore stations of low oxygen shown in Figure 20.

Quantities of plant material and amounts of photosynthetic activity under single square metres of sea surface may not necessarily show a close relationship. There are several reasons for this, among them the availability of light and nutrients. Large populations of plants may reflect past rather than contemporary conditions of growth and destruction (grazing), and show that favourable conditions prevailed formerly at least, but not necessarily that they continued until the time of sampling. Small populations may mean poor growth conditions in the history of the population, or they may be the consequence of heavy grazing on a primarily large population no longer able to grow rapidly enough to maintain high levels. Chlorophyll a values shown in Figure 22 may give us an indication of plant quantities in the surface waters of the study area, but there are no good grounds for using them to interpret activity rates at the times of sampling. The oxygen distribution map (Figure 19) may in fact approximate far more closely the trends in surface water plant production rates, and used in conjunction with Figure 22 indicate that the relatively high chlorophyll levels of the delta waters do not necessarily signify a correspondingly high photosynthetic rate. At the same time, offshore waters in which chlorophyll levels are lower than nearer to shore may be producing at a greater rate than those closer to the delta.

It is held nevertheless that chlorophyll a values may be used to indicate standing stock levels, if not to reflect photosynthetic rates, and therefore that they may be used to compare phytoplankton quantities in different waters. Figure 41 shows chlorophyll a levels measured at various dates in the Beaufort Sea, and expressed as mg/m^2 in the upper 20 metres. The Beaufort Sea values, given by the same symbols as were used in Figure 1, were highest in late June and early July, lower and very variable in late July and August. Superimposed along the same time scale are curves of comparable values from the adjacent Eskimo Lakes and from Frobisher Bay, the latter in the eastern Canadian

