ASPECTS OF SIZE DISTRIBUTIONS, CLAY MINERALOGY, AND GEOCHEMISTRY OF SEDIMENTS OF THE BEAUFORT SEA AND ADJACENT DELTAS, NORTH ARCTIC ALASKA

by

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INTRODUCTION

This report concerns primarily with the description of the surficial or near surficial sediments of the continental shelf of the Alaskan portion of the Beaufort Sea. The distributional patterns of the granulometric, clay mineralogic and chemical compositions of the surficial sediments are displayed on maps. The characteristics of the size distributions of particles are discussed in light of the present hydrodynamic and ice conditions and on the limited knowledge of the late Pleistocene history of the Beaufort Sea continental shelf. Clay mineral compositions are discussed in terms of the possible terrigenous sources and their dispersal by prevailing currents. Baseline concentrations and yearly fluxes of a suite of metals pertaining to sediments are established. An attempt is made to understand the partitioning patterns of the metals in various sediment fractions.

In this report an effort is made to relate the granulometric composition of surficial sediments to potential engineering hazards in the Alaskan Beaufort Sea. However, some of the foregoing discussions must be considered somewhat speculative, in view of the fact that no specific complementary measurements of the engineering properties of substrates were made. The potential usefulness of mapping the surficial geology of any marine area, to provide a basis for presenting and understanding some of the hazards that may be associated with engineering construction activities, was lucidly discussed (with special reference to the Canadian Arctic) elsewhere by Pelletier (1379).

Additional discussions in this report refer to the sedimentation rate measurements in the lagoons, possible mechanism for the unusual concentrations of sediments in sea-ice, and the origin and stability of the barrier island-lagoon systems.

This report should provide baseline data to detect and, possibly also provide criteria to predict impacts of anthropogenic activities in the North Arctic Alaska.

Salient features of the regional climate, geology and hydrography for the Beaufort Sea nearshore, North Arctic Alaska were earlier summarized by Naidu and Mowatt (1974) and Northern Technical Services (1981), and therefore these will not be repeated here.

MATERIALS AND METHODS

All data available since 1972 (Dygas *et al., 1971;* Tucker, 1973; Barnes, 1974; Alexander et al., 1975; Naidu, 1979, 1982; and Naidu and Mowat t, 1974, 1975a, 1975b, 1976 and 1982) on the size distributions of sediments were collated and integrated into this paper. The textural data gathered by Carsola (1954), however, were purposely excluded because the calculation of grain size statistical parameters by him were based on Inman's method (1952), which was significantly different than those adopted since 1970 (e.g., Folk and Ward, 1957). This synthesis is based on size analysis of 330 grab or core top sediment samples from the open Beaufort Sea (Fig. 1), and about 100 analyses of grab sediment samples and 10 vibrocore samples from the deltaic environment (e.g., lagoons, sound, bays, beaches, dunes, etc.). The locations of the latter suite are shown in Figures 2a, 2b, 3, 4 and 5a. The granulometric analyses were achieved by the usual sieve-pipette technique (Folk, 1968). Each of the values of gross textural attributes (e.g., percentages of gravel, sand, silt, clay

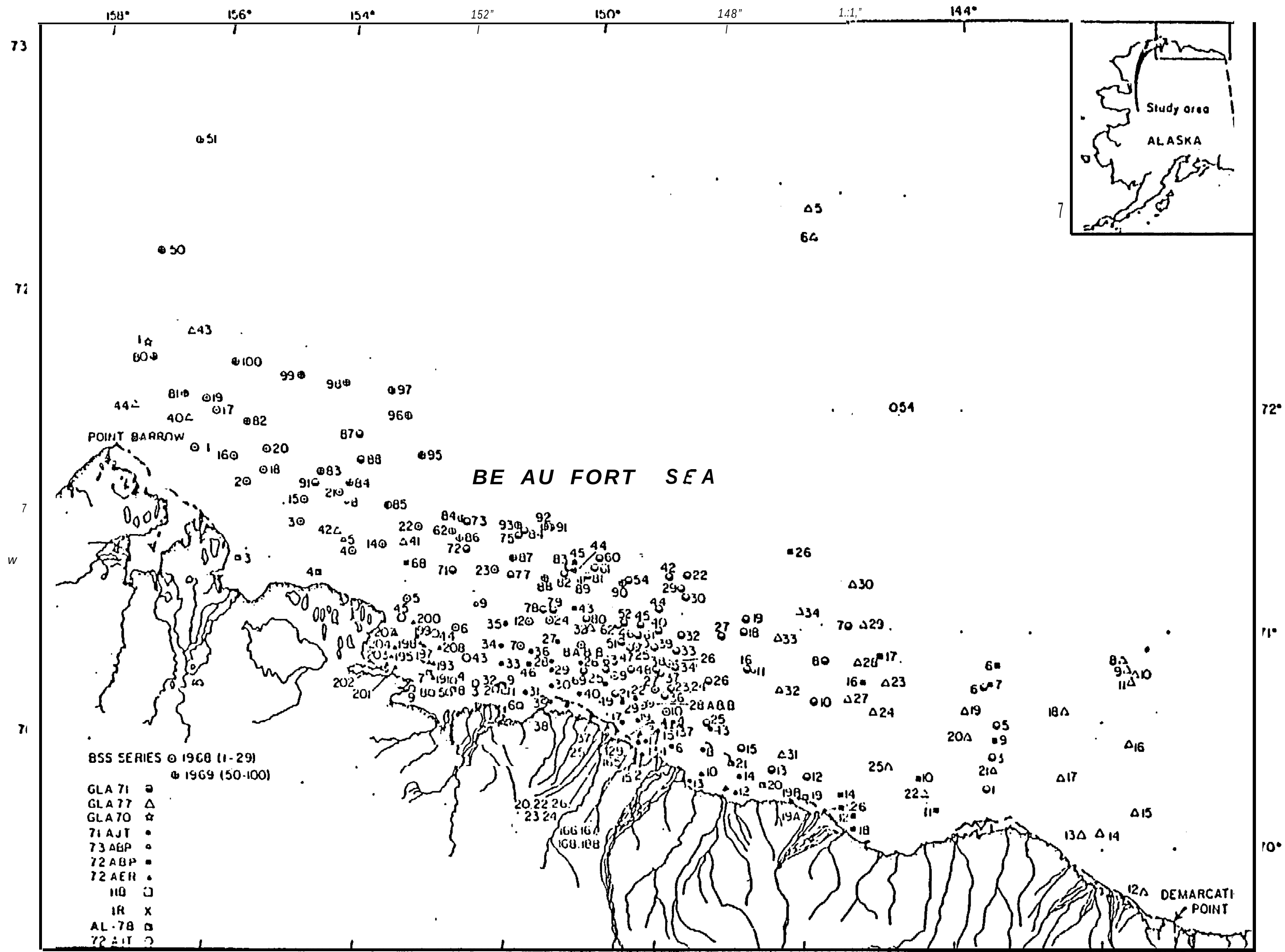

Figure 1 . Station locations for Beaufort Sea.

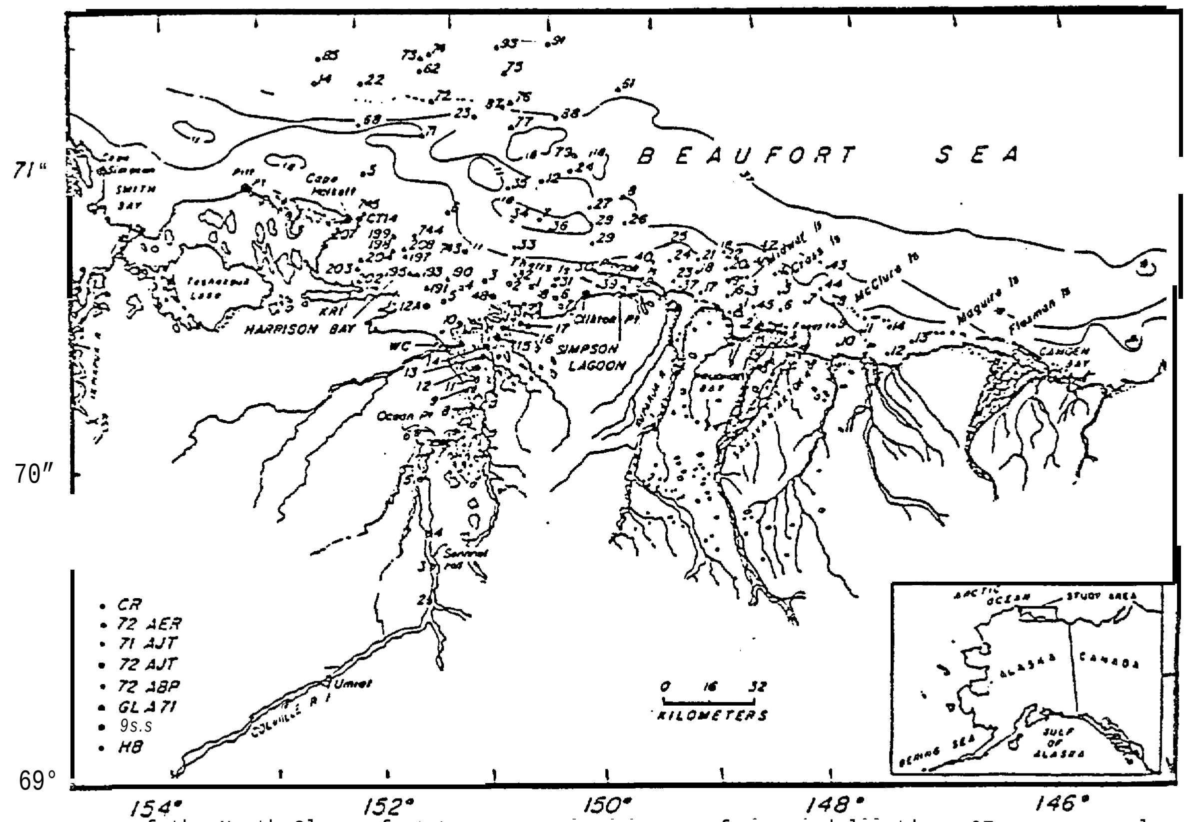

Figure 2a. Map of the North Slope of Alaska, showing the deltaic area of study and locations OF sediment samples. The depth contours are in meters.

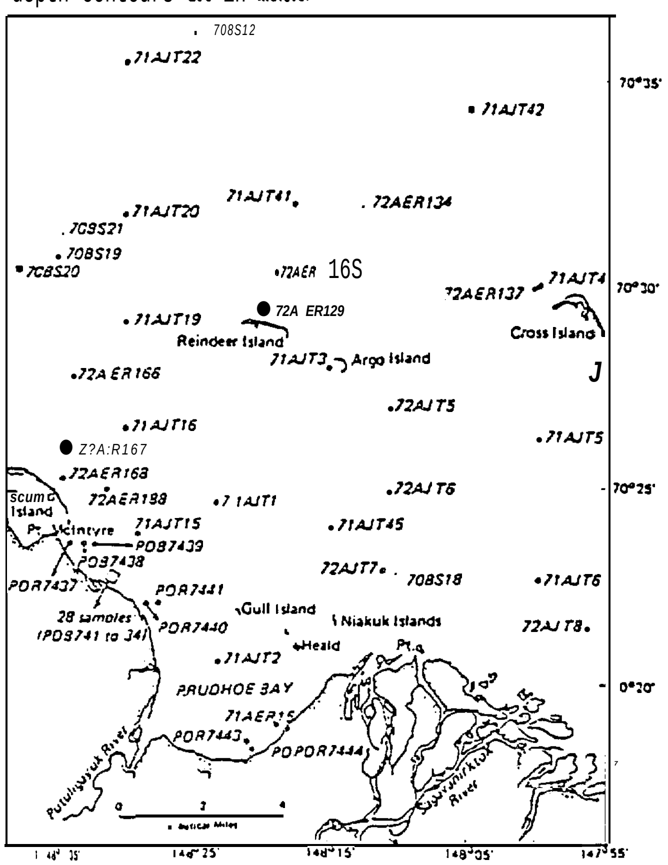

Figure 2b. Locations of sediment samples in the Prudhoe Bay and adjacent shallow marine environment of north arctic Alaska.

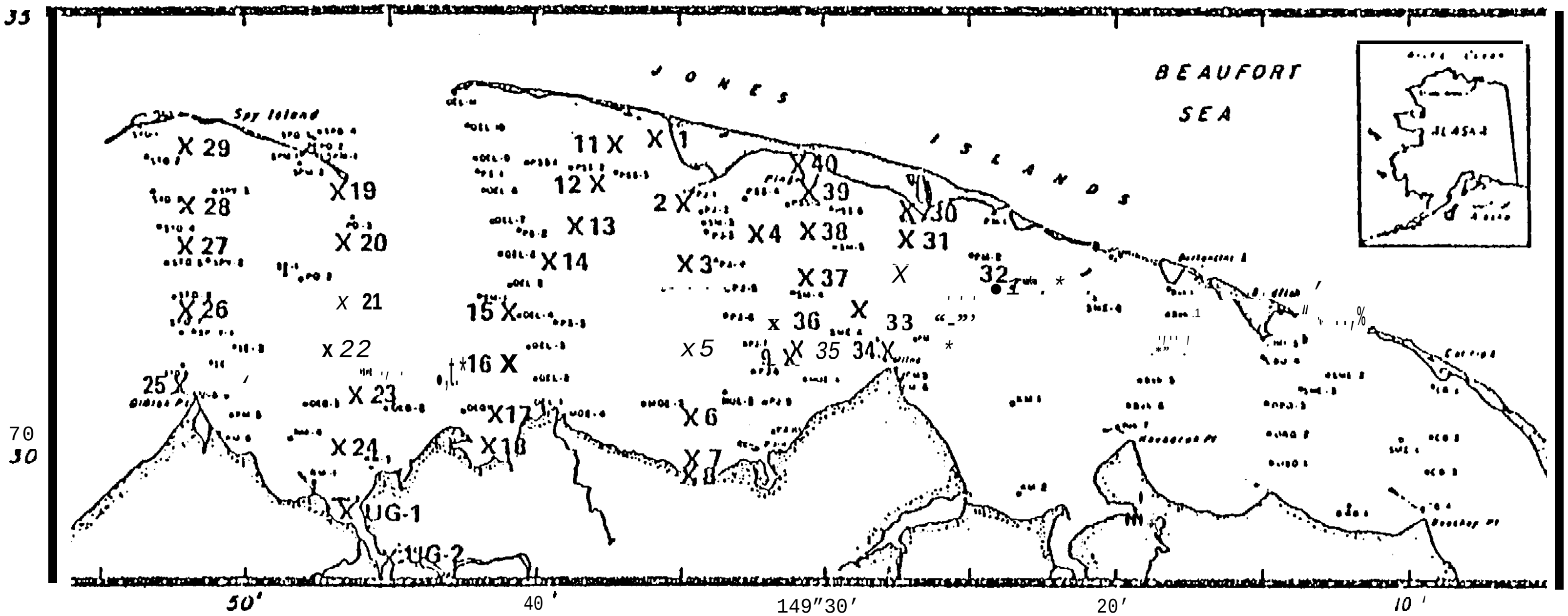

Figure *3.* Sample locations in Simpson Lagoon. Locations depicted by heavy crosses indicate samples collected in Summer 1977. The remaining samples were collected by Tucker (1973) and size analysis data on them are already available.

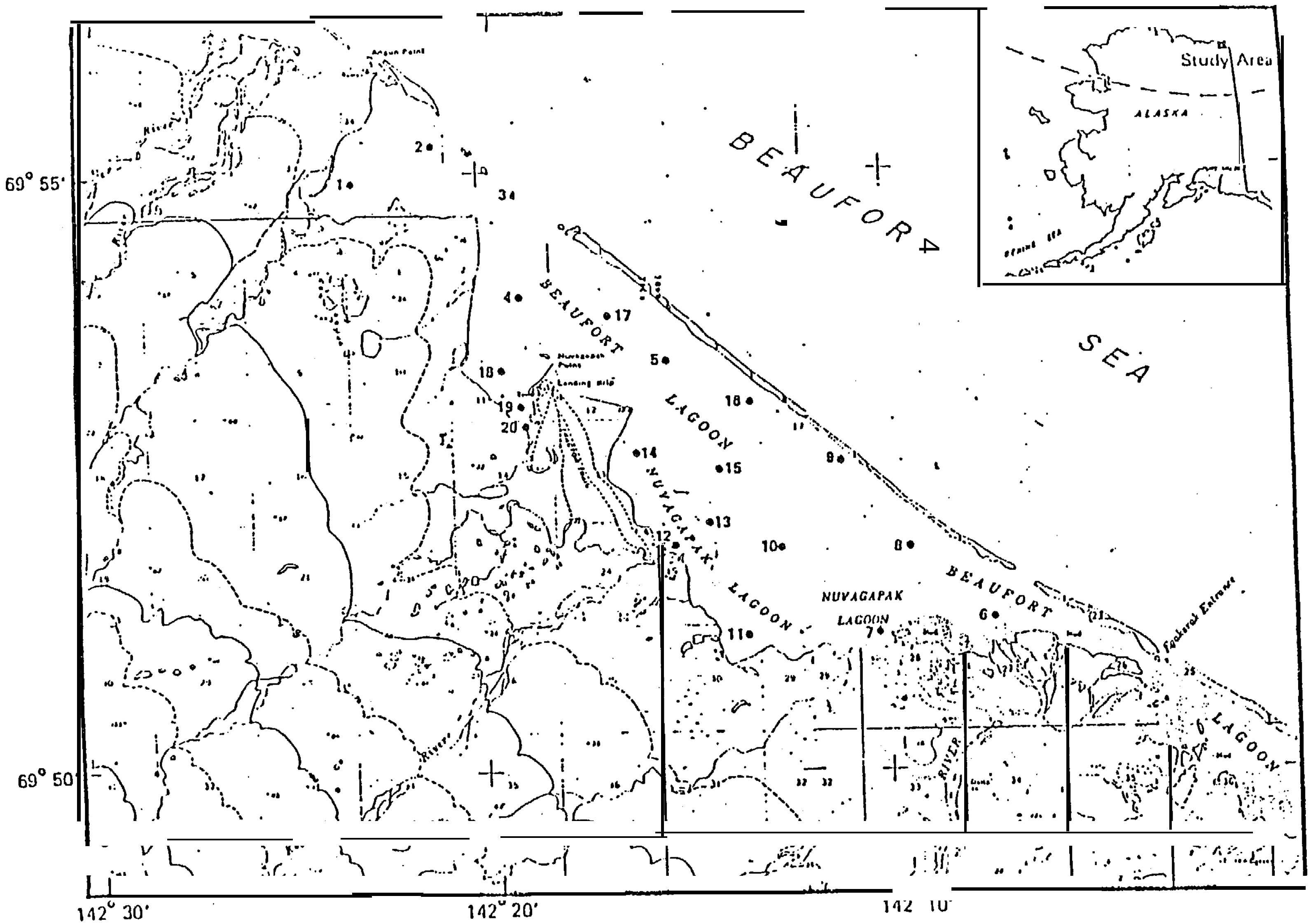

Figure 4. Map showi g the locations of sediment samples from he Beaufor Lagoon, north arcti Alaska.

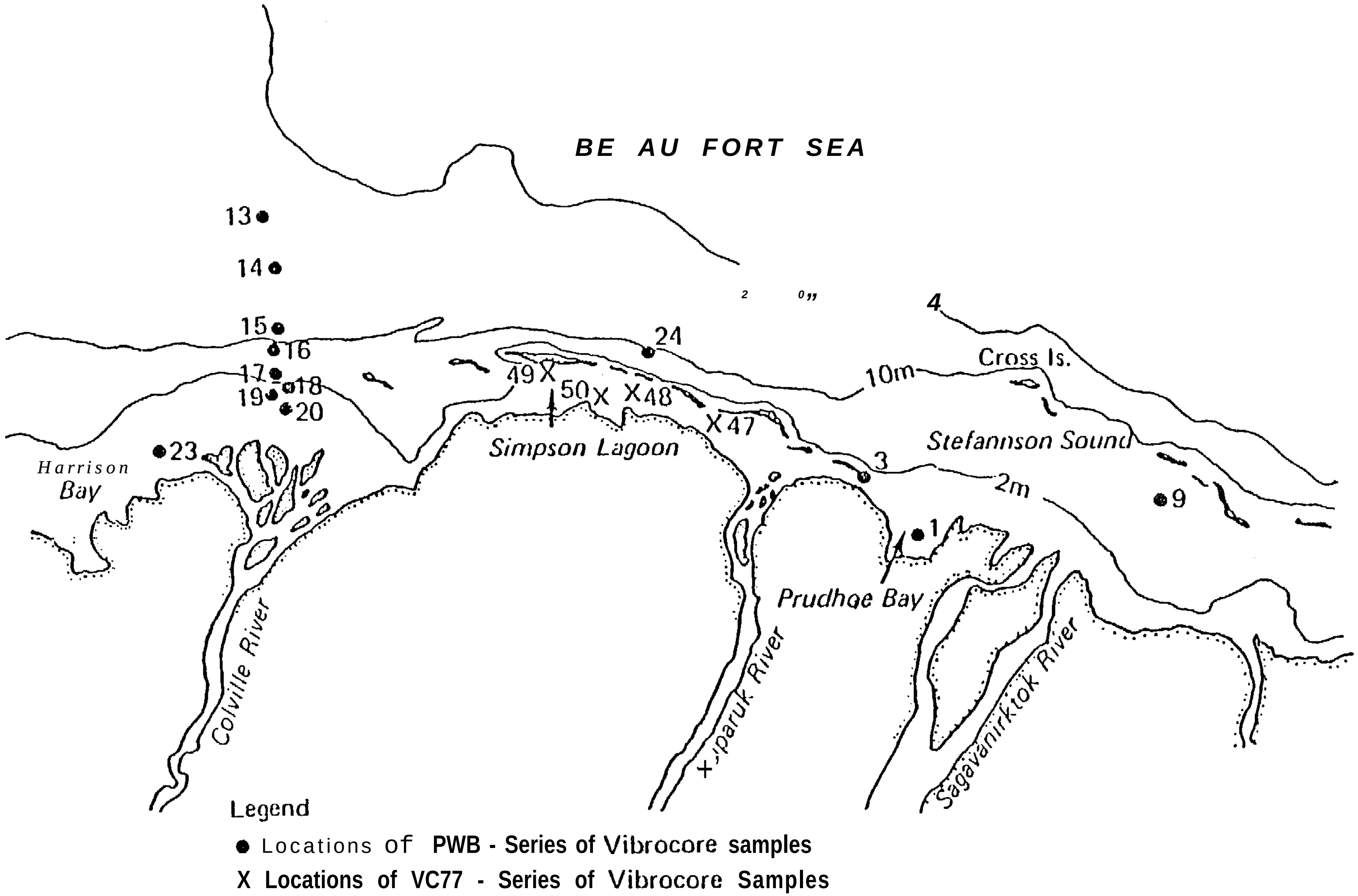

Figure 5a. Locations of vibrocore sediment samples that have been collected by Drs. P. W. Barnes and E. Reimntz of the U.S. Geological Survey In 1976 and 1977. Splits of core samples from locations depicted by heavy dots have been provided to us for study.

and mud) as well as two conventional grain size statistical parameters, mean size and graphical standard deviation (after Folk and Ward, 1957) were digitally transferred onto maps of the Beaufort Sea and isopleths plotted.