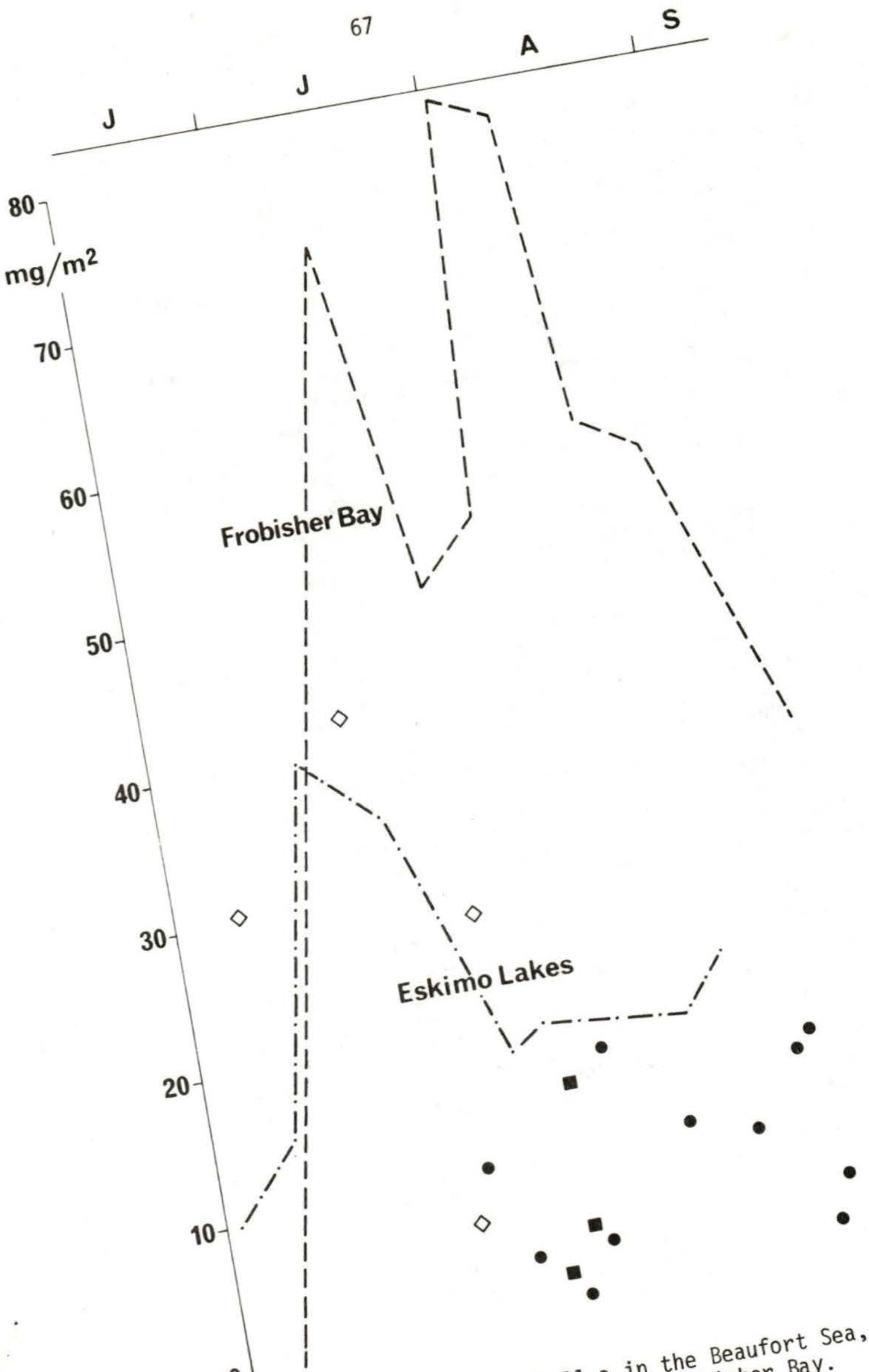

Figure 41. Chlorophyll a in the Beaufort Sea, Eskimo Lakes and Frobisher Bay.

arctic (data from Grainger and Lovrity 1975 and Grainger 1971a). The Eskimo Lakes levels were not greatly different from those in the Beaufort Sea, although rather higher in late summer. Quantities in Frobisher Bay however were far higher in general than in the Beaufort Sea, with the curve moved somewhat to the right along the time scale. The Frobisher values are higher than those from the Beaufort Sea by a factor of 5 to 10.

In Frobisher Bay an annual phytoplankton production rate expressed as 50 to 100 g carbon per m^2 per year has been described (Grainger in press). Without trying to relate plant stock to phytoplankton rate in strict numerical terms, it remains reasonable however to assume a significantly lower production rate for the South Beaufort Sea than for Frobisher Bay on the basis of compared standing stocks of primary producers.

There is at the present time a virtually complete lack of hard information on the flora of the sea ice of the south Beaufort Sea. Certain inferences can be made on the basis of information available from the Eskimo Lakes and the inshore sea off Point Barrow, Alaska. Clearly it plays a role in the economy of the Beaufort Sea. Noted initially in the antarctic, probably the first reference to the under-ice flora of the arctic was Bursa's (1963) from off north Alaska. Meguro, Ito and Fukushima (1966) also described the ice flora and associated features from north of Alaska. They showed it to be a vital community, consisting of diatoms. Later, Horner and Alexander (1972) found a more varied flora and associated fauna. They discussed diatoms, dinoflagellates, flagellates, ciliates, heliozoans, nematodes, polychaete larvae and a copepod, and showed that the copepod and worms were feeding on other organisms, mainly diatoms.

The relationship between the ice flora and the spring phytoplankton, which often develops under the ice, is not yet clear. Meguro, Ito and Fukushima (1967) claimed that there was a direct connection between the release of plants from the lower surface of melting sea ice and what they evidently thought to be the initiation of this by the phytoplankton bloom under the ice. Alexander (1974) claimed however that the release of ice plants to the water was not a trigger for the phytoplankton bloom, on the basis of differences in the composition of the two floras and the existence of a time lag between the end of the ice bloom and the beginning of the water bloom. This is a problem which clearly requires a solution.

Whether or not the ice flora "seeds" the phytoplankton bloom, it is concerned with an important trophic sequence including the forms listed by Horner and Alexander above and additional copepods, amphipods and fishes. The arctic cod (*Boreogadus saida*) the most abundant small pelagic fish known from the whole of the Canadian arctic, and frequently found in association with sea ice, is obviously bound to this trophic series which starts within the sea ice.

The numbers of zooplankton species found in different parts of the study area reflect mainly salinity-temperature barriers to the various populations associated with specific kinds of environments. The total number of species reported (at least 92) is large for an arctic region of this size. In fact, the study area represents, as was pointed out in earlier sections of this report, a two-layer estuarine system. The total salinity range of zero to more than 34‰ and the temperature range of less than -1°C to nearly 18°C encompasses environmental conditions reaching from river mouth to Arctic Surface water, at the surface, and to Atlantic water at depth.

Inshore stations in Mason Bay and Tuktoyaktuk Harbour and in Liverpool Bay supported the greatest number of organisms, represented however by only 4 copepod species (and by only 5 species of all groups). *Acartia clausi* and *Eurytemora herdmani* were very abundant, *Pseudocalanus minutus* somewhat less so and *Limnocalanus macrurus* next.

Stations with the next largest numbers of individuals were located off Tuktoyaktuk Peninsula, and they supported mixed populations of estuarine and normally more offshore species. The stations farthest from shore, and with the smallest apparent standing stocks were the deepest ones. They showed low standing stocks, in contrast with their large species diversity. At those stations the large numbers of species, most of them at depth, were consistently represented by small numbers, and the few species of the upper 50 metres were also represented by far smaller numbers than were found in the mixed surface waters closer to shore. Smallest stocks certainly are characteristic of the river mouth region.

The species reported here (Table 1) include all but 4 known formerly from the south Beaufort Sea (Grainger 1965). They are the hydrozoans *Eumedusa birulai* (Linko) and *Ptychogena lactea* Agassiz, the ctenophore *Mertensia ovum* (Fabricius) and the amphipod *Hyperoche medusarum* (Krøyer).

The total standing stock of zooplankton, expressed as mg/m^3, is shown along with comparable numbers from Frobisher Bay in the eastern Canadian arctic (Frobisher data from Grainger (1971a)) in Figure 42. Apart from 6 collections, one in Liverpool Bay, one in Tuktoyaktuk harbour and 4 made in 1971 off the north coast of Tuktoyaktuk Peninsula, numbers of individuals were small in the