The clay mineral analytical procedures were discussed in detail elsewhere (Naidu and Mowatt, 1974); therefore, only a brief description follows. The sediment was initially treated with H_2O_2 to remove organic matter, and then dispersed in deionized-distilled water into suspensions. Dispersion was achieved by repeated washing. The < 2 μm equivalent spherical diameter (e.s.d.) size fraction from each of the sediment suspensions was separated by settling techniques. The < 2 μm fractions were smeared on glass slides (Gibbs, 1965) and air dried. Prior to, as well as following glycolation by vapor phase exposure for 24 hours, the slides were run for clay mineral analysis on a Phillips-Norelco X-ray diffractometer with a scintillation detector, using Ni-filtered copper K_α radiation.

Criteria adopted for the identification of the various clay minerals were outlined elsewhere (Mowatt *et al.* , 1974; Naidu and Mowatt, 1974). The Expandable Group included all clay minerals that expanded upon glycolation and displayed a basal diffraction peak in the vicinity of 17 Å. Given the large number of samples involved, and the reconnaissance nature of this initial work, we have refrained from attempting to resolve further the various expandable mineral phases (e.g. , vermiculites, mixed-layer phases, etc.) besides smectite that might be embraced within the above group. However it should be noted that some of the expandable clay mineral components exhibit characteristics similar to materials described by Weaver (1958a) in Ordovician Womble Shale of southeastern Oklahoma, and, hence are most likely "degraded" (depotassicated) detrital illites. This is substantiated by studies (Mowatt et al., 1974) on several unglycolated and glycolated clay samples that were initially saturated with either 1N $MgCl_2$ or KCl solutions. Although we recognize the potential value of more detailed characterization (Hayes, 1973), no attempt was made to resolve and quantify the more complex mixed-layer clay mineral phases, minor amounts of which appear to be present in some samples as illite-smectite or illite-chlorite, with varying amounts of "vermiculite". The term "illite" is used primarily in the sense of Brindley (in Brindley and Brown, 1980, p. 182), but includes various micas in the < 2 µm particle size range as well. Despite certain limitations, in particular with regard to interpretation of mixed-layering, the method adopted by Biscaye *(1965)* was followed for semi-quantitative estimation of clay minerals. The relative abundances of chlorite and kaolinite were estimated on the basis of the 3.5 Å region diffraction peaks (Biscaye, 1964). Overall analytical precision was ± 5 percent. The relative abundances of the various clay minerals and the kaolinite/chlorite ratios were digitally transferred onto maps of the Beaufort Sea and isopleths plotted.

Carbonate in the sediment was determined manometrically (Hülsemann, 1966). Organic carbon abundance in the sediment was calculated from the difference between total carbon and carbonate carbon. Total carbon was estimated in a LECO, TC-12 automatic carbon determinator.

Baseline trace element analyses were performed on gross sediment samples. For this purpose a representative portion of the gross sediment sample was taken, dried at 110°C and pulverized into fine powders using an agate mortar and pestle. Subsequent elemental analyses were on 10% HNO_3

solutions of $HF-HNO_3$ digests of sediments (Rader and Grimaldi, 1961), by atomic absorption spectroscopy using a Perkin-Elmer, Model 603, unit. Analytical precision for the gross metal analysis was better than 12%, and the accuracy was checked with reference to U.S.G.S. Standard rock powders G-2, AGV-1 and BCR-1 (Table 1).

Selective leaching experiments (see results section) were done on lightly disaggregate sample splits to acquire information on the partitioning of eight metals (e.g. Fe, Mn, Zn, V, Cr, Co, Cu and Ni) among the sediment constituents. The metal analyses were performed using the Model 603, and the Perkin-Elmer Model 5000 unit with HGA 500 graphite furnace.

Thin sections of 105 selected rock chip specimens of erratic boulders and cobbles strewn along the beaches and coastal plain were studied under a petrographic microscope, and the rock identification was supplemented by X-ray diffraction analysis as appropriate. The depositional rates were derived from ^{210}Pb measurements as a function of core depth, using the approach described by Koide *et al.* (1972). The method for ^{210}Pb analysis was similar to that described by Nittrouer *et al.* (1979). Coarse fractions (> 62 μm) and microfossils of various sections of *two of* the vibrocore samples (V-48 and V-49) were studied under a binocular microscope. Representative microfossil specimens were submitted to Dr. D. M. Hopkins of the U.S. Geological Survey (Menlo Park) for identification by the survey personnel.

In attempting to understand the processes of sediment entrainment in sea ice of lagoons and sounds, four samples of ice cores were taken from the Stefansson Sound, and 6- to 7-cm long continuous sections of the ice

TABLE 1

AVERAGE CONCENTRATIONS (μg/g, except for Fe which is in 10^4 μg/g) OF SOME HEAVY METALS IN STANDARD U.S. GEOLOGICAL SURVEY ROCKS: AGV-1, BCR-1, & G-2.

U.S.G.S. Standard Sample	V	Cr	Mn	Fe	Co	Ni	Cu	Zn
AGV-1								
This Study -1		9.6		4.67	15.0	13.0	59.2	99
This Study -2	127	12.8	767	4.79	14.6	14.5		
Reported Literature Values								
Flanagan, 1969	121	12.9	728	4.76	15.5	17.8	63.7	112
Flanagan, 1973	125	12.2	763	4.73	14.1	18.5	59.7	84
Range (Flanagan, 1969)	70-171	8-45	640-870	4.26-5.21	10-30	11-27	52-83	64-304
BCR-1								
This Study -1		10.7			33.7	5.9	17.5	136
This Study -2	500	14.6	1425	8.98-8.94	35.7	6.4		
Reported Literature Values								
Flanagan, 1969	384	16.3	1350	9.44	35.5	15.0	22.4	132
Flanagan, 1973	399	17.6	1406	9.37	38	15.8	18.4	120
Range (Flanagan, 1969)	120-700	8-45	1040-1600	9.02-9.97	29-60	8-30	7-33	94-278
G-2								
This Study	38	10	258	1.58	15	17	7.6	88
Reported Literature Values								
Flanagan, 1969	37	9.0	265	1.93	4.9	6.4	10.7	74.9
Flanagan, 1973	35.4	7.0	260	1.85	5.5	5.1	11.7	85
Range (Flanagan, 1969)	26-60	5-29	180-360	1.53-2.44	2-21	2-14	<2-17	42-138

cores were split, thawed and the particle concentrations analyzed. One red/dark pink granite sample from the Flaxman Island was submitted to Dr. D. L. Turner of the University of Alaska for dating by the K-Ar method. Representative portions of two basal peats, one separated at 150 cm from the top of the vibrocore V-49, and the other from under an 84-cm overburden of sand and gravel exposed in a section at the seaward beach of the spit west of Pingok Island, were dated by the C-14 method.

For the estimation of sedimentation rates in Simpson Lagoon seven short (15 to 33 cm long) core samples were collected from the western and central lagoon (Fig. 5b). All cores were obtained from more than 2 m depth to avoid sampling of sediment sequences that might have been disturbed by ice gouging. The westernmost core sample was retrieved by a Phleger gravity corer and the others by a manually driven unit. Sedimentation rates were derived without be. -fit of correction for the quantity of background-supported ^{210}Pb. Such a correction was not possible because background-supported ^{210}Pb concentrations could not be obtained as the cores were quite short and facilities for direct measurement of ^{226}Ra were not available with us for every core split. Thus, the rates presented represent upper limits of sedimentation.

GRANULOMETRIC COMPOSITION

Continental Shelf Sediments

The broad regional variations in the granulometric compositions of the Beaufort Sea substrate are graphically displayed in Figures 6 to 12.

Generally, the middle and outer continental shelf areas are carpeted by poorly-sorted sandy muds (with almost equal proportions of silt and

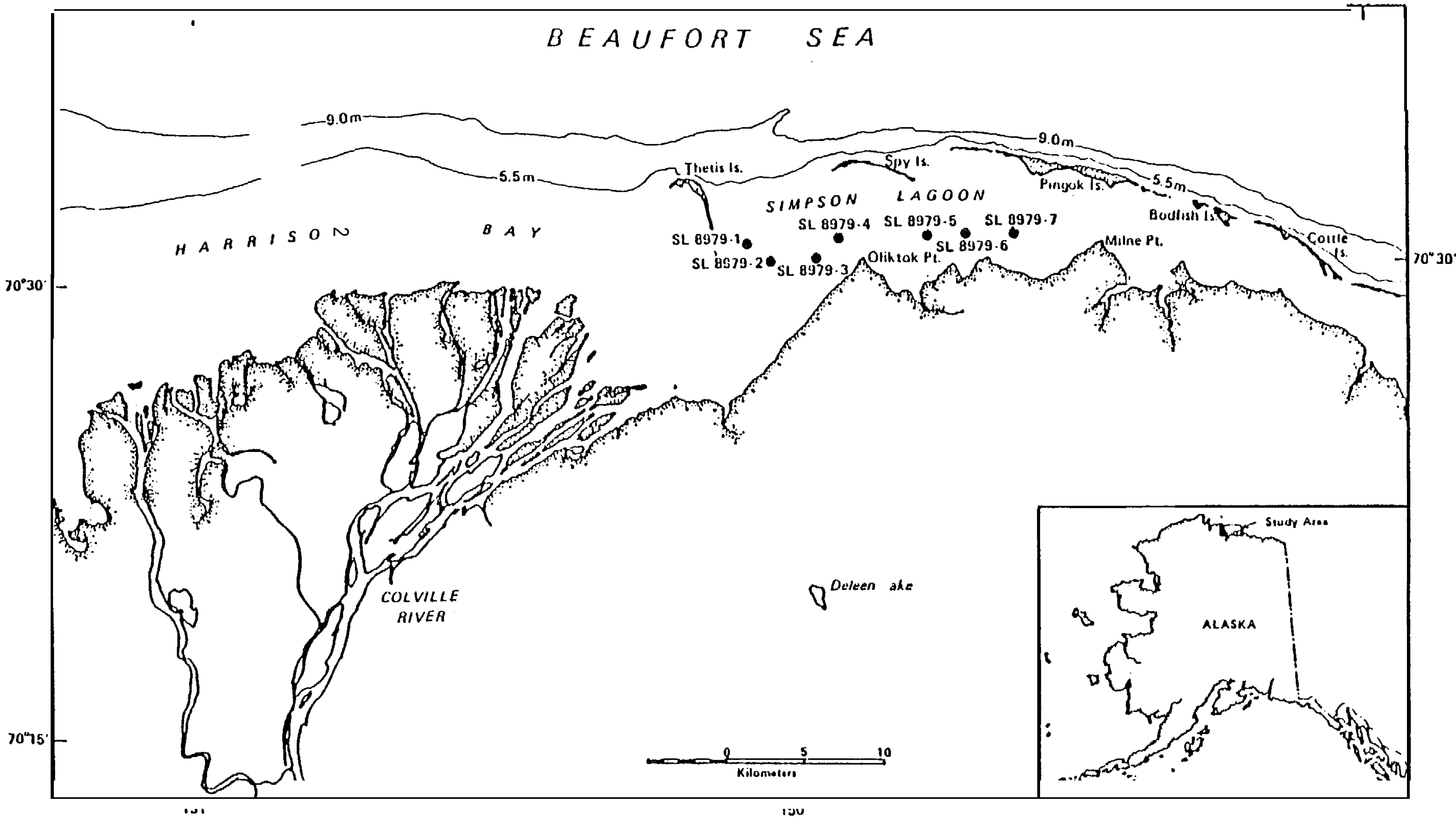

Figure 5b. The area of study showing locations of the core samples in the Simpson Lagoon, east Harrison Bay and Deleen Lake.

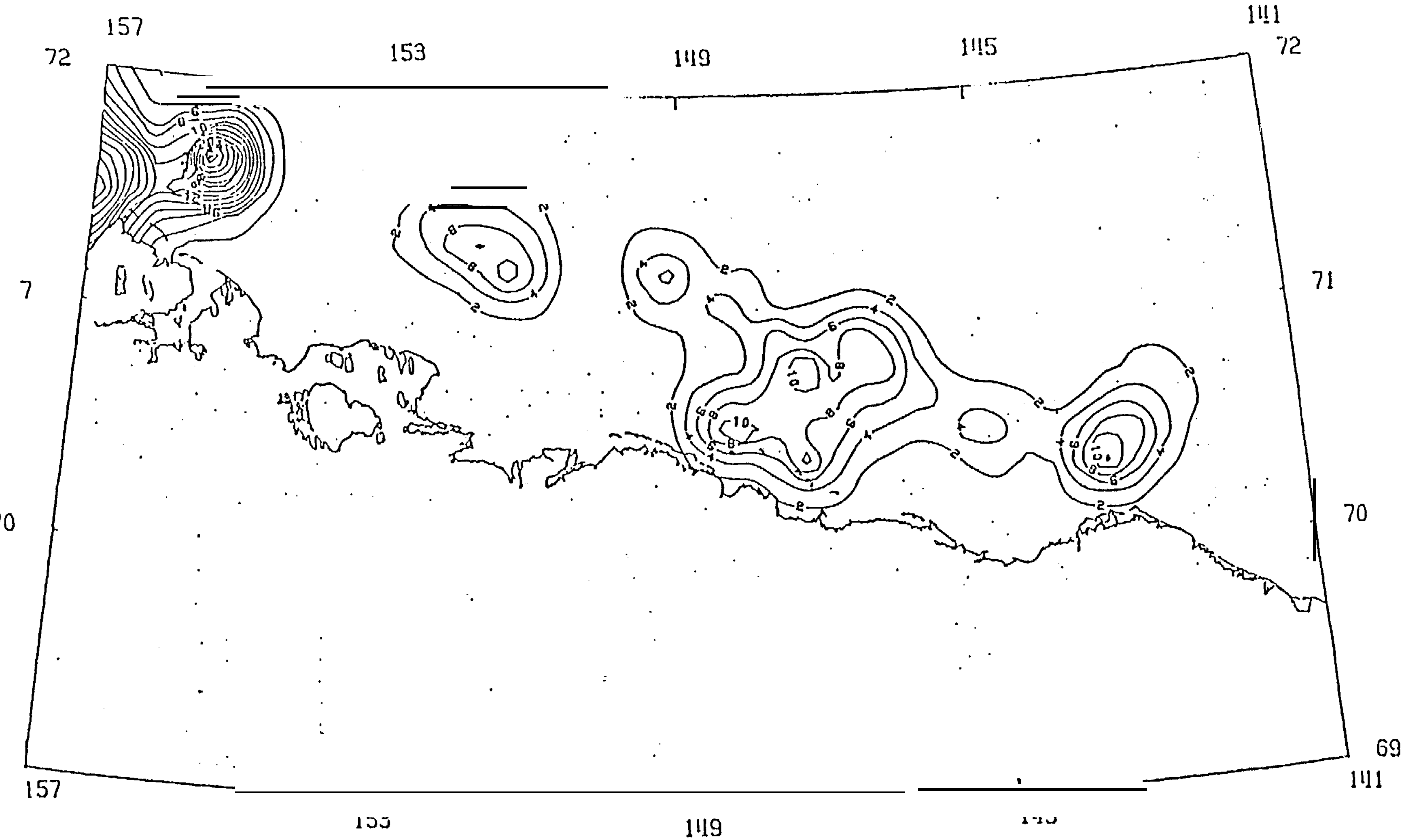

Figure 6. Map of the Beaufort Sea showing the distribution of gravel concentrations (wt. %).

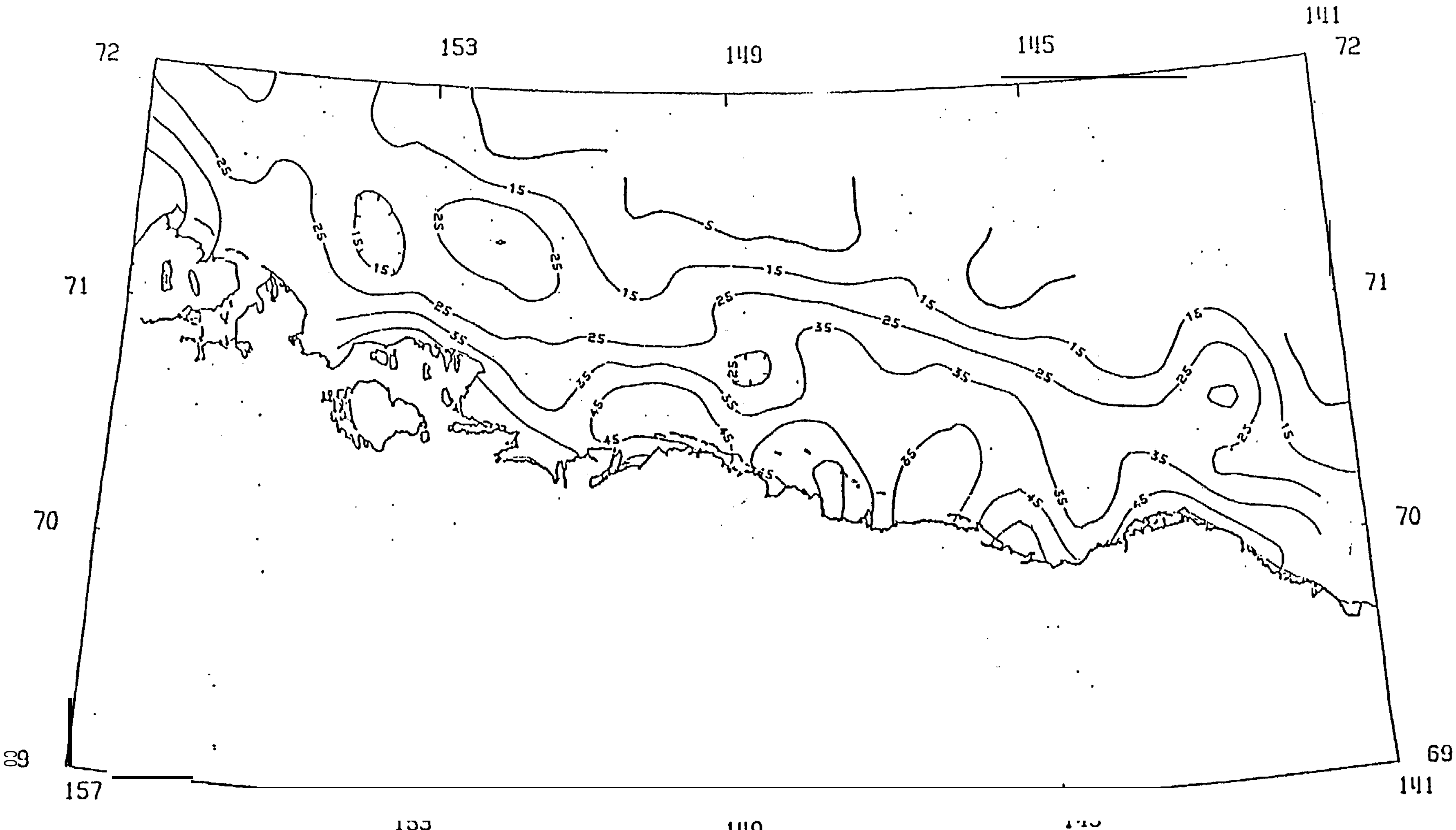

Figure 7. Map of the Beaufort Sea showing the distribution of sand (wt. %).

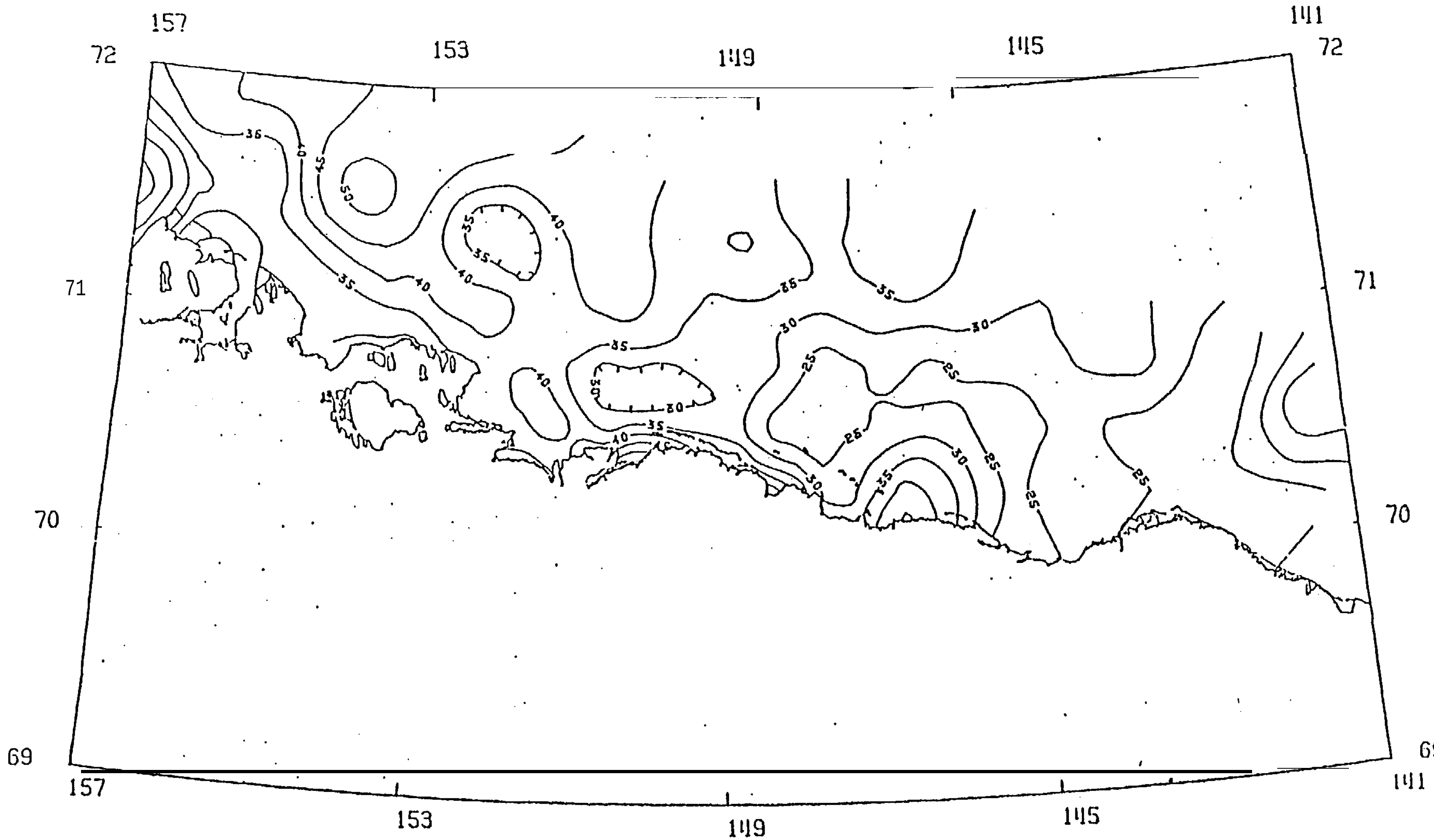

Figure 8. Map of the Beaufort Sea showing the distribution of silt (wt. %) .

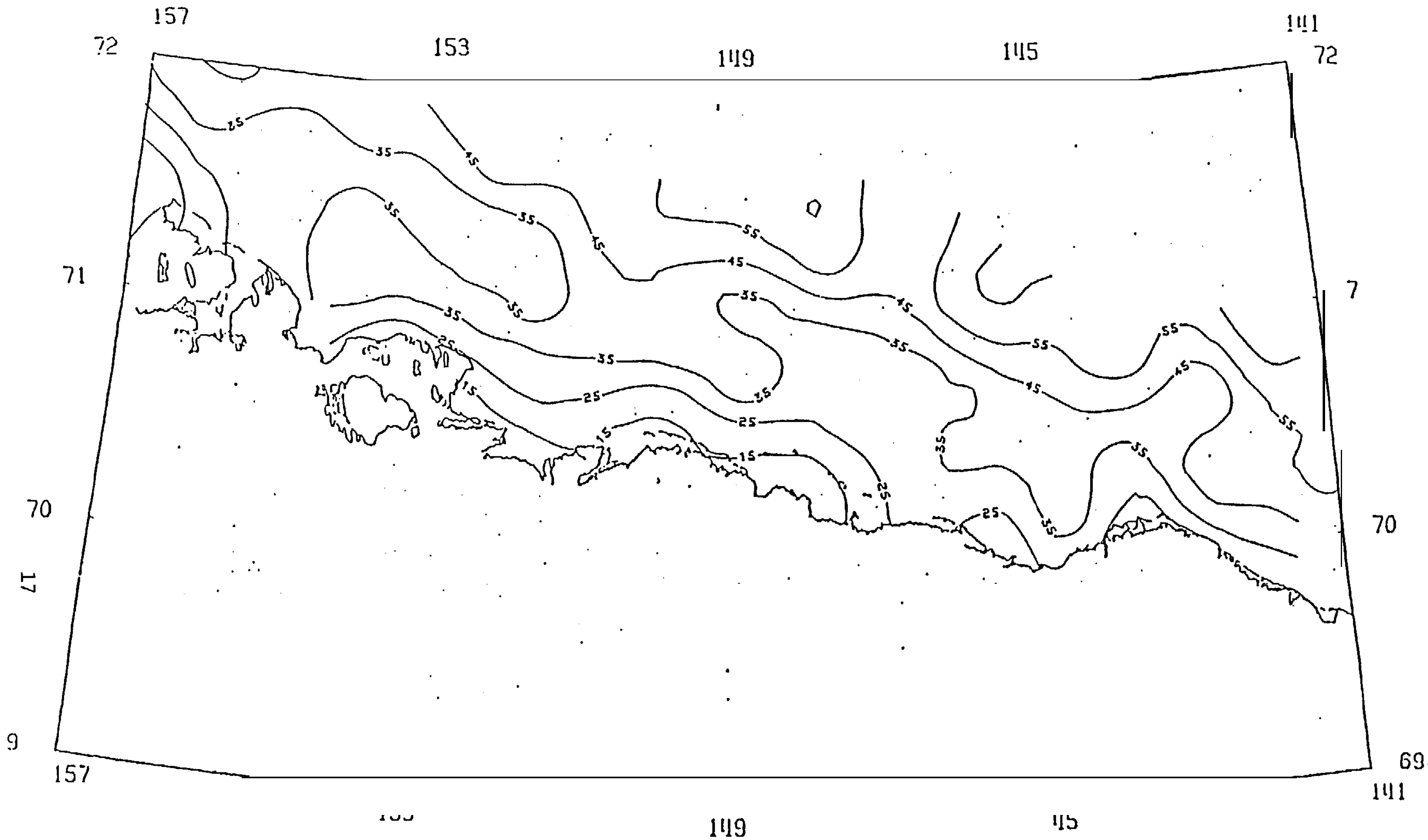

Figure 9. Map of the Beaufort Sea showing the distribution of clay (wt. %).

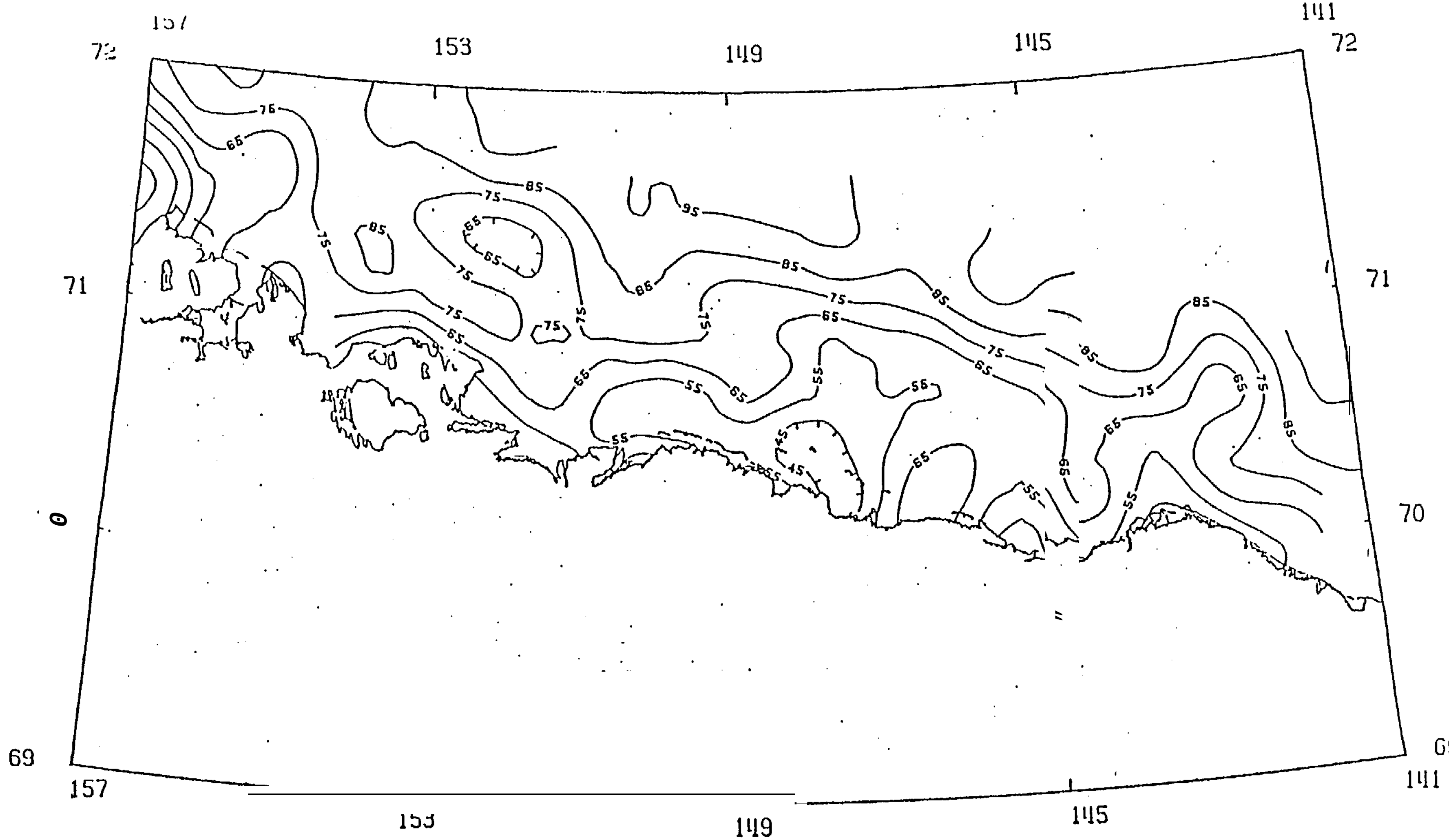

Figure 10. Map of the Beaufort Sea showing the distribution of mud (wt. %).

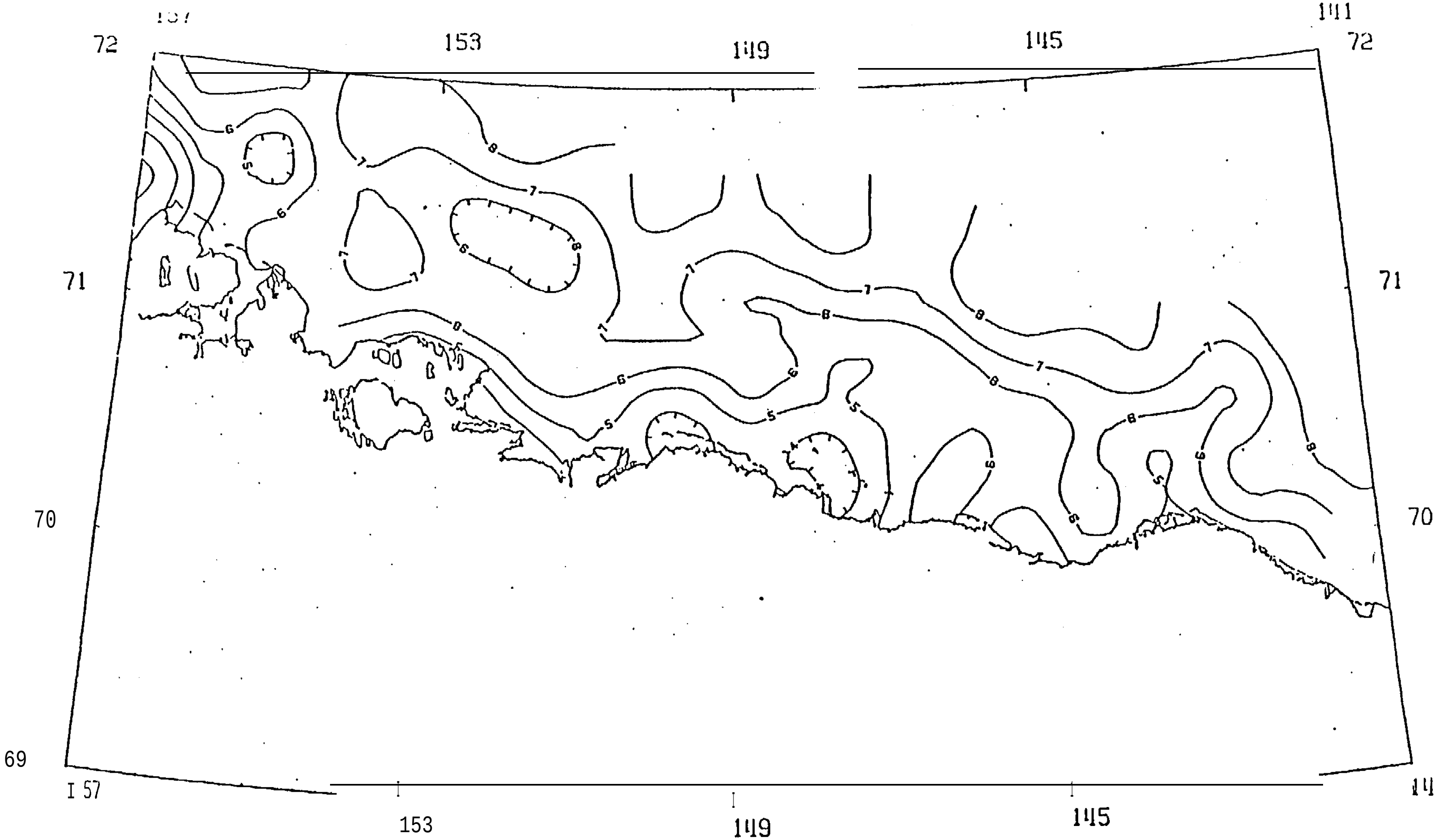

Figure 11. Map of the Beaufort Sea showing the variation of the phi mean size (M_z) of the sediments.

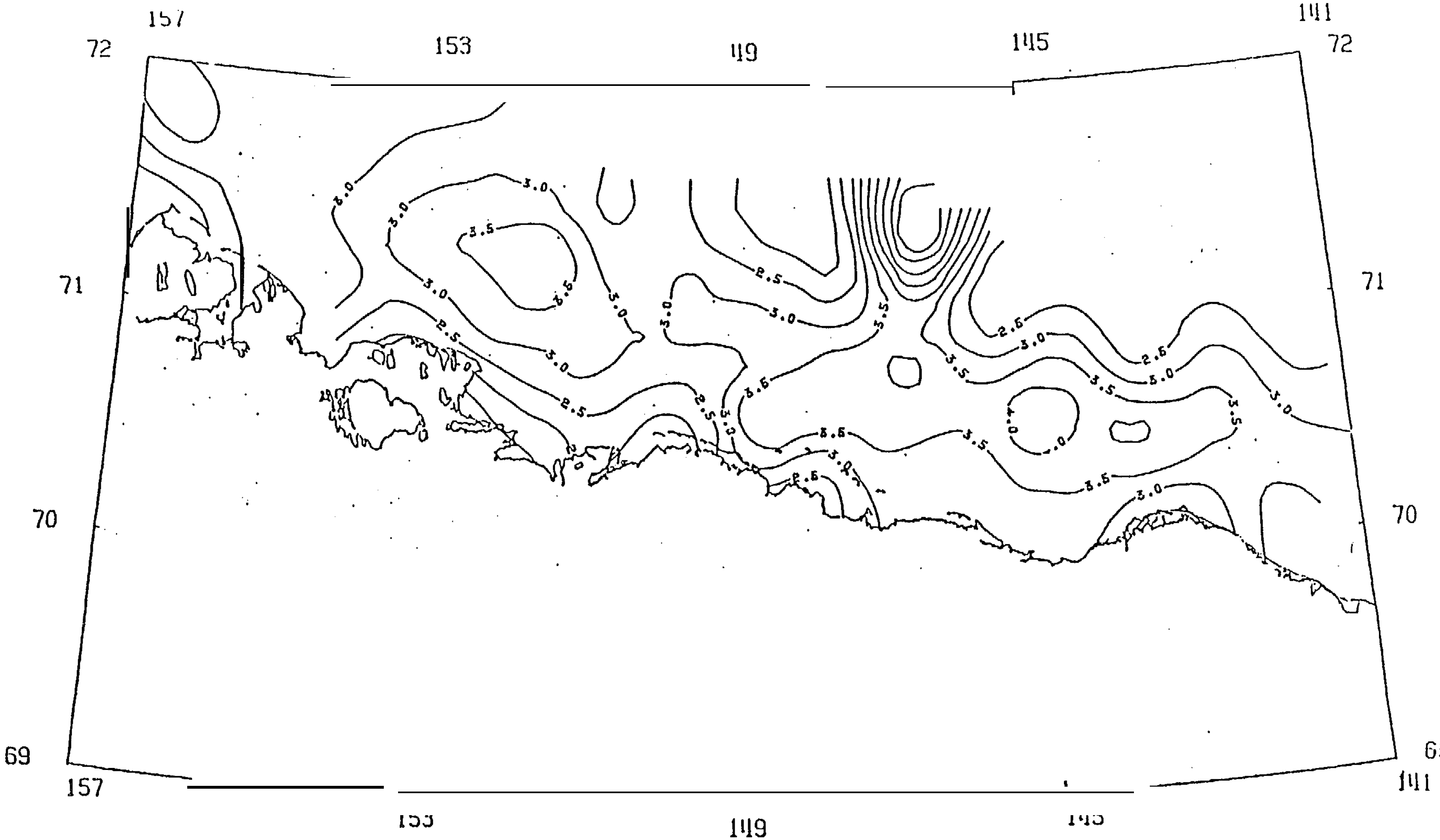

Figure 12. Map of the Beaufort Sea showing the variation in sorting of sediments.

clay). Invariably size distribution curves of these sediments are positive-skewed to nearly symmetrical and platykurtic. The inner shelf and inland bays are characterized by silty-sand to sandy-silt substrate with minor clay and occasional gravel-size particles. No unequivocal lithological gradation is observed across the Beaufort Sea shelf. There are a few extensive regions within the middle shelf of the eastern Alaskan Beaufort Sea where significant amounts of gravel are encountered (Fig. 6). Naidu (1974) and Naidu and Mowatt (1974) have discussed the various possible modes of origin of these gravel deposits. The consensus of the above authors and the majority of geologists working in the Beaufort Sea area would seem to suggest that the gravels are ice-rafted deposits. However, some differences in opinion exist as to whether the gravels are contemporaneously transported by ice or are relict ice-rafted elastics laid down during Pleistocene higher sea-levels. I believe that for the most part the gravels on the Beaufort Sea shelf are relict. This conclusion is primarily based on the observations that the transport presently of gravel by ice-rafting is insignificant (Naidu, 1974). Furthermore, several of the gravels have a thick, horizontal rim of Fe-Mn encrustations (Naidu, 1974) implying that these gravels have been lying undisturbed on the Beaufort Sea floor for quite a while. These relict deposits have remained exposed on the shelf surface because they have not been blanketed by contemporary muds and/or sands. In this context I agree with Carsola's (1954) contention that the, eastern shelf of the Alaskan Beaufort Sea is essentially devoid of supply of mud from the Mackenzie River. Likewise it would also seem that although large volumes of terrigenous mud are being ice-rafted offshore from the Alaskan coast, the transport and deposition of this mud is apparently bypassed in the shelf area of the Alaskan eastern Beaufort Sea. It is believed that the western Beaufort is the depositional site for the coastal-derived mud. Thus , it would seem that the presence of relatively higher amounts of gravel in the eastern shelf perhaps does not reflect a state of unusually higher wave-current regime in that area. Therefore, engineering construction in this area may not be faced with any special problems at least as far as hydrodynamic conditions are concerned. However, the occurrence of the gravels may offer greater resistance and thus impede drilling operations or pile driving. Nowhere on the shelf outcrops of rocks were encountered, which means that for foundation concerns special care must be exercised in designing shallow engineering structures.

The poorly-sorted nature of the central and outer continental shelf sediments are probably a resultant of reworking and mixing of various sedimentary units that is brought about by ice gouging action (Reimnitz and Barnes, 1974; Reimnitz et *al.*, *1972, 1973, 1977)* and bioturbation. I am, however, not aware how frequently any area on the Beaufort Sea shelf is exposed to the bulldozing effect of grounded ice, although some attempts have been made to estimate this by Barnes and Reimnitz *(1979)*. This later information would be of potential use in the designing of offshore engineering structures, for the effects of ice keel dragging and undercutting by ice gouging, and the possible subsequent burial of pipelines, cables, as well as footings (that may be placed on the sea floor) by the gouged sediment could be substantial.

No volumetric estimates are available on the gravel deposits of the Beaufort Sea continental shelf as a potential source for building material. Considering the extensive deposits more readily available on the adjacent coastal plain (in paleofluvial channels), I believe that exploitation of the shelf gravels, at least at present, may not prove very cost effective. Additionally, although the gravel deposits on the shelf seem to be quite extensive they occur typically as haphazard patches interspersed between stiff muddy deposits. Consequently, systematic exploitation of such deposits may pose a problem. In another context effects of any future dredging operation associated with gravel mining on the Beaufort Sea ecosystem are unknown, but could very well have deleterious impact on the ecosystem.

In the continental shelf of the Alaskan Beaufort Sea patchy deposits of an "over-consolidated", stiff mud are quite frequently observed either on the shelf surface or a few centimeters below. These muds have also been frequently encountered in the nearshore between the Reindeer Island and the Prudhoe Bay. Presumably these deposits are relict and their unusual stiff nature has been commonly attributed to progressive dewatering of the mud resulting from alternate freezing and thawing of the substrate brought about perhaps by periodic ice loading in the past. However, as far as I know no empirical data are available to substantiate such a contention. At any rate it would seem important to note that these stiff muddy substrates which apparently do not exhibit thixotropic characteristics may provide a more favorable foundation for offshore engineering structures. However, in another context these areas may be specially hazardous. Because of the higher impermeability of the stiff muds, the surface of permafrost zone may be relatively shallower under these muds.