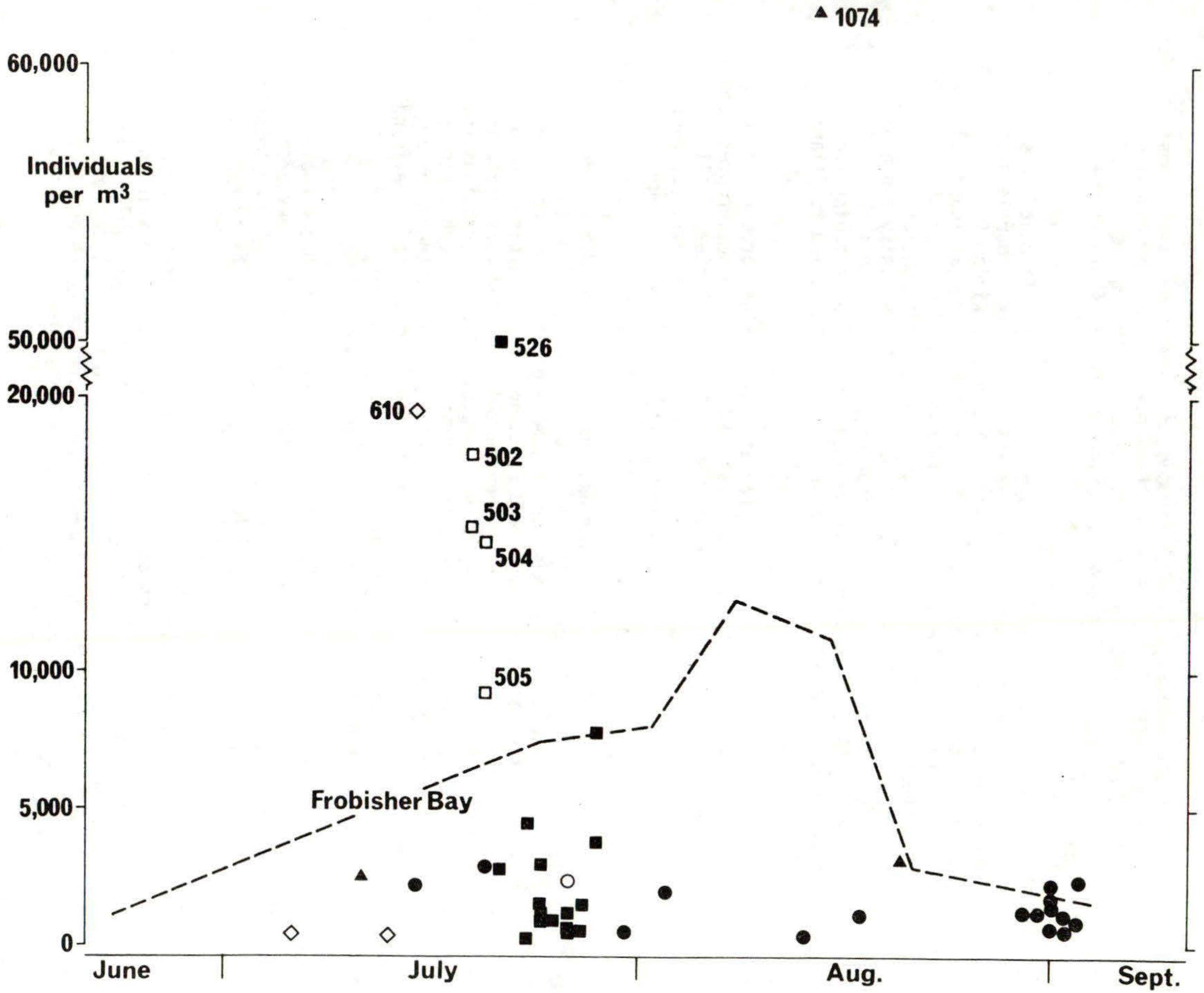

Figure 42. Zooplankton concentrations in the Beaufort Sea and Frobisher Bay.

south Beaufort Sea, and very much smaller than were found in Frobisher Bay. Indicative of the nature of the large populations found in the high density inshore stations is the dominance of single species at those stations. At station 61-1074, for instance, more than 53000 of the approximately 63000 organisms collected were *Acartia clausi* copepodites and unidentified copepod nauplii, probably most of them *Acartia*. At station 73-526, there were more than 43000 *Cyclops* in a total animal count of a little more than 49000.

The 1971 stations may be used to illustrate an important feature of the south Beaufort Sea which was referred to often above. This is the fluctuating balance between the Mackenzie River output to the sea and the counter force of the offshore waters. Controlled mainly by variations in the wind and in river flow, the river plume changes constantly, and the balance between brackish and high-salinity organisms shifts accordingly. Such fluctuations in conditions increase the problems of describing the environment satisfactorily and mean that brief and infrequent periods of observations may be even less useful in the Beaufort Sea than in other, more stable regions. In 1971, for example, stations 502 and 504 were sampled on 18 and 19 July off the coast of Tuktoyaktuk Peninsula. In 1973, stations 528, 529 and 530 were sampled on 22 and 23 July. Geographical locations and times of the year were close. Temperature and salinity data from the two sets of observations are shown in Figure 43. The two sets of data differed without overlap in their combined T-S properties. The water in 1971 was of high salinity and cool; in 1973 it was of low salinity and on the average,warmer. Observations made in 1973 followed a period of settled weather, under which the river plume would be expected to extend well off the delta and the coast of Tuktoyaktuk Peninsula. Conditions found in 1971 suggest that northerly winds had influenced the region before the collections were made, driving offshore water into the observation area.

Table 2 shows the species composition at the two groups of stations. The 21 species of 1971 included 15 not found in 1973, and among the 12 species of 1973 there were 6 species not found in 1971. Nearly all the species taken only in 1971 are associated with waters found farther from shore at other times, and they are normally found in salinity and temperature conditions indicated by the lower right quadrant of Figure 43. In contrast, at least 5 of the 6 species taken only in 1973 are associated with inshore river-mouth waters and are usually found in salinity and temperature conditions indicated by the upper left corner of Figure 43. Species common to the two years, only 4, have generally wider T-S tolerance than the exclusive 1973 species, but they are characteristically associated with waters of fairly low salinity.