Recapitulation of the Pleistocene depositional history of the Beaufort Sea continental shelf region has been somewhat thwarted, primarily because of the absence of some typical" submarine geomorphic clues (e.g. terraces/ benches, paleofluvial channels, etc.) that can be related to episodes of climatically induced sea-level oscillations. The Pleistocene paleogeography of the adjacent shelf areas (e.g. Chukchi, east Siberian and Laptev Seas) are presumably better understood. However, it would seem unreasonable to extrapolate data from the latter areas to the Beaufort Sea, for the glacial history of the different shelf areas were probably not the same. I believe that the reconstruction of the Pleistocene history of the Beaufort Sea would be quite crucial to the development of any model to predict the distribution of permafrost in the coastal and upper continental margin areas of the Beaufort Sea. I am aware of the progress made on studies along this direction by Dr. D. M. Hopkins (RU 204 and 473), but do feel that serious data gaps still exist.

One of the justifications for carrying out size analysis of surficial sediments and preparing lithological maps was to identify different benthic substrate habitats for the Beaufort Sea. However, whether such habitats can actually be delineated or not on basis of sediment granulometric distributions can only be verified in cooperation with the benthic zoologists (e.g. Dr. A. G. Carey, RU 6). My responsibility was to generate the necessary grain size statistical parameters for sediment samples that were jointly collected with the biological samples, and this task has been fulfilled. I assume that sufficient number of sedimentological and benthic data sets are available for several of the stations that a meaningful attempt can be made to correlate the two. The outcome of such a comparative study will be of great potential use to managers who may look for guidelines applicable to the Beaufort Sea, to predict the changes in benthic communities resulting from possible large-scale alteration in substrate sediment budgets triggered by anthropogenic activities (e.g. causeway, dock, off-shore island constructions, etc.).

Deltaic Sediments

Grain size statistical parameters for contemporary sediment samples from several subfacies of the deltaic complex in North Arctic Alaska were determined.

Results of the granulometric analysis of the various subenvironments are summarized in Table II. Evidently the deposits of the lagoon, bay and open shallow marine environments cannot be differentiated on the basis of the conventional grain size statistical parameters. However, the coastal beach, dune and deltaic plain sediments have distinctive lithologies. It is contended that with the exception for coastal dune (Table II) gross textural relationships do not seem to be rigorously definitive with regard to delineating paleosedimentary subfacies of polar deltas and this endorses our earlier observations (Naidu and Mowatt, 1975, 1976). The distinctive granulometric composition of North Slope coastal beaches is predominantly attributable to a local unique provenance (e.g. , gravel-enriched Quaternary Gubik Formation underlying coastal tundra), rather than solely to depositional processes prevailing in the polar region. Naidu and Mowatt (1975, 1976) have suggested that other criteria, such as the overall three-dimensional framework of the deltaic sequences and sediment structures may be more reliable means to reconstruct the paleogeography of the shallow-marine and coastal areas of the Beaufort Sea. These restrictions must mean that any attempts to develop models on the basis of the geological history,

TABLE II. SUMMARIZED DATA ON THE TEXTURE OF RECENT DELTAIC SEDIMENTS ON, THE NORTH SLOPE, ARCTIC ALASKA. DESCRIPTIVE GRAIN SIZE PARAMETERS CALCULATED BY FOLKS (1958) METHOD

Environment	Gross Texture	Md (ϕ)	M_Z (ϕ)	σ_I	Sk_I	K_G
River Channel	Gravelly-sand to clayey-sand	-3.4 to 5.6	-2.4 to 5.9	Very poorly to poorly sorted	Positive to very positive	Platykurtic to extremely leptokurtic
Tundra Deltaic Plain (Marsh)	Structureless peaty organic muck, with" sparse inorganic particles, and occasional frost-heaved gravela and eolian sand					
Mainland Coastal Beach	Gravel-gravelly-sand, and sand	-2.8 to 1.3	-2.8 to .06	Poorly sorted (many); moderately sorted (few)	Continuous range from positive to negative	Platykurtic (predominantly) to leptokurtic
Bay	Sand, silty-sand and sandy-silt	2.8 to 6.6	2.9 to 6.8	Very poorly sorted to poorly sorted; few well sorted	Continuous range from positive to negative	Platykurtic to very leptodurtic
Lagoon	Sand, sandy-silt, silty-sand, and sand-silt-clay	2.2 to 6.2	2.1 to 7.0	Very poorly sorted; few well sorted	Most positive, few nearly symmetrical	Highly variable mesokurtic to extremely leptokurtic
Coastal Dune	Medium to fine sand	1.8	1.8	Well to very well sorted	Nearly symmetrical	Mesokurtic
Barriers	Gravel, gravelly-sand, and sand	-2.5 to -8.0	-1.5 to -8.0	Well sorted to very poorly sorted	Very positive to very negative	(Not available)
Open Marine (Delta front platform?)	Sand-silt-clay to silty-clay	2.2 to 8.3	1.2 to 8.1	Very poorly sorted	Most positive, few very positive	Platykurtic to extremely leptokurtic

to predict the distribution of permafrost in the Beaufort Sea coastal area, will be faced with difficulties.

Further discussion on the characteristics of the granulometric compositions of lagoon sediments of North Arctic Alaska are included in latter sections of this report.

STRATIGRAPHIC STUDIES ON CORE SAMPLES

In this section are discussed the depositional processes in the marine facies of the Colville Delta area (Fig. 5) as inferred from examination of the stratigraphic variations in lithology of short unconsolidated cores (Figs. 13 and 14). It would seem that in the proximal end of the pro-delta (?) sediments are deposited under fluctuating hydrodynamic conditions. This is evident from the presence of alternate bands and laminations of relatively high and low sand contents as displayed in cores PWB76-18, 19, 20 and 23. It is possible that the highly sandy layers reflect deposition at intensified wave action during storms. Additionally, it is suggested that in the area of the shelf from where these cores were retrieved reworking of sediments by bioturbation and/or ice gouging has not prevailed in recent times. This is inferred from the lack of stratigraphic homogeneity in the four core samples. However, the core PWB76-1 (Fig. 13), which was retrieved from the Central Prudhoe Bay (Fig. 12) at 3 m water depth, consists essentially of homogeneous clayey silt with no evidence of sediment layering on basis of textural and/or structural analysis. This would obviously mean that sediments of the Prudhoe Bay have either not been completely free from reworking by ice gouging, or deposition in the bay has continued under similar hydrodynamic conditions during recent times.

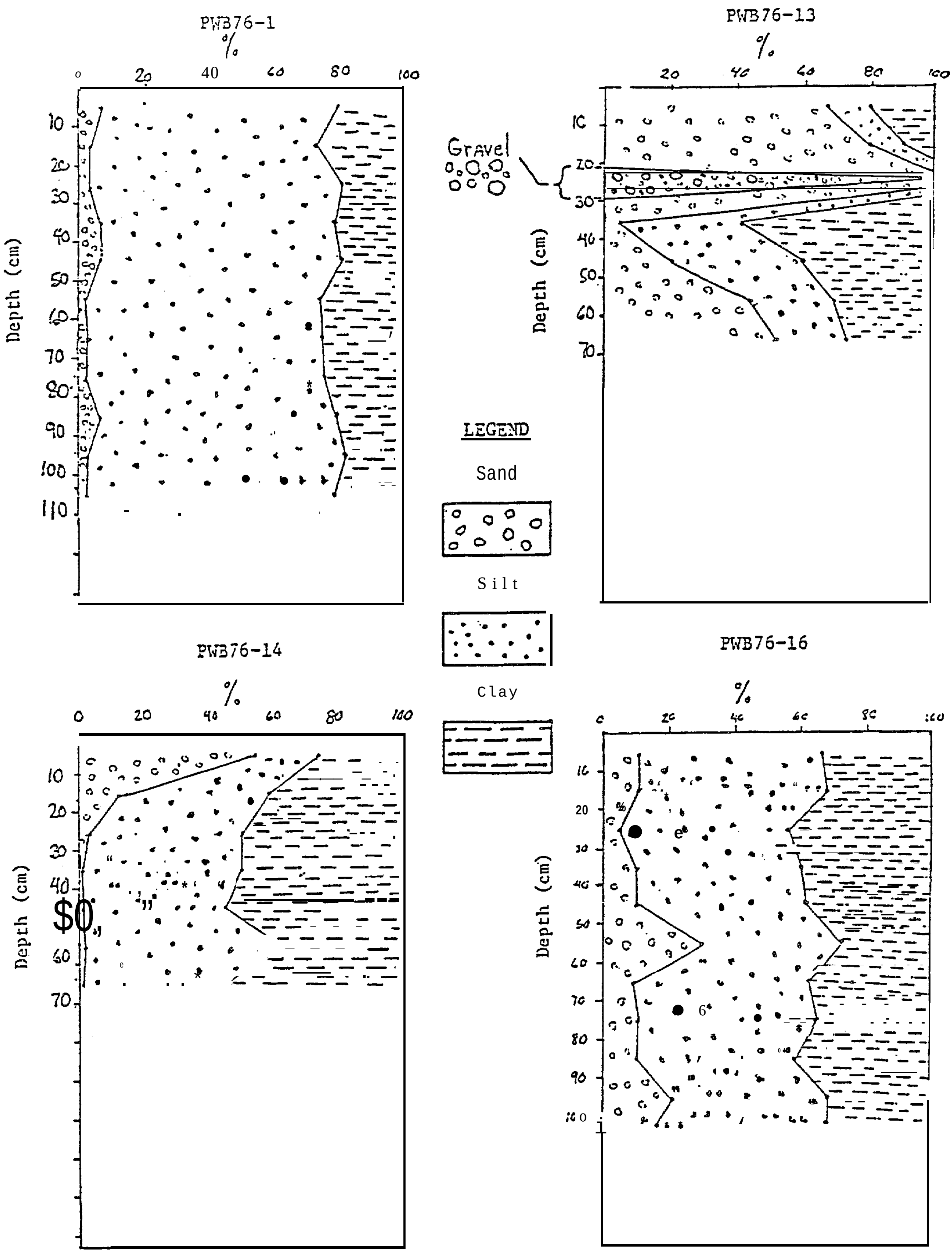

Figure 13. Variation of sediment texture with depth of PWB76 core samples.

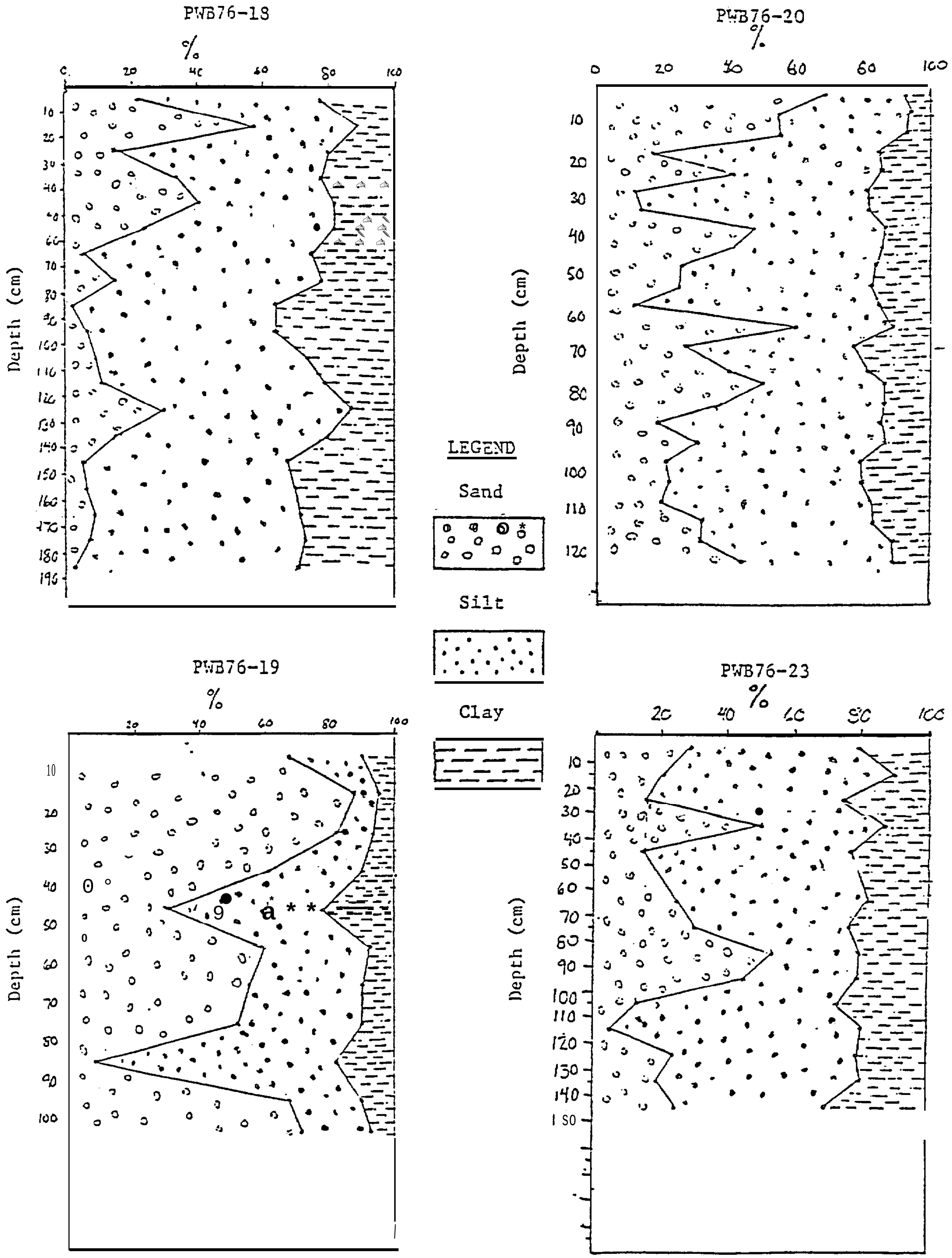

Figure 14. **Variation of sediment** texture with depth of PWB76 core samples.

^{210}Pb stratigraphic studies on a sediment core collected from the central Prudhoe Bay show no definite exponential decrease in ^{210}Pb down the core, which seem to substantiate that reworking of sediments perhaps by ice gouging in the area has been quite intense. This would imply that cautionary steps must be taken to mitigate possible undercutting by ice on engineering structures and submarine pipe lines that may be emplaced in 'this and similar shallow marine areas.

The granulometric analysis on a suite of core samples shows that the overall volume of gravel are generally low within the surficial 1 to 2 m sediment sequences from the Beaufort Sea nearshore. On the basis of this restricted sampling it would seem that the prospect for potential gravel deposits in the nearshore for economic exploitation is generally not very high.

BARRIER ISLAND-LAGOON SYSTEM OF THE ALASKAN NORTH ARCTIC COAST

Geomorphic Characteristics

A number of chains of barrier islands border the Beaufort Sea coast of Alaska (Figs. lb and 2a). In the west a chain designated as the Plover Islands extends eastward of *the* barrier spit anchored to Pt. Barrow. Two chains of barrier islands stretch westward from west of the Sagavanirktok River and Canning River mouths. There is a third interspersed chain east of the Canning Delta that continues up to Demarcation Point.

By conventional definition, barrier islands, barrier spits and bay barriers are offshore subaerial depositional features of current/wave action. Therefore, offshore lands such as mud islands, erosional remnants of relict coastal plains, subaerial reefs, volcanic islands, and sea stacks *sensu stricto* are not barrier islands. Following this definition some offshore islands along the Beaufort Sea coast, such as Pingok, Bertoncini, Bodfish, Flaxman, Tigvariak and perhaps also Cottle are not barrier islands. Unlike the barrier islands, the latter islands for the most part have much higher relief, up to 5 m above mean sea level (a.m.s.l.), and are remnants of ancient coastal plain as suggested by the presence of an active tundra blanket, a stratigraphy similar to the adjacent coastal plain and continuous permafrost. Long barrier spits have subsequently extended laterally to some of these islands. Thus, in this paper unless otherwise stated, discussions will not be apropos to the tundra-blanketed islands.

The islands are typically low (1 to 3 m above MHW), with lengths ranging from 100 m to 27 km and are elongated parallel to the coastline. The notable exception to the latter pattern is the island chain extending due west of the Canning River mouth, the alienation of which progressively deviates farther away from the coast towards the west. Generally the seaward beaches of the Alaskan arctic barriers are straight; it is only following an occasional storm that beach cusps and/or ridge-runnel physiography is observed along the barrier islands. There are, however, a number of microrelief features typically associated with the ice-stressed beaches of the Arctic. For the most part these are elongated sand/gravel ridges resulting from landward bulldozing of beach deposits by overriding ice or movement of the deposit from backshore to foreshore by shifting ice at spring thaw. Furrows resulting from ice gouging are seen across the beaches; low mounds of gravel piling ('kaimoos') are also observed and believed to have formed from in-place ablation of shorefast ice entrained with gravel and/or storm-ice foots. These features were more thoroughly characterized by Rex (1964) and Greene (1970).

The barrier islands are separated from one another by tidal inlets (or channels), the depths of which can vary between less than 1 m to about 6 m (e.g., Egg Island inlet). The dimensions of the lagoons — semi-enclosed bodies of waters encompassed by the barrier islands and the mainland coast — can vary widely. The widths may extend from a few hundreds of meters to 4 km, whereas the length may continuously stretch up to 40 km. The lagoons are typically 1 to 3 m deep. The semi-enclosed body of water encompassed by the Midway-McClure-Stockton-Maguire group of islands and the mainland coast east of the Canning River Delta (Figs. lb and 2a) is relatively wider, more extensive and deeper (about 5.5 m average depth; 10 m maximum depth) than the typical adjacent lagoons. Additionally, the hydrodynamic conditions in this littoral water body are influenced to a greater extent by the open marine environment. It would, therefore, seem more appropriate to class such an environment as a sound rather than a lagoon. Following this reasoning, this water body is presently called Stefansson Sound. However, such a definition should not construe that Stefansson Sound has dimensions comparative to some well-known larger sounds elsewhere (e.g., Pamlico and Long Island Sounds in the U.S. east coast) and its usage in this paper is purely descriptive. Review of the open literature clearly demonstrates that there can be marked variability in the dimensions, geomorphology, sediment characteristics and the physiochemical and biological facies between the barrier island-lagoon systems of different regions of the world. Glaesser (1978) contended that barrier islands are typically developed along marginal sea and trailing edge (passive or non-subductive) coasts (Inman and Nordstrom, 1971; Davies, 1973). Hayes (1979), from his worldwide experience, classified barrier island morphology as a function of tidal current and wave energy, and concluded that the development of barriers are more extensive in coastal areas where the tidal range is less than 4 m and that are wave dominated. Furthermore, Hayes (1976, 1979) noted a distinct morphological difference between barriers from microtidal (O-2 m tidal range) and mesotidal (2-4 m tidal range) coastal belts. The generalizations asserted by Glaesser (1978) and Hayes (1979) can be extended to the North Arctic coast of Alaska only to a limited extent. The latter coast with a mean tidal range of less than 16 cm do indeed have extensively developed barrier island-lagoon systems. However, along the Beaufort Sea coast of the Arctic some significant deviations are observed from the ideal geomorphic model related to barrier islands of microtidal areas of the temperate coasts. Presence of a "hot dog" morphology, storm-surge washover terraces and fans, as well as large flood-tidal deltas and a paucity of tidal inlets, are claimed as typical features of barriers of microtidal provinces (Hayes, 1979). However, presence of these features is not substantiated in the Beaufort Sea. It is of interest to note that occurrence of the washover terraces and fans were reported by Hayes (1979, p. 11) in an adjacent microtidal area of the Alaskan arctic (e.g., Kotzebue Sound, along the Alaskan Chukchi Sea coast).

Another notable feature of the Beaufort Sea barrier island system is the lack of any definite pattern of lateral variations in the interbarrier inlet widths, or degree of downdrift offsets. A close examination of LANDSAT images and aerial photographs of the Beaufort Sea coast discloses that in the majority of cases the relatively wider end of the barrier islands is disposed toward the downdrift of the net littoral currents. The foregoing observations on the north-Alaskan barriers are in contrast to the conclusions on barrier islands of mesotidal coasts (Hayes, 1976, 1979). Additional peculiarities of the north-arctic barrier islands are the virtual absence of some of the depositional subfacies such as the sand dunes at barrier crests, fringing salt marshes (with halophytic vegetation), tidal channels and flats on the lagoonward shores, and beach ridges. These subfacies are commonly well evolved in temperate and tropical barrier islands (Shepard and Moore, 1955; Chapman, 1960; Shepard, 1960; Allen, 1965; Dickinson *et al.*, 1972; Hayes and Kana, 1976; Hill and Hunter, 1976; Godfrey *et al.*, 1979; and McCann, 1979), and several of the facies are reported to be developed as well in the barriers along the microtidal southern coast of Gulf of St. Lawrence, Canada (McCann, 1979).

The tundra-covered islands are, as mentioned earlier, significantly different from the barrier islands. The lagoonward beaches of the tundra islands are generally irregular and the lower foreshores are blanketed by slushy, peaty deposits. The seaward shore (excluding that of the barrier spit) may or may not have a clearly defined beach. When a seaward beach is well developed, as on Pingok and Bodfish Islands, it is quite similar to the barrier island beach. Alternately, when the seaward beach is virtually absent (e.g., Flaxman Island) the shoreline is characterized by steep coastal bluffs.

The foregoing suggests that the barrier islands of North Arctic Alaska have a number of unique characteristics. Because the barrier island-lagoon environment in the North Alaskan Arctic is quite extensive, it was necessary to restrict the sedimentologic and geomorphic studies to a few type areas. 'The Jones Island-Simpson Lagoon situated along the central Beaufort Sea coast of Alaska (Fig. lb) represents a type area off gently sloping coastal plain adjacent to an extensive deltaic complex, whereas the Icy Reef-Beaufort Lagoon in the eastern end of the study area represents a type area off a relatively steep coastal plain with less widespread deltation. Stefansson Sound, which is the only representative of the so-called sound environment along the above coast, is situated between the two type areas of barrier island-lagoon systems (Fig. lb).

Reasons for Arctic Barrier Island Peculiarity

In the preceding section it was contended that the barrier islands along the Beaufort Sea coast have geomorphic characteristics that do not conform to the model generally outlined by Hayes (1976; 1979) for barrier islands of microtidal coasts of the tropical and temperate climatic belts. The uniqueness of the Beaufort Sea barriers is considered part of a local phenomenon that cannot be extended to the entire ice-stressed circum-coastal regime of the Arctic. It is suggested that the very unusual characteristics of the Beaufort Sea barriers are most likely related to the prevalence in the area of low annual current/wave energy. The Beaufort Sea coast is subjected to a mean astronomical tidal range of less than 16 cm, and the tidal current velocities in the tidal inlets are also suggested to be generally low (less than 6 to 7 cm sec^{-1}). The absence of flood tidal deltas may be ascribed to the net seaward flow of bottom currents (of tidal and fluvial outflow origin), and by implication an over-all sediment transport from the lagoon to the open sea. Because of the unusually low tidal range it is contended that development of extensive tidal flats and salt marshes is particularly hampered on the lagoonward shores of the north Alaskan barriers. There is, as yet, no comprehensive statistical data base available on the wave climate for the Beaufort Sea coast. Preliminary data gathered by Wiseman *et al.* (1973) and Dygas and Burrell (1976) suggested that the wave field in ice-free seasons is dominated generally by wind-waves with 1.9 to 3.0-second period, that are punctuated by occasional swells with 8.0 to 10.0-second period and heights of 1.5 to 2.0 m impinging on the Beaufort Sea coast. However, storm-surges with heights ranging from 1.5 to 3.0 m a.m.s.l. are known to occur at about 25 to 50 years intervals (Reimnitz and Maurer, 1978). One of the primary reasons for the prevalence generally of the low wave energy, and less frequent storm-surge annually in the north Alaskan Arctic, is to be attributed to the extended period of ice cover. For eight to nine months in a year the Beaufort Sea is blanketed totally by ice, while during the summer three months open water may extend only within the 10-15 km inshore. The total fetch for wave generation is thus effectively much reduced in the Beaufort Sea in comparison to the ice-free tropical-temperate microtidal coasts. Therefore, except during periods of rare storms when the barrier islands can be completely inundated by sea (Reimnitz and Maurer, 1978), the potential development of the washover terraces and fans is generally inhibited in the North Arctic barriers.

In another context the lack of washover features can perhaps also be accounted for in the presence of numerous tidal inlets between the Beaufort Sea barriers. The inlets, by serving as suitable channels to transfer portions of the storm-surges into the lagoons, would concurrently minimize the possibility of surges passing over barriers. We also suspect that the prolonged ice-stress conditions in some, as yet, unknown way deviates the barrier morphology from the ideal 'hot dog' type, and better understanding of the role of ice will be a part of our future study.

Thus, it is quite evident that the model of barrier island formation, as stipulated by Hayes (1976, 1979), did not adequately take into account the possibility that there can be a marked variation in the model because of the role of ice in microtidal coasts such as those of North Arctic Alaska. The close resemblance of the West Arctic Alaskan barriers to the 'hot dog' prototype, and the association of washover terraces and fans with them (e.g. barriers of Kotzebue Sound) are considered by us as atypical features of the barriers of intensely ice-stressed microtidal coasts. The above 'abnormality' is attributable perhaps to relatively much intense storm-surge and wind-wave actions in that particular arctic area. In comparison to the Beaufort Sea, the Alaskan Chukchi Sea is known to have a much wider ice-free marginal zone in summer (Wiseman *et al.*, 1973) plus a significantly shorter duration of ice cover annually.

The absence of sand dunes on the Beaufort Sea barrier islands is an additional peculiarity in contrast to barrier islands of temperate-tropical coasts. Some of the prerequisites for the development of sand dunes on barrier islands are the presence of (1) and adequate source of sand on the seaward beach, (2) net onshore winds with thresholds adequate to transfer the beach sand to the dune site at the backshore, (3) vegetation and/or some other barriers to promote the accumulation of the onshore transported sand, and, (4) sufficient exposure of the beach sands, in a dry state, for onshore winds to pick them up. The availability of the beach sand, in turn, is effected by a number of more primary hydrodynamic and geomorphic factors that control the overall sediment budget at the beaches (e.g. the competency, capacity and rate of alongshore sediment drift, barrier configuration with respect to the wind-wave fronts, the volume of sediment exported periodically from the beaches and across the barriers by storm-surge washovers, etc.). We contend that the chief reasons for the virtual absence of sand dunes on the North Arctic barriers are the lack of vegetation and prolonged exposure of the beach sands to wind transport, notwithstanding that there is adequate volume of beach sand as a source and a net strong onshore wind. It is conceivable that because of the prolonged annual ice cover the total onshore transport of sand by wind is considerably reduced in comparison with ice-free barrier regions. McCann (1979, p. 49) referring to Owens (1974, 1975) maintained that barrier elevations and extent of dunes on barriers are closely associated with longshore sediment transport rates. Although along the Beaufort Sea barriers some short-term littoral transport rates were estimated (Wiseman *et al.*, 1973; Burrell et *al.*, 1975), these data are grossly inadequate to take into serious consideration in context of Owens' contentions.

Granulometric Compositions of Lagoon Substrates

The areal variations in the granulometric characteristics of the Simpson Lagoon substrate are displayed in Figure 15 whereas those of the Beaufort Lagoon (Fig. 4) were reported by Naidu (1980, 1981).

Following the classification scheme of Folk (1954), it is surmised that Simpson Lagoon sediments are very poorly sorted, slightly gravelly, muddy sands to slightly gravelly, sandy muds with the mean size generally in the silt category. In addition, the sediments display very positive- to positive-skewed (fine-skewed) and platykurtic to leptokurtic size distributions. Some broad areal variations in the gross texture were identified within Simpson Lagoon (Tucker, 1973; Naidu, 1981). From trend

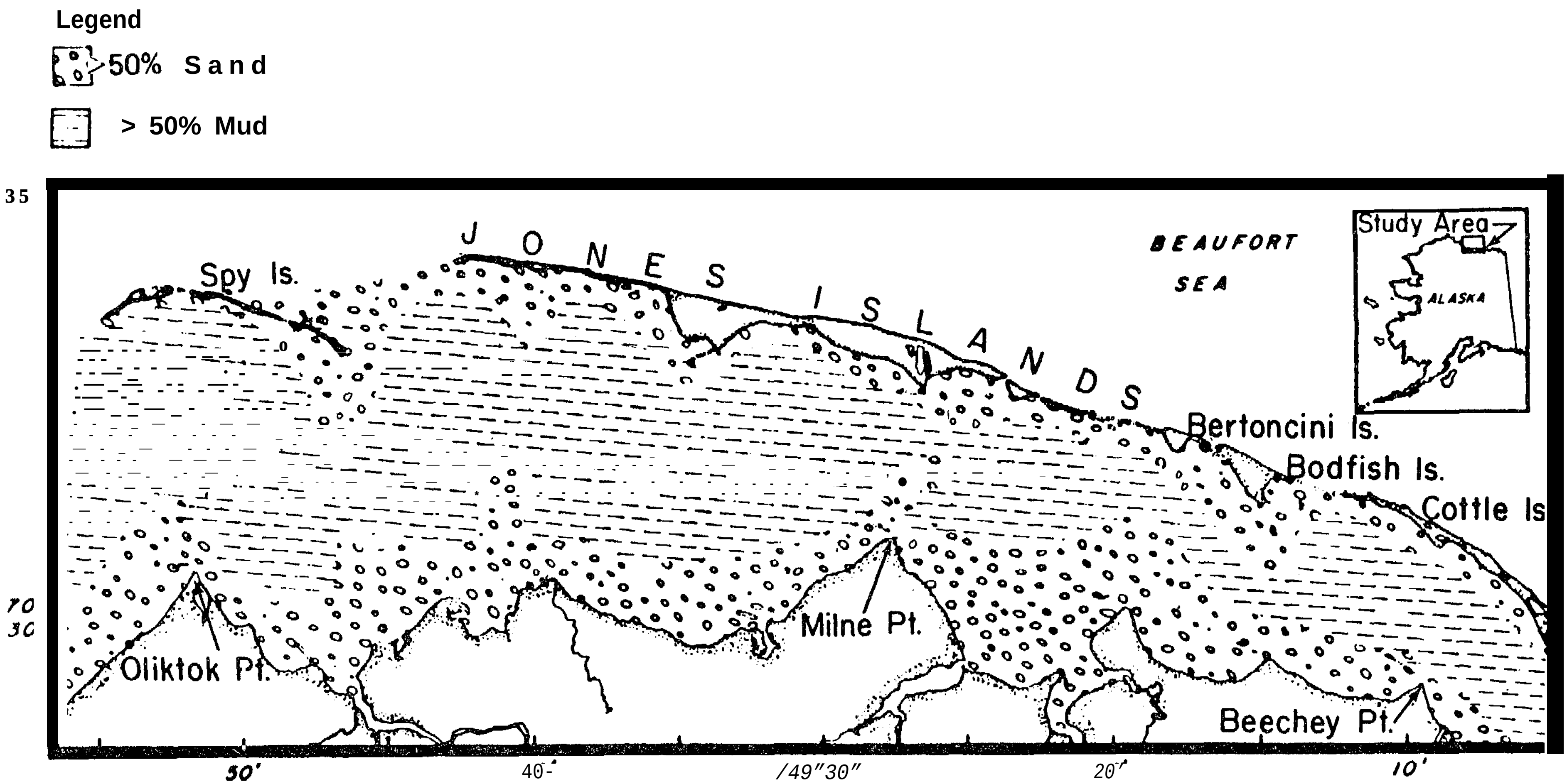

Figure 15. Characteristics of substrate lithology in Simpson Lagoon.

surface analysis, Tucker (1973) concluded that there is a net decrease in the mean size of sediments from the nearshore shallower portion to the deeper central lagoon. Substantiating this trend is the areal variation in the sand and mud contents (Fig. 15) . No definite regional patterns, however, were noted in the sorting and skewness values of size distributions. For the most part, Beaufort Lagoon sediments have textures quite similar to those of Simpson Lagoon; the only notable difference is in the virtual absence of gravel-size particles in Beaufort Lagoon. The Stefansson Sound substrate varies widely between muddy sands and sandy muds with occasional minor amounts of gravel and clean sands. Generally, the sediments are very poorly sorted, and strongly fine-skewed with the mean size between fine sand to fine silt. The above generalization on the Stefansson Sound substrates, which is based on analysis of grab samples, does not convey the actual situation, for the sound is widely strewn with boulders up to 1 m wide (K. Dunton, personal communication). In places, the course debris is sufficiently concentrated to form discrete boulder patches. All deposits of the barrier islands as well as those of the seaward beaches of the tundra islands are poorly to very poorly sorted, and consist either of gravelly sands, sandy gravels or clean gravels; the gravels are generally in the pebble size category. The mainland coastal beach sediments have similar size distributions. More precise size analysis data show that these sediments are either gravels, gravelly sands or sands that have poor to very poorly sorted, coarse- to fine-skewed and platykurtic size distributions. Exposures of boulders are restricted to beaches and onshore areas of the tundra islands and mainland coast, in addition to Stefansson Sound in the area of study.

Longitudinal sections of the four vibrocores from central Simpson Lagoon are displayed in Figure 16, and stratigraphic variations of the textures of two of the vibrocores are further shown in Tables III and IV. The lithology and structure between the four cores vary widely. In core V-49 the basal section (140-150 cm) is constituted mostly of finely divided and fluffy peat intermixed with fine sand, silt and occasional fossil residues of the freshwater gastropod *Valvata* and the pelecypod *Psidium*. Overlying this section is a 65-cm sequence of cross-bedded; silty fine sand with a few pelecypod shells of *Cyrtodaria kuriana* and *Serripes groenlandicus* (at 120-130 cm core section). This bed, in turn, is overlain by a 75-cm sequence of clayey to sandy silt displaying typical mottled structure in the base and laminated deposits the rest of the core. Core v-48 which shows more dramatic stratigraphic changes in lithology (Fig. 16) apparently is devoid of any freshwater sediment sequence. The lower 55 cm is a section with typical mottled structure with a number of the ostracod *Heterocyprideis sorbyana* Jones, 1886. There is a 20-cm laminated silty sand sequence intercalated between two layers (60 to 90 cm and 110 to 115 cm) constituted chiefly of gravels and pelecypod fragments. The top 60 cm of this core is a homogeneous silty sand. Stratigraphic analysis on cores V-47 and V-50 have not been completed. Presence of a laminated layer, however, is obvious in the top 50 cm of core V-50, whereas the rest of *his core and the entire core V-47 are apparently structureless and consist of homogenous clay-silt-sand. Examination of the vibrocore samples suggests that any designing of piling or footing driven into lagoon substrate must provide allowance for possible soft, peaty, muddy substrate.

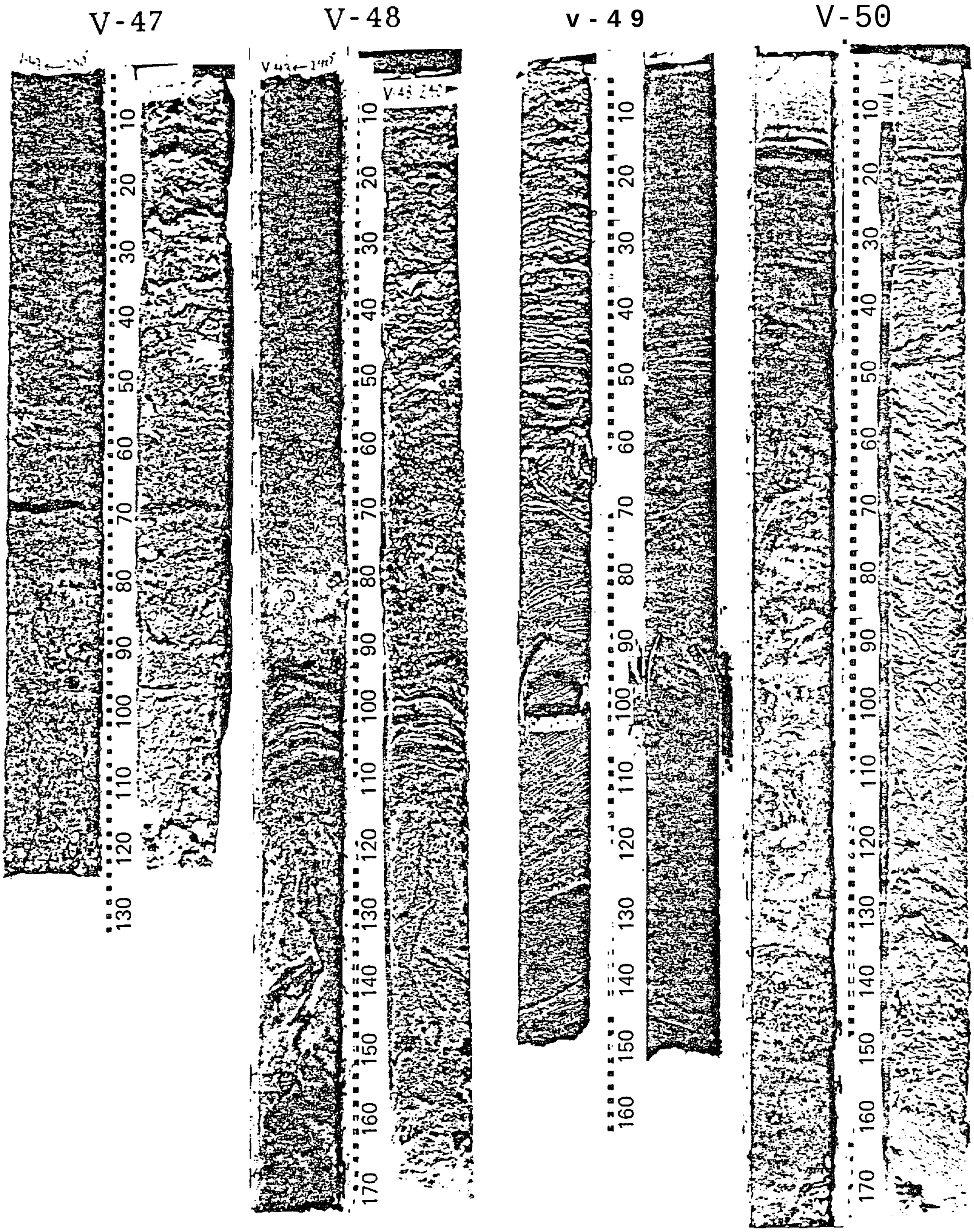

Figure *16.* Vertical sections of vibrocore samples from Simpson Lagoon showing variations in sediment structure.

TABLE III

Stratigraphic Variations in the Sediment Texture in the Vibrocore Sample V-48 from Simpson Lagoon

Core Section (cm)	Gravel %	Sand %	Silt %	Clay %	Md	M_z	δ_I	Sk_I	ʻG
0- 10		21.20	68.28	12.52	5.21	5.45	2.16	0.19	1.20
10- 20		13.60	77.24	9.16	5.03	5.42	1.73	0.33	1.38
20- 30		26.55	68.02	5.42	4.76	4.91	1.94	0.09	1.18
30- 50	1.42	28.80	65.96	3.83	4.41	4.68	1.92	0.15	1.09
40- 50	3.74	33.25	59.40	3.61	4.30	4.31	2.15	0.03	0.92
50- 60	2.55	69.38	25.58	2.49	2.06	2.35	1.94	0.65	0.95
60- 64	0.39	67.95	27.83	3.83	2.75	3.69	2.08	0.61	1.09
64- 70	0.08	75.81	21.48	2.62	2.66	3.17	1.72	0.55	1.31
70- 75	3.21	65.16	29.36	2.26	2.97	3.10	1.84	0.11	1.42
75- 95	100	-							
95-100		100							
110-120	0.31	75.64	23.50	0.55	3.40	3.29	1.25	0.06	1.55
120-130	0.75	72.14	24.75	2.36	3.23	3.18	1.43	0.13	1.41
130-140	0.71	71.48	25.18	2.62	3.15	3.20	1.48	0.24	1.37
140-150	0.18	64.36	33.11	2.35	3.53	3.45	1.40	0.13	1.44
150-160		67.09	30.71	2.20	3.36	3.36	1.45	0.19	1.33
160-165		56.13	40.12	3.75	3.79	4.03	1.79	0.23	1.39

TABLE IV

Stratigraphic Variations in the Sediment Texture in the Vibrocore Sample V-49 from Simpson Lagoon

Core Section (cm)	Gravel %	Sand %	Silt %	Clay %	Md	M_z	δ_I	Sk_I	KG
0- 10		15.35	78.55	6.10	4.72	5.16	1.46	0.47	1.08
10- 20	0.14	9.05	81.31	9.50	5.21	5.54	1.74	0.40	1.38
20- 30		5.52	86.79	7.69	5.91	5.90	1.38	0.13	1.40
30- 40	0.09	25.73	61.03	13.15	5.29	5.38	2.24	-0.02	2.56
40- 50		48.91	46.38	4.71	4.11	3.98	2.07	0.03	0.92
50- 60	0.73	64.26	31.39	3.63	2.78	3.73	2.12	0.58	1.03
60- 70		30.45	63.11	6.45	4.94	4.77	2.16	-0.02	1.03
70- 80	0.54	73.72	23.21	2.54	2.38	3.02	1.82	0.54	1.08
80- 90	0.67	99.33	-		1.87	1.85	0.49	-0.06	1.10
90-100	0.09	99.91	-		2.10	2.15	0.47	-0.15	1.21
100-110	0.12	99.88	-		2.39	2.39	0.39	-0.01	0.92
110-120		100.00	-		2.11	2.05	0.71	-0.17	0.91
120-130	0.46	92.02	5.98	1.53	2.19	2.12	1.00	0.02	1.46
130-150	1.70	51.25	26.13	20.92	3.69	4.18	2.63	0.21	1.22

Evolution of the Barrier Islands and the Associated Lagoons

Our studies relating to the evolution of the barrier islands along the Alaskan Beaufort Sea coast are not complete as yet. At this point in time we have rudimentary knowledge of the direction of alongshore net mass sand transport, which is based largely on the morphology of the barrier spits and long-term migration patterns of barrier islands. Studies were recently extended on the stratigraphy of vibrocore samples. Without adequate knowledge of the paleogeographic history of the inshore area, wave refraction patterns, sources and transport pathways of sand-sized particles, and submarine bottom profiles off the islands, it would be difficult for us to elucidate the barrier island evolution.

Field observations would seem to suggest that the Pingok, Bertoncini, Bodfish, Flaxman and other tundra blanketed islands are Pleistocene *relict* coastal highlands. In contrast to the above, islands with sand and/or gravel substrates, which are more abundant along the Beaufort Sea coast, are most likely resultants of contemporary marine constructive processes. By conventional definition* they are to be considered modem, notwithstanding that the gravel and sand constituting them may have been reworked from older residual deposit (e.g. deposit left from erosion of ancient tundra islands and/or coastal bluffs). The presence of several bars, hundreds of meters long and elongated roughly parallel to the Beaufort Sea coast, suggests that at least some of the barriers might have grown subaerially from bars as a result of progressive sediment accretion via alongshore drift. Incidentally, Wiseman *et al.* (1973) have reported the formation of several

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*For conventional definitions of relict, contemporary (or modern and palimpsest deposits, refer to Swift *et al.* (1971).

bars in the Beaufort Sea inshore as a result of standing wave action. Although evolution of the barriers can be addressed from several stand points (refer to Schwartz, 1973 for a review), our approach has been restricted to gathering geological evidences.