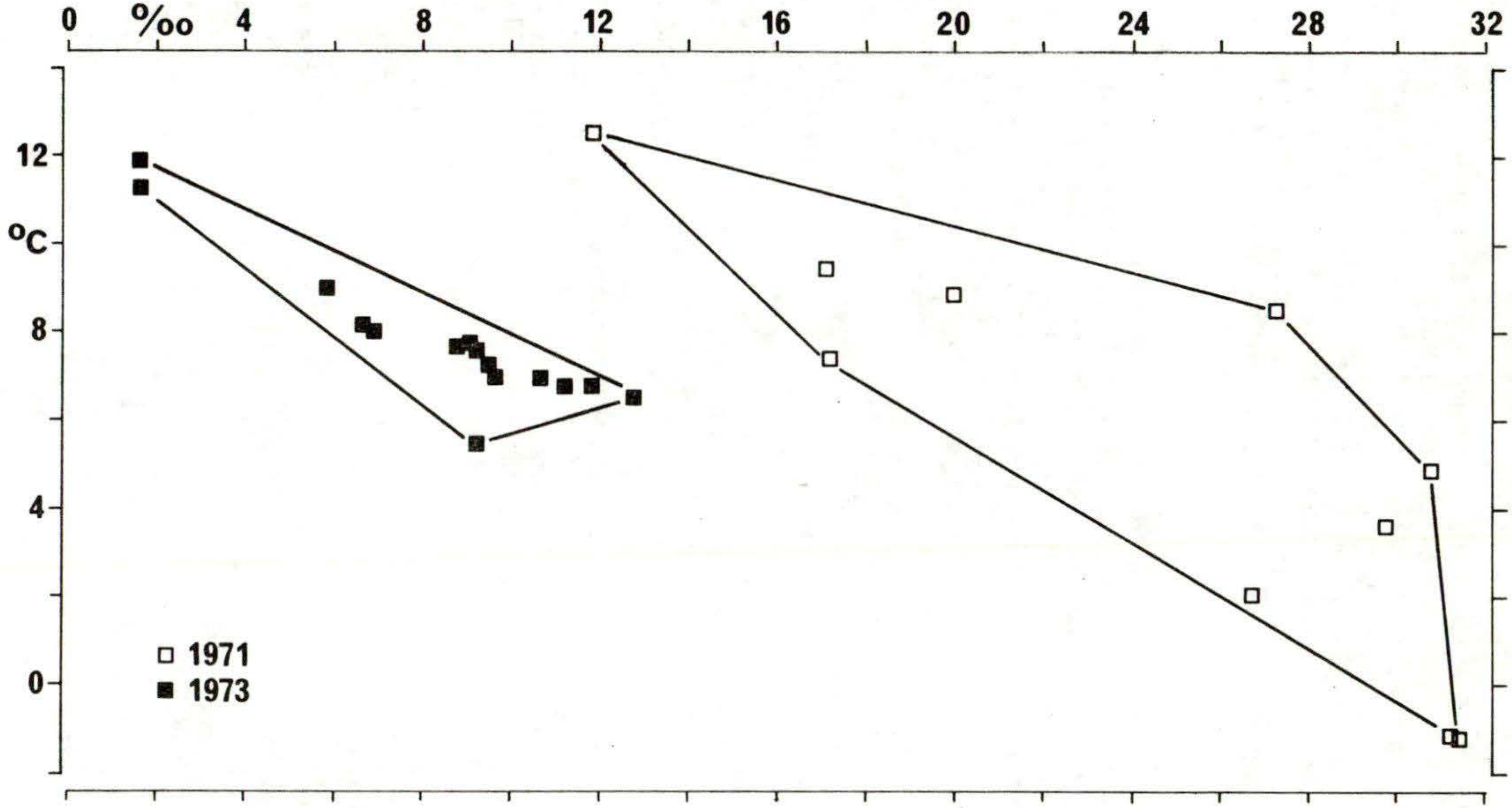

Figure 43. T-S diagram of conditions off Tuk Peninsula in 1971 and 1973.

Table 2. Zooplankton species taken off Tuktoyaktuk Peninsula in late July of two years.

Stations 502, 505 (1971)	Stations 528, 529, 530 (1973)
-----	1. Halitholus cirratus
1. Aglantha digitale	-----
2. Aeginopsis laurenti	-----
3. mollusc larvae	-----
4. unidentified annelids	2. polychaeta larvae
5. Acartia clausi	3. Acartia clausi
6. A. longiremis	-----
7. Derjuginia tolli	-----
8. Calanus glacialis	-----
9. Calanus hyperboreus	-----
10. Limnocalanus macrurus	4. Limnocalanus macrurus
11. Metridia longa	-----
12. Microcalanus pygmaeus	-----
13. Pseudocalanus minutus	5. Pseudocalanus minutus
-----	6. Eurytemora herdmani
14. Oithona similis	-----
15. Oncaea borealis	-----
-----	7. Cyclops sp.
-----	8. Cyclopina sp.
16. Copepod nauplii	9. Copepod nauplii
17. Cirripede larvae	-----
-----	10. Mysis sp.
-----	11. Diastylis sp.
18. Monoculodes sp.	12. Monoculodes sp.
19. Eukrohnia hamata	-----
20. unidentified chaetognaths	-----
21. Oilopleura vanhoeffeni	-----