At the beginning of the investigations it was felt that the interpretation of the stratigraphic changes in both lithology and structure of the Simpson Lagoon cores (Fig. 16) would be a straight-forward simple effort, and that the recapitulation of the Holocene paleogeography of the North Slope coastal area and thus the origin of the barrier islands would not be too difficult to follow. However, it would seem that the recent paleogeographic history of the Simpson Lagoon area has been quite complex. This is indicated by the stratigraphic dissimilarities observed between the four cores that were collected from not-too-widely-apart locations within the lagoon. In spite of this fact, identification of the progressive changes in lithology, structure and coarse fractions of sediments in two core samples retrieved from Simpson Lagoon due southeast and south of Pingok Island (cores v-48 and V-49 in Fig. 5a), and coastal retreat measurements (Naidu *et al.*, 1982), have provided us with sufficient data that can be used to recapitulate the paleogeographic scenario pertaining to the lagoon evolution.

Basal sections of core V-49 suggest that the Simpson Lagoon region due west and south of the tundra islands was dominated in the recent geologic past by low-lying tundra coastal plain with a number of freshwater coastal lakes and/or ponds very similar to that of the present time. These lakes supported the freshwater gastropod *Valvata* and the pelecypod *Psidium*, and provided a relatively quiescent environment for growth of freshwater marsh vegetation and/or accumulation of terrigenous plant debris, now represented as a basal peat. As suggested by the carbon-14 date of the basal peat sample (separated at approximately 150 cm from the top of core V-49), the afore mentioned coastal plain with lakes dominated the above area around 4500 years B.P. Some time thereafter, it is believed that the lakes were occasionally breached and came to be in tidal communication with the sea either through tidal channels and/or heightened wave surge, as implied by a modest presence of faunal residues such as *Cyrtodaria kurriana, Serripes groenlandicus* and species of estuarine and/or marine foraminifera and ostracods (Table V) intercalated with seeds of a number of freshwater plants (e.g., *Chara, Hippuris vulgaris* L., and *Potamogeton* over the basal peat layer (at 120-130 cm below the V-49 core top, Fig. 16). The breached lakes then progressively coalesced and eventually were inundated by sea water (most likely coincident with subsidence of the lake beds resulting from subsurface permafrost thawing, and synchronous with the progressive deglacial rise in sea level).

Pingok Island and the adjacent tundra-blanketed islands delineated the inundated lakes from the open sea to form the present Simpson Lagoon. Obviously the upper 70 cm of muddy sediments in core V-49 are contemporary lagoonal deposits, whereas the sandy cross-bedded sequences between 70 cm and 145 cm in core V-49 most probably represent beach facies of the ancient shallow lagoon.

It is uncertain how much time elapsed between the formation of the lacustrine peat and marine inundation at the site of core V-49. Based solely on mean coastal retreat of 1.1 m yr^{-1}, about 2500 years are required to inundate Simpson Lagoon to this point according to the model of coastal bluff retreat (Naidu *et al.*, 1982). This implies a hiatus of 2000 years. Alternately, coastal retreat then may have been slower than the present mean rate, and Simpson Lagoon may have been inundated to the site of core V-49 shortly after 4500 y.B.P.

TABLE V

Species of Foraminifera and Ostracods in Some Sections of Vibrocore Samples of Simpson Lagoon, and in recent Sediments of Beaufort Lagoon

CORE v-48

120-130 cm;	Foraminifera:	*Elphidium excavatam alba* *Elphidium incertum* *Elphidium Orbiculare* *Buccella frigida* *Polymorphina suboblongata*
130-140 cm;	Ostracod:	*Heterocyprideis sorbyana*

CORE v-49

120-130 cm;	Ostracods:	*Rabilimis septentrionalis* *Paracyprideis pseudopunetillata* *Eucytheridea bradii* *Cytheretta edwardsi* *Candona rectangulata* *Illyocypris bradii*
	Foraminifera:	*Elphidium excavatum alba*

Beaufort Lagoon (Recent Sediments)

Foraminifera:	*Elphidium excavatum alba* *Buccella frigida* *Polymorphina suboblongata* *Elphidium nanum*
Ostracod:	*Paracyprideis pseudopunctillata* *Cytheromorpha macchesneyi*

The evolutionary history of eastern Simpson Lagoon has been complex and, perhaps, this is true for all lagoon areas of north-arctic Alaska that are now encompassed by barrier islands. It is probable that core V-48 did not extend sufficiently deep to encounter coastal plain deposits. A lack of any well-defined freshwater deposits, and the presence of well-preserved foraminifera and ostracod tests throughout core V-48 imply that eastern Simpson Lagoon was probably in tidal communication roughly at the time when the western lagoon was part of a coastal plain. This interpretation is consistent with the coastal bluff retreat model discussed by Naidu *et* al., 1982. Again, based on mean coastal retreat of 1.1 m yr^{-1}, only about 1500 years are required to inundate Simpson Lagoon to the site of core V-48. Regardless of when inundation occurred, it is possible that inundation of site V–48 preceded inundation of site V–49 by approximately 1000 years. The mottled structure as displayed in the lower 50 to 55 cm layer of gravelly silty sand of the core is suggestive of intense bioturbation of substrate some time in the past. The occurrence, however, of a well-defined, thin gravel layer between 75 cm and 95 cm of V-48 and sandwiched between gravelly silty sands connotes that the depositional process in the eastern lagoon was briefly punctuated by the formation of a transient gravel bar, barrier island or barrier spit.

Stability and Growth Rate of the Pingok Island Barrier Spit

It is now reasonably well documented that almost all barrier islands along the Alaskan Beaufort Sea coast have undergone some degree of temporal geomorphic changes, irrespective of the nature of the islands whether they are tundra blanketed or not. The changes in the configuration of some of the islands over a few decades (from 1906 to 1974) have been assessed by Wiseman *et al.* (1973), Barnes *et al.* (1977), Lewellen (see Hopkins *et al.*, 1977 and Naidu *et al.*, 1982). The relatively short-term changes within one summer season for the Pingok–Leavitt island have been documented by Wiseman *et* aZ. (1973) and Dygas *et al.* (1972). Areviewof the above literature shows that the lateral growth rates of the barrier spits of the various islands are significantly different, and within any one summer great fluctuations in the above rate can be noted. However, there is a general consensus among most geologists working in the Beaufort Sea coast that the net alongshore drift of sediments along that coast is toward the west.

One of the many research objectives, embodied in RU 529, was to look for evidences that might assist in assessing the long-term net alongshore sediment transport direction, as well as to estimate the long-term growth rate of barrier spits along the Alaskan Beaufort Sea coast. In attempting to fulfill the latter objective, field surveys on Pingok Island were conduc ted. During the course of this survey a peat formation was encountered on the seaward beach at the proximal end of the sand-gravel barrier spit extending to the west of the Pingok Island (e.g., the Leavitt Island). Evidently the peat deposit was not a remnant of an old collapsed coastal bluff, because it was quite an extensive contiguous formation. At the high-water mark where a vertical section of the north shore of the spit was exposed, the peat was observed to lie under an overburden of 84 cm of sand and gravel. Apparently the same peat layer extended continuously under the barrier spit, as suggested by the detection of another peat deposit under 79 cm of sand-gravel over–burden in a trench in the center of the barrier spit. It was assumed that a radiocarbon date on a sample of the upper layer of the peat would indicate the geologic age when the sandy-gravel barrier spit most likely started to grow westward from the Pingok Island*. The peat sample thus dated provided an age of 2600 years B.P., implying that the barrier spit was geologically quite a young formation. Additionally, on the basis of this date and the approximate 5.5 km length of the spit (included the Leavitt Island) as recorded in 1977 it would seem that the average long-term linear growth rate of the spit on a steady state basis was around 2 m/year. Further, assuming that the average thickness and width of the spit (as estimated in 1977) was 1 m and 140 m respectively, it would seem that the long-term accretion rate of the spit volume was in the order of approximately 280 m^3/year.

It is interesting to compare the growth rates for the western Pingok Island spit that we have estimated on long-term basis and those reported earlier by Wiseman *et al.* (1973) on a seasonal basis. The latter estimated the spit growth rate in summer 1972 based on evidences gathered in the field, as well as taking into consideration data from Dygas *et al.* (1972).

The linear growth rate of the Pingok barrier spit, as cited by Wiseman *et al.* (1973) was 6 m/year while the rate for volumetric increase was about 7.1 x 103/summer. These accretion rates of the barrier spit in question are considerably higher than our figures. It would be of interest to check what portions of the total length and volume of the spit accretion in summer could be ascribed to catastrophic storm action and what portions to normal current/wave action. It would also be of importance to estimate the decrease

*This contention assumes that the upper portion of the peat and the sand-gravel unit lying over it are more or less a continuous sequence of sediments and that there was no great depositional time gap between the sedimentary units.

in the spit areal size consequent to ice bulldozing during the ice stress season. As observed by us as well as several others, occasional storm surges can bring about large-scale degradation (e.g., in the order of 10-15 m) along some beach stretches, with almost concomitant progradation at other beach sites along the Beaufort Sea barriers. The sum total resultant of the storm and ice-ploughed actions on the sediment "budget" of the spit is unknown, but is conceivable that the two counteracting processes will eventually amount to net spit growth rates which are relatively much lower than the estimates that were provided by Wiseman *et al.* (1973) on a seasonal basis. It is, therefore, no wonder that Wiseman *et al.* (1973) have observed only a modest change in the spit length west of Pingok (tundra) Island between 1908 and 1972 (e.g., 64 years). Presently it would seem imperative that additional long-term data must be gathered before more precise estimates can be provided of the barrier spit growth rate on the Pingok Island.

In conclusion, barrier islands of the North Arctic coast of Alaska are a dynamic component of the geomorphology of the above coast. Migration and growth rates of these islands vary widely (perhaps between 1 to 30 m) and their lateral growth on a long-term basis is determined by sand nourishment via the net westward littoral drift. No reliable, quantitative estimate of the littoral drift are available presently. Without the latter data and complementary information on the wave energy flux as well as wave diffraction patterns, it would be difficult to predict what may be the possible impacts on the physical integrity of the barrier island-lagoon-inlet composite, consequent to building of causeways, offshore islands and docks, and dredging. It is quite conceivable that the overall sediment budget in the Beaufort Sea littoral zone may be so significantly perturbed as a result of the above anthropogenic activities that large-scale erosion of some barriers followed by unusually high deposition of the eroded sediments at inlets or other barriers may finally alter the circulation pattern in the adjacent lagoons and nearshore. This could ultimately lead to deleterious effect on the ecosystems of the adjacent lagoon and the nearshore. At present there is a serious data gap pertaining to littoral transport estimates. Perhaps these estimates must be obtained on a site specific basis or for various stretches of the Beaufort Sea coast, because the rate of migration and growth of the various barrier islands vary widely and thus data from one coastal area to another can not simply be extrapolated.

In another context, the highly migratory nature of the barriers and adjacent bars implies that any pipelines, cables and footings emplaced on the sea bottom surface of the inshore areas may be buried.

STRUCTURE AND ORIGIN OF TURBID PLUMES IN COASTAL AREAS IN LATE SUMMER

Satellite images clearly display that movement of turbid plumes along the nearshore lagoons and bays of North Alaskan Arctic was either in the form of long continuous plumes or disconnected irregular streaks and wedges. With the exception of the Tigvarik Island area where an eastward moving turbid gyre was apparent, along the rest of the Alaskan Beaufort Sea coast the nearshore turbid plume was invariably seen to move westward. The latter water movement was impelled by the prevailing westward littoral currents. However, it would seem that the tongues of turbid plumes in the lagoons and bays in mid and late summer (i.e., late July-September) could not, to any large extent, be ascribed to fluvial discharge and/or thermoerosion of coastal bluffs and barriers. No such direct association was apparent from detailed scrutiny of several multi-year satellite images, although invariably extensive turbid plumes do occur in the vicinity of large river mouths. It is important to note that waters relatively free from suspensions (about 1 mg/l) are discharged in late summer from mouths of the major distributary channels, while presence of relatively turbid waters can be delineated at some distance off the mouths. Additionally, the satellite images displayed that the parcels of lagoon waters extending up to a few meters away from the coastal bluffs and barrier islands were observed to be relatively less turbid than the rest of the lagoon. A notable example was the Dease Inlet region. All of these observations led us to suspect that in mid and late summer when the fluvial outflow was low, much of the turbidity in coastal waters could be associated to resuspension of the cohesionless substrate particles from shallow-water regions by wave induced agitation. Since the region slightly off the river mouths are generally more shallow and are constituted of unconsolidated clays it was not surprising that relatively high turbid waters are associated with such areas. Subsequent to resuspension the particles are carried westward in the form of a turbid plume.

No estimates are available on the concentrations of sediment particles that are resuspended off the river mouths by waves in late summer. I have documented for 1981 summer the concentrations of suspended particles on water samples that were collected from certain known geographic locations of the Beaufort Sea nearshore and which coincided with the LANDSAT satellite passages overhead in that region. These ground truth data on suspensates were forwarded to Dr. W. J. Stringer of the Geophysical Institute, University of Alaska (Fairbanks). Dr. Stringer will be generating density-sliced

LANDSAT images synchronizing for those days and time when our water samples were collected. Hopefully, correlating the image densities with the ground truths on suspensate concentrations reliable criteria would be developed to provide with a means to infer the concentrations of particles off the river mouths.

It is contended that the quantification of the concentration of particles resuspended naturally by wave-induced turbulence may have important bearing in attempting to predict the possible ecological impacts of increased turbidity resulting from anthropogenic activities such as dredging and occasional discharge of drilling spoils. Will the concentrations of particles that are naturally resuspended be similar to those in the discharged spoils? If no significant difference can be identified between the two then the above-mentioned anthropogenic activities may not pose a serious environmental hazard in the Beaufort Sea. Alternately, if substantial differences in the suspended loads are shown then environmental managers will be compelled to regulate the rate and volume of discharge of dredge and drilling spoils to closely match natural situations of water turbidity.

Our investigations has led us to believe that any initial deposition of fine-grained dredge or drilling spoils (and perhaps also any inorganic or organic pollutant scavenged by naturally depositing mud) will be periodically resuspended from the inshore areas of the Beaufort Sea, during the open-water season by wave-induced turbulence. Because such resuspended particles will be quickly redispersed and laterally diffused by the littoral currents the initial deposition of any pollutants may not pose a permanent hazard to benthic communities of the inshore areas. This seems to be substantiated by the field and complementary laboratory studies conducted by

Northern Technical Services, Anchorage (1981) on drilling effluents in the Reindeer Island site of the Beaufort Sea. However, any large-scale resuspension of pollutant charged substrate at the freeze-up period may get entrained and concentrated in the sea-ice, with possible deleterons effect on the frazil organisms in the sea-ice.

SEDIMENT DYNAMICS STUDY

Tripod Experiments

It was only recently that serious process-response sedimentological investigations were initiated for the Beaufort Sea nearshore. Results of preliminary sediment dynamic studies were reported by Naidu (see 1979 to 1981 Annual Reports Submitted to OCSEAP). Our progress was limited by quite frequent losses of instruments which were not specifically designed for work under ice-stressed conditions. The instrumented package on a tripod - the Sediment Dynamics Sphere (SDS) -which was used by us was originally designed by the University of Washington (Lahore *et al.*, 1977), to obtain time-series hydrodynamic parameters in context with sediment dynamic studies, in ice-free continental shelf area. This instrument was subsequently redesigned by us to operate satisfactorily in the arctic; the fabrication of the latter prototype model was completed and is ready to be deployed. We believe, therefore, that we have now the right type of instruments to pursue sediment dynamic studies in the Alaskan Arctic. Limited investigations would seem to suggest that the processes of sediment entrainment, transport and deposition in summer 1979 in the Simpson Lagoon were not the same as those which prevailed in summer 1978. Plotting of the summer 1978 time-series data exhibited apparent correlations between wind strengths and suspensate concentrations at the

Milne Pt. tripod station. On the basis of those correlations, Naidu (1979) suggested that the threshold of wind to induce wave-current sediment resuspension in Simpson Lagoon at the tripod station was about 8 m/see. That conclusion does not seem to be well substantiated by the summer 1979 data which indicate quite suspension-free waters at 10.5 to 13 m/see winds at the tripod station (about 2.9 m water depth) in the Simpson Lagoon. It is to be noted that in 1979 the spring break-up was unusually earlier, and in middle and late summer (August-September) abnormally high sediment-laden fluvial discharge was observed. Implication of these unusual events, if any, on summer 1979 suspended load budgets could not be assessed because of lack of LANDSAT images for the period.

Conceptual Model for Sediment Concentration in Frazil Sea-ice of North Arctic Alaska

The presence of sediments in frazil sea-ice, in concentrations 2 to 3 orders of magnitude higher than in ambient coastal waters, has been an enigma to investigators working on sea-ice problems in the nearshore of Beaufort Sea. The question that has been time and again raised refers to the mechanism which leads to the entrapment of sediments in ususual concentrations in the ice. Many ideas were presented (refer to Schell, 1980 for detailed discussion on the subject), but none seem to have offered a satisfactory answer. A commonly held notion has been that occurrence of storms during the incipient freeze-up period is critical to entrain large quantities of sediments into the water column, and that the subsequent fixation of the suspended particles on ice could account for the unusual particle concentration in the sea-ice (Barnes *et al.*, 1982). However, the exact mechanism for such fixation was not defined by the above authors. The other ideas prescribed took into consideration adfreezing of suspended charged waters, which would seem untenable in most cases. It is hard to believe that in the Beaufort Sea nearshore intensified wave action during occasional storms is capable of suspending fine sediments in concentrations as much as 200 to 750 mg/ℓ – the levels generally observed in sea-ice*. Alternate concepts for the unusual sediment accumulation in sea-ice refer to possible anchor ice sediment entrainment, or to occasional 'ducking' and sediment scraping by highly fragmented frazil ice by storm surge wave action. The lack of any textural correlation between sediments of substrate and overlying sea-ice for any specific inshore region, does not seem to add much credence to the thesis of sea-ice scraping bottom sediments. Additionally, the occasional scrapping process would tend to be manifested in sediments occurring as streaks, blebs, and bands in an otherwise clean sea-ice, which are definitely not observed.

In the following is presented a hypothesis that might explain the processes leading to the unusual sediment concentrations in sea-ice. During freeze-up period** when continuous fluxes of suspended particles, borne in laterally moving currents of water impinge on highly porous, undulating slushy*** sea-ice the particles are assumed to retain by the mesh of slushy ice crystals. It is further contended that as the sea-ice grows, fresh surfaces are successively exposed for continuous retention of suspended sediment particles. Moreover, occurrence of storms during freeze-up time would seem to be a critical factor for the sediment accumulation at the vicinity

*The extremely turbid water debauching from the North Slope rivers generally has between 70-100 mg/ℓ of suspended-particles, and this fluvial plume stands out in LANDSAT images. None of the LANDSAT images during freeze-up time (or storms) show such turbid waters offshore.

**After the formation of pan-cake ice.

***Slushy and rough nature of sea-ice seems critical for particle adherence.

of sea-ice/water interface, because higher water turbulence will maintain the slushy nature of the accreting sea-ice surface in addition to providing larger fluxes of suspended particles for potential accumulation at the surface. For particles to accumulate at concentration levels equivalent to those generally observed in the ice (i.e., 200 to 750 mg/ℓ) it would be crucial that the concentrations, supply and accumulation rates of particles at the sea-ice/water interface are sustained at a certain optimum level and are commensurate with the sea-ice growth rate. It would seem that in the Beaufort Sea nearshore the critical particle supply and accumulation rates are adequately carried, as suggested by the followup computations. Assuming that during freeze up period the mean suspensate concentration in the nearshore waters is about 1 mg/ℓ, mean current strength is at 10 cm/see, and the slush-ice accretion rate is about 1 cm/day, it is estimated that the maximum possible sediment accumulation on sea-ice will amount to about 850 mg/ℓ. However, it is most likely that the suggested sediment accumulation process is less than 100 percent efficient. Assuming that the process is only 25 percent efficient it would still be possible to satisfactorily explain, within the said process framework, the nearly 200 mg/ℓ sediment concentrations generally observed in frazil sea-ice.

The general lack of sediment concentrations in the lower segments of sea-ice is perhaps attributable to the process by which those segments are formed. Accretion of sea-ice in the lower portions presumably occurs as relatively smooth, horizontal, and consolidated sheets rather than as porous, undulating slush. The lack of slushiness seems to be promotes by relatively tranquil waters, which in turn obviously results from the lack of fetch sometime after the initial frazil ice formation. It is surmised that the horizontal consolidated sheets do not offer as effective a surface as the rough surface of slush ice for sediment accumulation.

The hypothesis presented above is of course conceptual in nature, and must be verified by laboratory experiments conducted in freezing tanks and supplemented by correlation of time-series hydrographic measurements during freeze-up period and chronologic characterization of the ice structure and concentration of particles in sea-ice. At any rate, understanding of the processes which lead to the concentration of sediments in sea-ice will certainly have implication on several environmental related problems (e.g., pollutant entrapment by ice; the relevance of sediment in sea-ice to light attenuation and hence spring primary productivity, etc.) .