What is shown by the example is that had only the 1973 observations been made off Tuktoyaktuk Peninsula, the waters there could have been interpreted as supporting a sparse fauna of only brackish-water species. In the same way, observations made in 1971 could have prompted the conclusion that the same geographical location supports a rich and diverse fauna. What emerges instead, of course, is that this site supports faunas of both kinds at various times.

8. CONCLUSIONS

1. The biological nature of the Beaufort Sea is very much dependent upon the balance between Mackenzie influences and those of the offshore marine element. The typical river mouth structure of water of river origin and of low salinity overlying water of oceanic origin and of high salinity is shown in the Beaufort Sea, where the balance between these factors is in a constant state of flux and where variations in their ranges determine the distribution of many of the biological elements.

2. The sea ice cover is essential for the system. Variation in its thickness, extent and duration influence primary and successive levels accordingly.

3. Light availability to waters beneath the surface in the Mackenzie plume is low, with the compensation depth probably occurring within a few centimetres of the surface. This is variable, depending on the position and extent of the plume and the sea ice cover.

4. Nitrate-nitrogen is contributed to the plume area from the Mackenzie River. Inshore waters appear to retain a high level of nitrate, where consumption by plants is low. Waters farthest from shore, beyond the river plume, show depletion of nitrate during the summer productive period.

5. The Mackenzie River is probably not as important a source of phosphate-phosphorus as it is for nitrate.

6. Nitrate supply seems to be the major factor limiting primary production in waters outside the plume. No apparent mechanism exists for rapid replenishment during the summer growth season. Within the outer part of the plume conditions are less clear. Total elimination of phosphate suggests it may be the limiting nutrient there, but the available information is insufficient. Silicate is obviously in sufficient supply everywhere in the study area, hence nowhere a limiting factor.

7. Oxygen distribution shows lowest quantities in association with river outflow and increasing amounts seaward from the river mouths.

8. A similar pattern is inferred for photosynthetic rate, the lowest activity occurring in the turbid waters nearest to the river mouths, and the rate increasing towards the outer edge of the plume, mainly controlled by the availability of light.

9. Chlorophyll levels are low in the south Beaufort Sea, compared with other marine locations in high latitudes. On the basis of low chlorophyll and generally low light availability, a low annual primary productivity rate is indicated, even by arctic marine standards.

10. Data on the sea ice flora are almost totally wanting from the Beaufort Sea. Such a flora exists however and, from knowledge of the flora and its conditions of growth and relevance to the ecosystem elsewhere in the arctic, it may be inferred to be potentially important in the south Beaufort Sea. It almost certainly plays a highly significant role in the trophic sequence which involves pelagic fishes and their predators.

11. Zooplankton is well known in the south Beaufort Sea, and at least 95 species make up several quite distinct groups, on the basis of salinity-temperature ranges. Included are the almost freshwater species of the river mouth areas, the brackish species of surface waters of the river plume, the offshore, Arctic Surface species, and the underlying Atlantic water species found on and outside the slope. The deep, offshore waters support the most diverse fauna, which is sparse in quantity. The most dense concentrations of zooplankton occur either in small shoreline bays or in the region of mixed surface water (river plus offshore elements). The sparsest fauna and the poorest in variety occurs close to and in the Mackenzie River outlets to the sea. Standing stocks of zooplankton in the south Beaufort Sea are generally low by world standards.

9. IMPLICATIONS AND RECOMMENDATIONS

The Beaufort Sea appears to support at best a fairly low rate of primary and secondary production. This is probably subject to considerable annual variation, being influenced by variable sea ice conditions. It is also probably subject to variations associated with modification in river outflow and in climatic, mainly wind, conditions. Exhibiting perhaps more natural variation than many comparable marine regions, it is therefore all the more difficult to define in terms of "normal" state.

The pattern of water movement in the south Beaufort Sea, being governed as it is by an estuarine circulation system powered by river outflow and by a counter force from seaward, involving highly variable wind factors, is important in assessing impact effects. One might look, under these circumstances, for a greater spread of an impact effect than would be found in a physically simpler system.

Such a spread of a harmful impact would be expected to have especially undesirable effects on a biological system like this one, which may be especially vulnerable. It is suggested that estuarine biological systems may be in some ways the most fragile of arctic marine systems because, although they have wide temperature and salinity tolerance, they are not tolerant to full sea salinity and therefore they are dependent upon continued and almost unaltered river flow. River flow in this region is certainly far from unaltered over the year, and the results would be expected to show in a large annual variation in the size and extent of the plume. Unfortunately this has not been well demonstrated because of the small number of observations made other than in July and August. The essential estuarine nature of the fauna is dependent upon there being a plume at all times, and its disappearance, for even a short time, would effectively wipe out the special fauna of the estuary.

The Beaufort Sea is a sump to the Mackenzie River. Therefore, it is not only influenced by variations in volume of river flow, but it is vulnerable too to qualitative changes in the river water. Among possible harmful additives to the Mackenzie River is oil, the spread of which over the area of the plume could be great and exposure to it by all levels of the biological system immense.

Different parts of the ecosystem will vary in their vulnerability to oil impact, whether the oil reaches them from the river or shore or from far off shore. The plankton are probably among the least vulnerable, in the sense of immediate effects, of all the biological elements because of their 3-dimensional distribution pattern. They may avoid the upper surface of the sea, the bottom, the shore line and most surfaces on which oil tends to collect. Almost certainly the lower surface of the sea ice is highly susceptible to the effects of oil. Deterioration of the substratum and disruption of the trophic relationships alone would descroy the biological system beneath the ice, and with it the farther reaching ecological relevance of the under-ice biota.

Although quantitatively low, the primary production in the water and in the ice serves as the base of a food structure which supports fish and mammal populations. The relatively simple population structure of the inshore waters in particular suggests a relatively uncomplicated food chain, and this means fewer but relatively more important links in the chain and greater vulnerability on the whole than one would expect in a more complex web. Perhaps the commonest trophic sequence reaching the highest levels is diatom (water or ice) - copepod - fish - mammal. There are more complex chains than this, but it is probable that the lines are usually short and have few links and that the options are few. One of the main routes of course for the extension of oil effects through the system is along food chains.

Specifications of requirements for the assessment of impact effects upon an ecosystem are immensely difficult to present. Part of the problem is associated with the complexity of interactions within even simple arctic systems and our lack of deep and detailed knowledge of most of the factors which make a system like this one go. This is slowly accumulated knowledge, and it is regrettable that it is not being put together as rapidly as it is required for impact assessments. It is unfortunate that the present approach to problems of this kind is not designed to bring rapid progress. The recent history of marine environmental impact studies in the Canadian arctic has included a series of short-term investigations, too brief, too hurried and too restricted in funds to allow more than very superficial assessments to be made. In the Beaufort Sea, we face the possibility of exposure of the marine ecosystem to oil. We know that some of the effects of oil on biological components of the system are harmful. We know of none which are unquestionably beneficial. We are a very long way from having any good understanding of the overall effects upon the ecosystem. There is a great need to overcome this deficiency, and if realistic environmental impact assessments are to be made it must be overcome.

10. NEEDS FOR FURTHER STUDY

With respect to impact assessment, we require development of an understanding, which we do not have at present, of what the impact does to the ecosystem as a whole. This is a problem considered apart from studies on direct effects on individual components of the system. The questions which arise here are concerned with total effects.

There are many needs for further study. The data base should be expanded in both time and space, to give year-round information from the full extent of the study area.

The physical side of the study should be supplemented to give good detailed information on water movements at all depths, in all seasons and under the full range of the principal external forces which govern them. In this way, the route of the impact may be predicted, the variable patterns of nutrient and plankton distribution may be described, and the interactions among them may be better understood.

Better knowledge of the ice cover is needed, both of its geographical extent and its structure and content. The ice flora and associated features require extensive examination over the full geographical and time ranges.

Trophic relationships need to be quantitatively described, to take into account especially the phytoplankton - zooplankton - fish - mammal, and the ice diatom - zooplankton - fish - mammal sequences. There are requirements to know the degree of trophic interdependance at all levels of the system, the available options in trophic pathways and the details of impact spread through the food chain.

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