Sedimentation Rates

Several gravity and box core samples were taken to estimate the upper limit of sedimentation rates, based on ^{210}Pb dating techniques, for the Simpson Lagoon, Prudhoe Bay, Harrison Bay, a coastal lake, continental shelf and continental slope of the Beaufort Sea (Fig. 5b). In the eastern margin of Harrison Bay the rate ranged between 0.60 cm yr^{-1} and 1.64 cm yr^{-1}, and in the Simpson Lagoon there was a net decrease from 0.82 cm yr^{-1} in the western end to 0.52 cm yr^{-1} in the central lagoon due south of Pingok Island (Fig. 17). The lateral variations in the sedimentation rates within the continuous bay-lagoon region was obviously a reflection of the volume of deposition of the Colville River debris. No meaningful rate could be obtained for the continental shelf, central and western Harrison Bay, and central Prudhoe Bay because of a lack of a clear-cut net linear exponential decay in ^{210}Pb. Presumably, reworking of sediments by ice-gouging and bioturbation

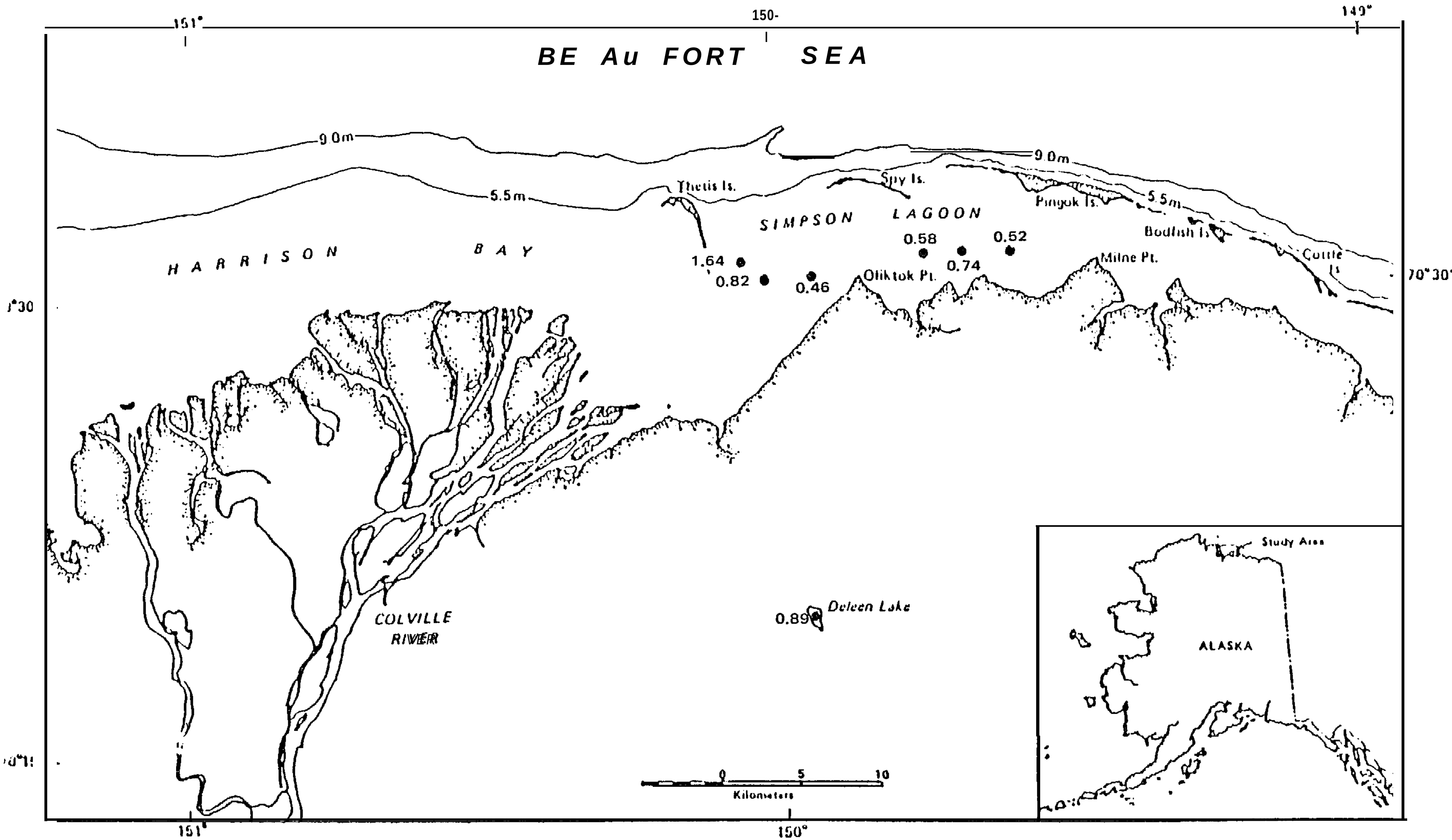

Figure 17. Sedimentation rates (cm/yr) in the Deleen Lake, east Harrison Bay and Simpson Lagoon, based on ^{210}Pb method.

homogenized the ^{210}Pb stratigraphy in the above regions. In the continental slope the sedimentation rate was relatively low (i.e. , between 0.70 to 0.45 mm yr^{-1}). In the coastal lake the rate was about 0.89 cm yr^{-1}.

Our 210Pb stratigraphic work suggests that with the exception of some semi-enclosed bodies of coastal waters, such as the lagoons, the sediments of the Beaufort Sea for the most part are subjected to frequent reworking and redistribution by ice-gouge action. The undisturbed nature of the lagoon sediments was additionally attested to in upper sections of vibrocore samples (Fig. 16), which clearly display the preservation of primary sedimentary structures and sediment sequences that are sharply delineated. On the basis of these observations it would seem that any pollutant that may be scavenged by, or codeposited with, the substrate marine sediments they would frequently be remobilized from subsurface layers and thus could be exposed periodically to biological communities. The common notion that sediments are generally a very effective means to permanently scavenge pollutants may have a limited relevance to the arctic shallow marine area.

Estimation of the baselines of sedimentation rates for various depositional sites would seem to be crucial in developing criteria to detect possible changes in sediment budgets and metal fluxes resulting from industry-related coastal activities. As discussed earlier, the ^{210}Pb technique in the north arctic would seem to offer a limited means to estimate these rates and fluxes and, as such other methods must be explored.

Sources and Origin of Erratic Boulders on Alaskan Beaufort Sea Coast

Results of the detailed petrographic studies on 105 separate samples of boulder chips and visual inspection of hundreds of samples in the field have enabled us to define the composition of the boulders that are scattered on the beaches of the Pingok, Bodfish and Flaxman Islands, and on the coastal plain in the vicinity of Prudhoe Bay and lower Canning River of North Arctic Alaska. Petrographically the coastal boulder and cobble specimens are diabases, volcanics, granites, elastic sedimentary rocks, carbonates, cherts and metamorphic (medium- to high-grade) rocks. Detailed descriptions of these rock types are included in Mowatt and Naidu (1974) and Naidu (1979). Based on knowledge of known rock types in the Brooks Range, Davidson, British and Romanzof Mountains and the MacKenzie River drainage area it would seem most unlikely that the boulder samples had their source in the hinterland of Northern Arctic Alaska or the adjacent Northwest Canada (i.e., MacKenzie Valley). Besides, no conceivable mode of transport can be invoked to explain the means of moving boulders from the far hinterland highlands to the Beaufort Coast. The lower area of the coastal plain of the North Slope was not glaciated by mountain glaciers during the last two glacial epochs and therefore, the boulders are not ancient morainic debris from the Alaskan Arctic. Possible fluvial transport of the boulders seems unacceptable considering the presence of glacial striae on some of the boulders and the angular nature of the boulders, and the long travel distances that might have been involved. Additionally, representatives of some of the typical lithologies among the boulder assemblages were not observed in the present fluvial bed loads of the North Slope rivers.

Based on the unique lithologic assemblage and the relatively old age of three separate samples of a red/dark pink granite (i.e., 1.6*, 2.1* and

*Ages kindly provided by S. Rawlinson from his unpublished reports.

2.4 billion years), and the regional geology of the archipelago and shield areas of Canada (Geol. Sot. Canada, 1970), it is contended that the boulders probably have a major source in the region due south of the Coronation Gulf of Northwest Territories, Canada (i.e., east of the Great Slave and Great Bear Lake Provinces). In the past, we had believed that the Ellesmere Island in the Canadian Archipelago could have been an important additional provenance for the boulder deposits. However, this notion is not consistent with the virtual absence of dolomites and limestones on the ice island T-3 (Stoiber *et al.*, 1956), and the common presence of boulders of these two rock types along the Alaskan Arctic coast. It is generally contended that the ice island T-3 calved from the Ellesmere Island ice shelf. We have not ruled out other possible source areas such as Northern Greenland (Hopkins, 1978a) for the coastal boulders in question. It is suggested that only further detailed geological mapping of the various potential areas will help resolve the boulder source(s).

The scenario which has been drawn in attempting to define the transport mechanics of the erratic boulders to the Alaskan arctic coast, dwells upon the theme that the boulders were ice-rafted by large bergs (Leffingwell, 1919; Naidu, 1974; Mowatt and Naidu, 1974) presumably some time during interglacial interval(s) when sea-level was at least 3 or 4 meters higher than the present (Naidu, 1974; Hopkins, 1978a,b). Hopkins (1979) further contended that with a synchronous rise in sea-level during the Pelukian Transgression (last interglacial) the above icebergs were calved and set free (with the boulder burden associated with them) from an ice shelf that presumably extended into the arctic continental shelf from northern Keewatin and south-central Elizabeth Islands of Canada

(Hughes *et al.*, 1977; Denton and Hughes, 1981; Hopkins, 1979). Lately I have become quite skeptical of the ice-rafted concept, because of the difficulty in accepting the incursion of large bergs with deep drafts into inshores of the Alaskan Beaufort Sea. It would seem that bergs, sufficiently large to be able to carry big boulders, would have been grounded around the continental shelf margin of the ancient Beaufort Sea just the way some of the larger ice islands (with mean thickness of about 17 m) do moving inshore in present time. Alternatively, the ice-rafting concept would imply that the ancient Beaufort Sea shelf was tectonically or isostatically depressed during the interglacial transgression when the boulders were ice-rafted and deposited at the North Alaskan Arctic coastal area. However, there is no substantiative evidence to support that the above coastal area has been tectonically very active.

In light of the foregoing context, I have been tempted to entertain an alternative idea. It is quite possible that the erratic boulders of the Alaskan Arctic coast were borne and transported by a continental ice sheet rather than icebergs. I contend that such a sheet was a distal tongue of the much larger Laurentide ice complex (Flint, 1943). Conceivably, such a sheet had extended at the height of the Wisconsinan glaciation (late Würm; around 18,000 y.B.P.) across the Northwest Territories (Canada) and along the southern margin of the Beaufort Sea continental shelf, as well as the adjacent coastal hinterland via the Coronation Gulf, Dolphin and Union Straits, and had an outlet into the Beaufort Sea at Amundsen Gulf. It is further conceivable that the boulders which were carried by such an ice were stranded as residual lag deposits at more or less their present sites of occurrence upon the melting of the Wisconsinan ice sheet. The possibility that such an ice sheet extended into the Beaufort Shelf is apparently implied by the successive inferred positions of glacial ice margins during the Wisconsin for North America (Prest, 1969; Denton and Hughes, 1981). It has been speculated by Prest (1969) that the retreating margin of the North American ice was at the vicinity of the mouth of the Amundsen Gulf around 14,000 years ago. Therefore, it would not seem unreasonable to assume that at the height of the late Würm glacial epoch (i.e., centered around 18,000 y.B.P.) the Wisconsinan ice might have extended farther out perhaps along the present Beaufort Sea coast and the adjacent hinterland and, thus, carried the train of boulders along with it. The foregoing scenario, although perhaps somewhat simplistic, nevertheless would seem to be more credible than the ice-rafting idea. It is suggestive that Prest's (1969) map showing the speculative ice-marginal positions during recession of the Wisconsinan ice-sheet complex may be somewhat out dated (see Hughes *et al.*, 1977; and Hopkins, 1979 for further discussion and additional references). If this is true, then the timing of the suggested extension of the Wisconsinan ice-sheet into the Beaufort Sea shelf may have to be revised (perhaps to early Wisconsin). More recently Hughes *et al.* (1981) offered explicit evidence to show that Laurentide ice lobes had in fact engulfed the coastal region of northeastern Yukon Territory in late Wisconsin time. Therefore, the proposed idea of transport of the boulders by an ice sheet rather than icebergs, remains for serious consideration.

CLAY MINERALOGY OF THE BEAUFORT SEA

The predominant clay mineral in the < 2 μm fraction was illite (45-70%) with relatively minor amounts of glycol expandable minerals, kaolinite, chlorite and mixed-layered phases. The dispersal patterns of the expandable minerals and the kaolinite/chlorite ratios in the continental shelf of the Beaufort Sea are exhibited as Figures 18,19 and 20, and the distribution of illite is shown in Figure 21 and was discussed elsewhere (Naidu and Mowatt, 1982). Significant regional variations existed in the concentrations of the expandable minerals in the Beaufort Sea. The marine facies of the Colville Delta had the highest concentrations (30 percent or slightly more) followed by a net seaward decrease to less than 10 percent off the delta. The adjacent nearshore region north of the Kuparuk and Sagavanirktok Deltas, the outer continental shelf of the Alaskan Beaufort Sea and the entire shelf off the Mackenzie Delta had a general paucity of expandable minerals. It is notable that a narrow isolated band, extending east-west in the central continental shelf off the Canning River, had relatively more (20 to 28 percent) expandable minerals (Figs. 18 and 19). Although no systematic downstream variations in the expandable minerals was recognized within the lower 170 km of Colville River (Mowatt *et al.*, 1974; Naidu and Mowatt, 1975), a definite net decrease in the concentrations of these mineral phases was identified seaward from the contemporary subaerial part of the Colville Delta (Fig. 22). An illite-enriched belt extended eastward of Point Barrow into the Beaufort Sea and was confined to the nearshore up to the western margin of the Colville Delta (Fig. 21). Subsequent lateral variations in illite abundances were sharply delineated along the coasts of the major deltaic systems of North Arctic Alaska. For example, sediments with relatively low (38 to 40 percent) illite were restricted to the marine facies of the Colville Delta including Harrison Bay, whereas a sharp increase (> 60 percent) was apparent off the Kuparuk and Sagavanirktok Rivers (Fig. 21). Coinciding with the relatively

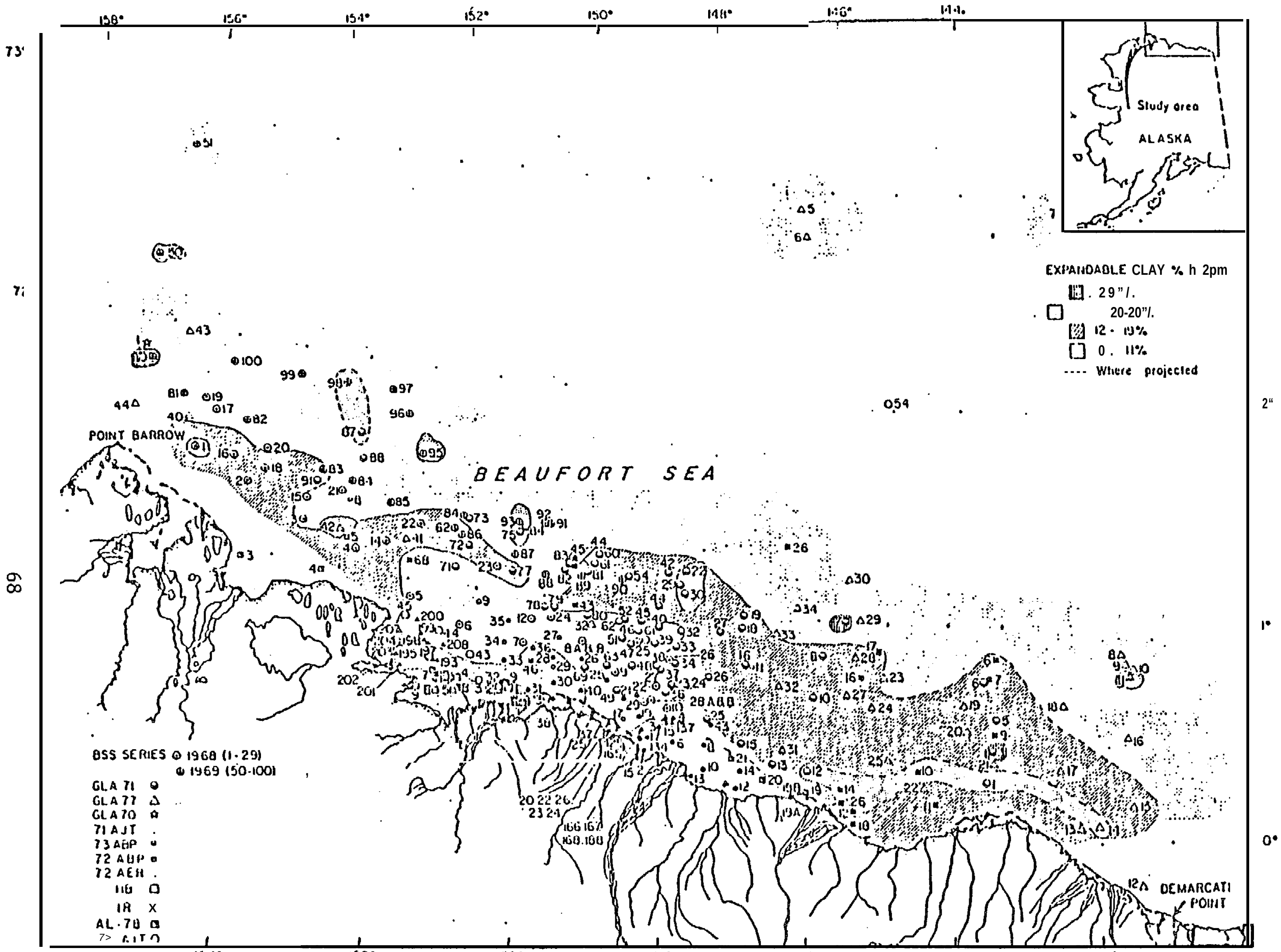

Figure 18. Expandable clay mineral distribution in Beaufort Sea surface sediments.

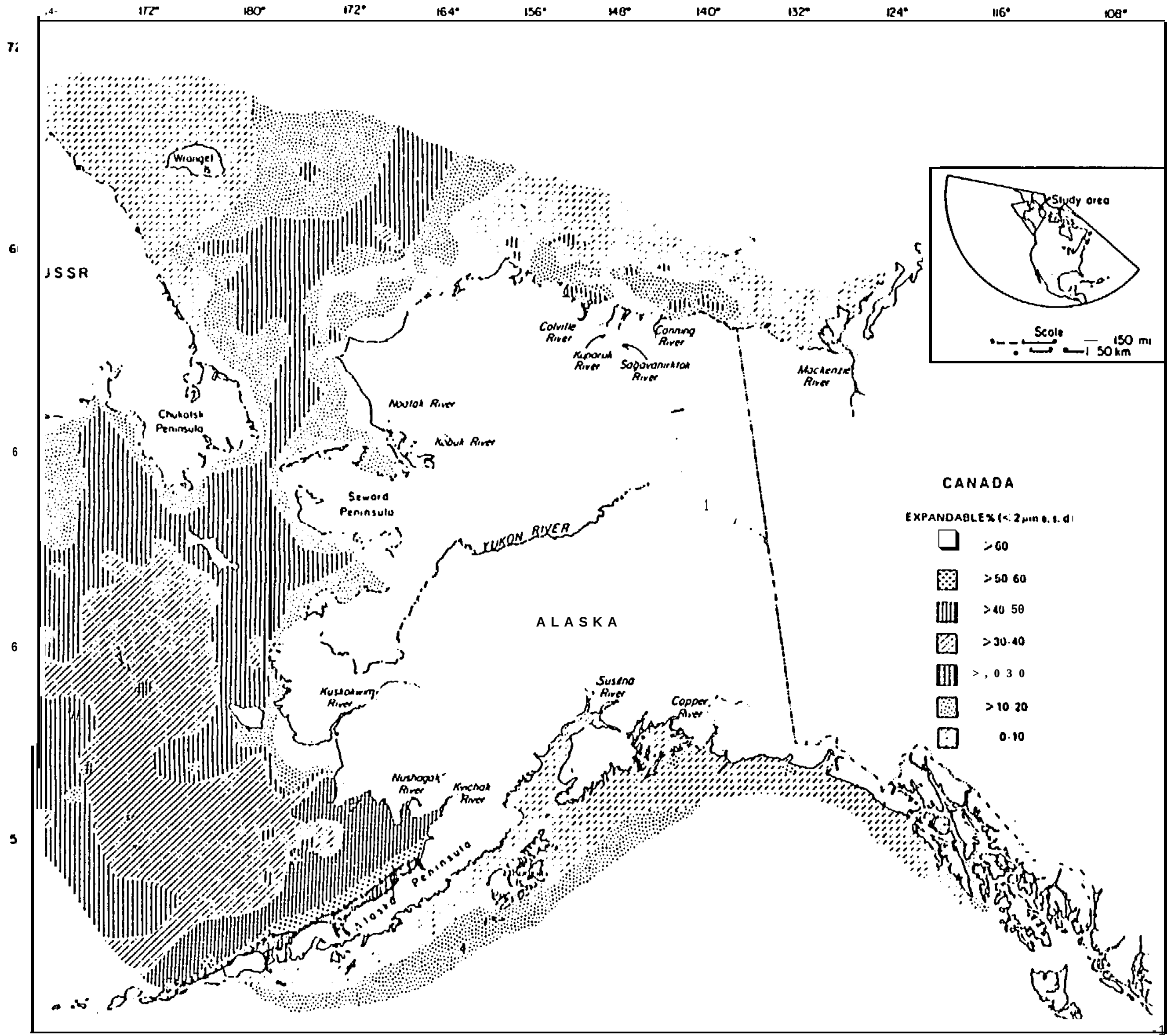

Figure 19. Distribution of the expandable clay mineral group in marine surface sediments of Alaska (After Naidu-and Mowatt, 1982).

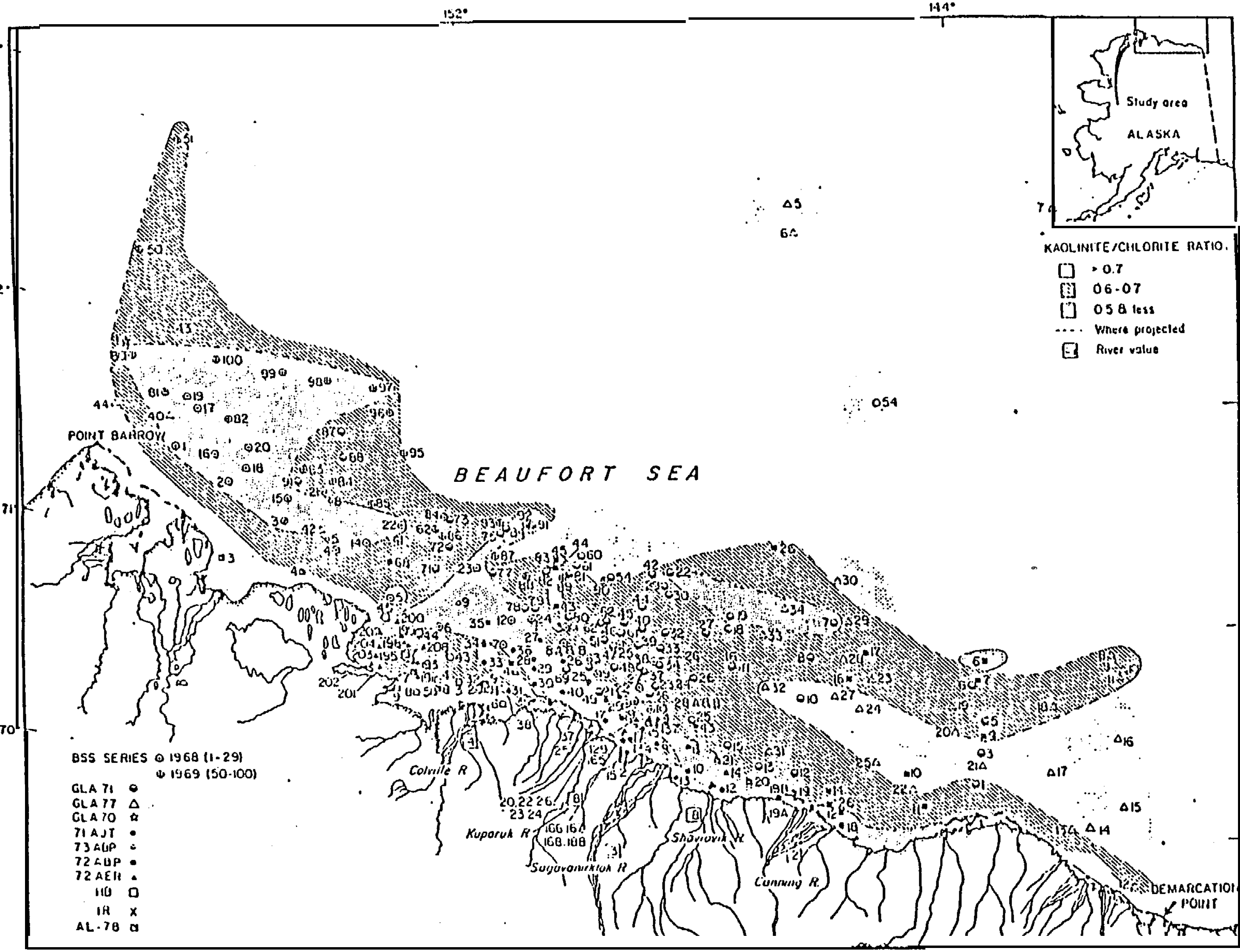

Figure 20. Kaolinite/chlorite ratio distribution in Beaufort Sea surface sediment.

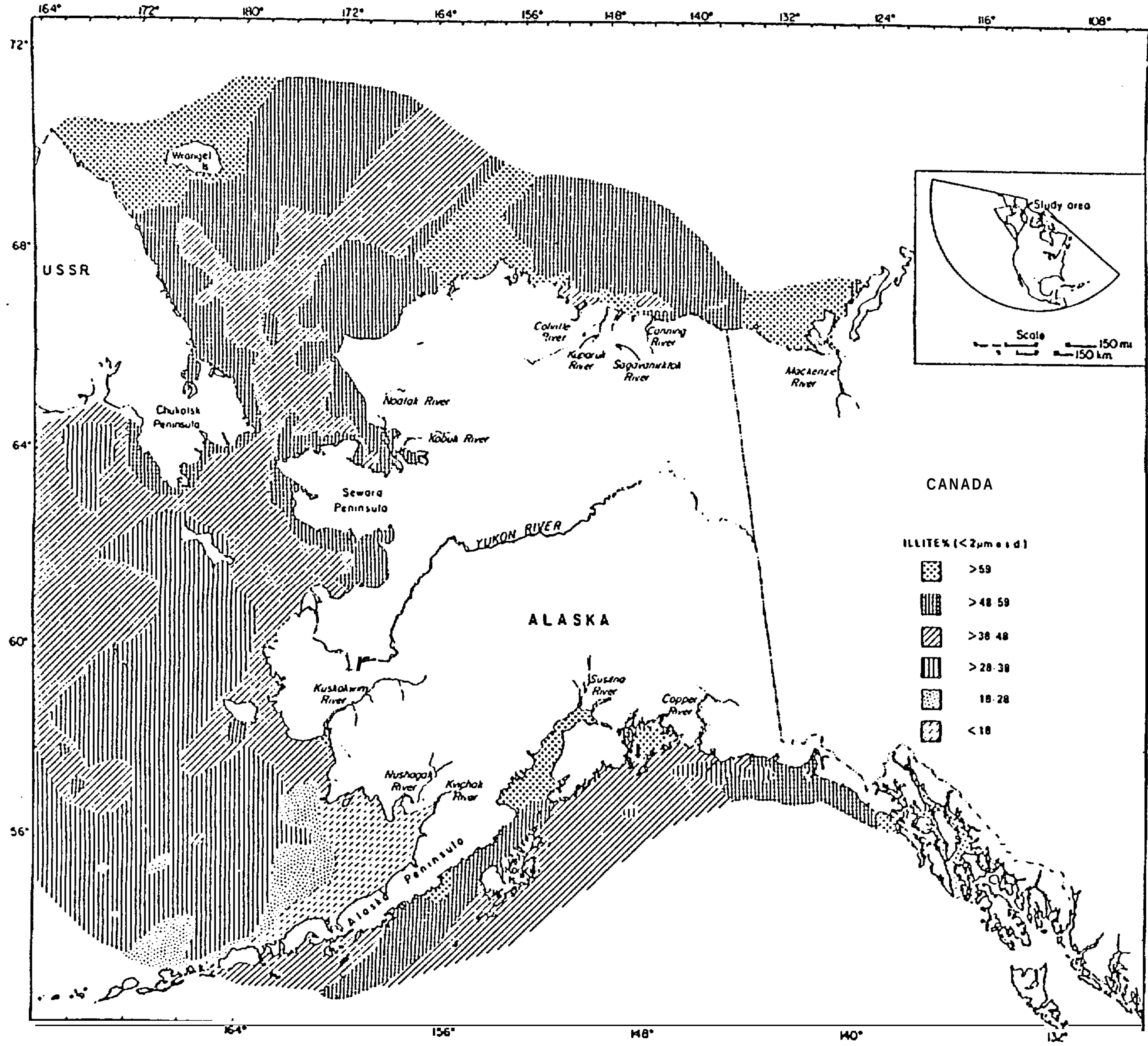

Figure 21. Distribution of illite in marine surface sediments of Alaska (after Naidu and Mowatt, 1982).

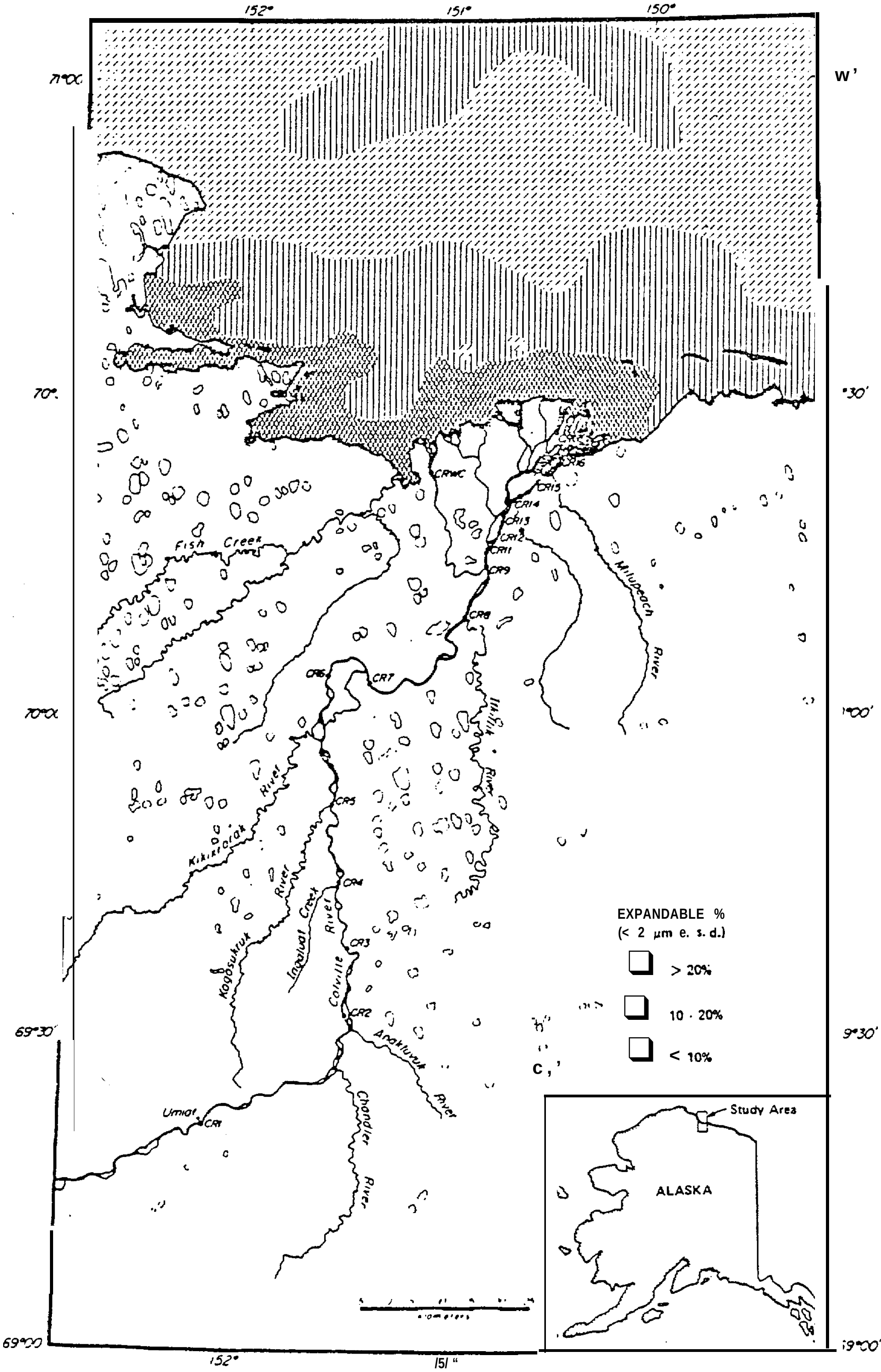

Figure 22". Variations in the expandable clay mineral distribution in the Colville Delta (after Naidu and Mowatt, 1982).

increased abundance of expandable minerals was an isolated, eastwest elongated band of low amounts of illite in the middle continental shelf north of the Canning River. The rest of the Beaufort Sea shelf was blanketed by moderately high (48 to 59 percent) amounts of illite (Fig. 21).

Additional clay mineral studies on the Colville deltaic sediments showed, as in case of the expandable minerals, no systematic downstream pattern of variation along the lower 170 km of the Colville River (Mowatt *et al.*, 1974; Naidu and Mowatt, 1975). However, an unequivocal net increase in illite seaward from the contemporary subaerial part of the Colville Delta are noted (Fig. 23).

The concentrations of kaolinite in the < 2 μm fraction of sediments ranged from 10 to 15 percent. The kaolinite/chlorite ratios (Fig. 20) seem to have offered a useful means to identify the relative variations of the two minerals. In the Beaufort Sea, the ratios were generally high throughout (> 0.5) as compared to the rest of the Alaskan shelves (Naidu and Mowatt, 1982), although appreciable lateral variations were observed in the ratios (Fig. 20). There was a net seaward decrease from the Colville River mouth. A band with the highest ratio (> 0.7) extended westward from the Kuparuk River, whereas the lowest ratios were identified adjacent to the coast of the Sagavanirktok and Canning Deltas, and extended up to Barter Island. In the central Beaufort Sea shelf, the lowest ratio extended northeast of Point Barrow, whereas a tongue of sediments with the highest kaolinite/chlorite ratios existed off the Canning River–Barter Island area.

The observed clay mineral distribution patterns on the inner continental shelf of Alaska (especially the Simpson Lagoon area, Fig. 24) generally can be attributed to various terrigenous sources, and to the subsequent dis-

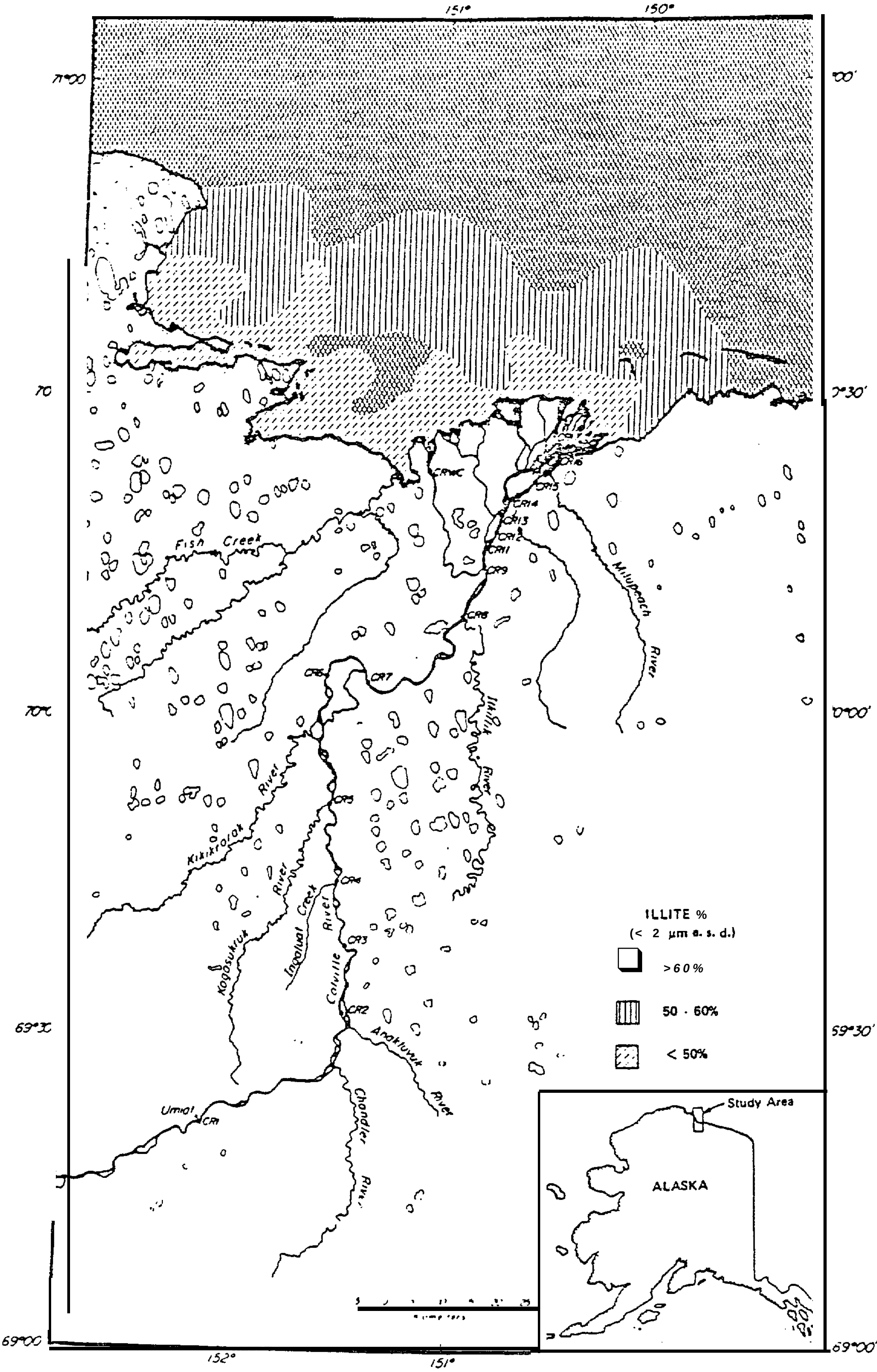

Figure 23. Variations in illite in the Colville Delta (after Naidu and Mowatt, 1982).

LEGEND

Colville influx, Almost Entirely (90%)

Predominantly Colville(85%); with minor influx of Kuparuk (10%) & Sagavanirktok Rivers (5%)

Predominantly Kuparuk River (80%) with minor Sagavanirktok River influx (15%) & Colville River (5% or less).

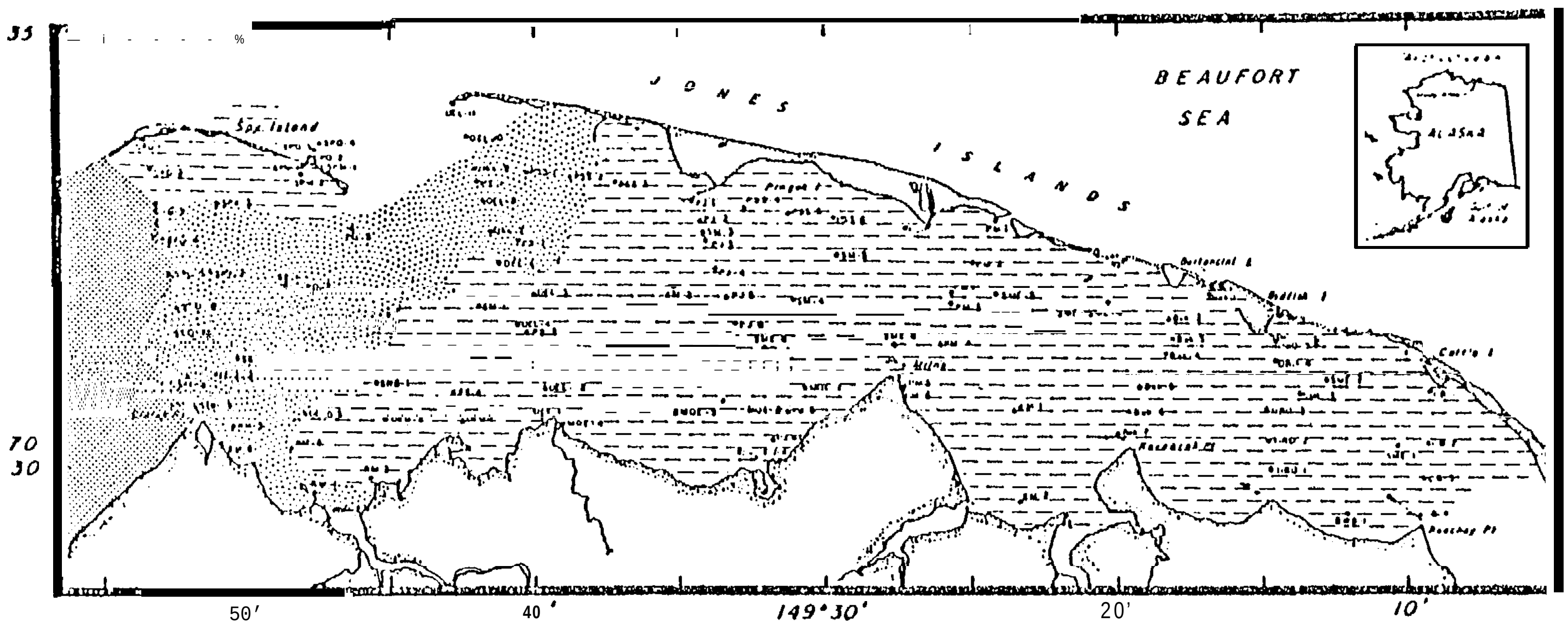

Figure 24. Sources of fine-grained (mud fraction) fluvial sediments* based on detailed clay mineral analysis.

*Sources of mud from coastal bluffs and barriers not considered, persal of the clays to the depositional sites by the prevailing current systems, rather than to chemical reactions between detrital clays and cations in sea water (Naidu and Mowatt, 1982).

A number of investigators (Biscaye, 1965; Griffin *et al.*, 1968; Rateev *et al.*, 1969) have shown that broad latitudinal trends existed in the distribution of kaolinite and chlorite in the world's oceans. Such trends were related to the generation of characteristic clay mineral assemblages under different pedogenic processes associated with latitudinal variations in climate. Our studies in the Beaufort Sea of Alaska would seem to show that the latitudinal trends in the distribution patterns of the clay minerals, as suggested by the above authors, were not maintained, for the concentrations of kaolinite and the kaolinite/chlorite ratios were similar to those found at middle latitudes. It was suggested (Naidu *et al.*, 1971) that this apparent discrepancy was related to the reworking of kaolinite-bearing sedimentary rocks of Northern Alaska, and the subsequent supply of kaolinite to the adjacent Beaufort Sea.

In the Beaufort Sea, with the exception of the coastal area, the clay mineral assemblages do not appear to provide unequivocal means to elucidate the sources and depositional sites of fine-grained sediments in the middle and outer continental shelf areas. The patchy distribution of clay minerals in the central and outer continental shelves are presumably attributable to the highly seasonal nature of sedimentary regimes, ice-cover effects, the haphazard transport of clays by ice-rafting, and the occasional reworking and redistribution of sediments resulting from ice gouging, all of which are phenomena peculiar to the arctic sedimentary regime (Reimnitz and Barnes, 1974; Reimnitz *et al.*, 1977). The identification of an extensive, isolated area of sediment, with unexpectedly low illite (Fig. 21), accompanied by relatively high proportions of expandable clay minerals (Figs. 18 and 19) and high kaolinite/chlorite ratios, in the outer eastern shelf of the Alaskan Beaufort Sea (north and east of the Canning River delta) has proved to be an enigma. Initially, we were led to believe that the clay deposit was a contemporary sediment originally derived from the Colville River. This conclusion was based on the presence of large amounts of expandable clay minerals in the Colville River bedload (Naidu and Mowatt, 1982) as well as in the deltaic sediments off the river mouth. Currents with a net eastward vector and of sufficient strength (up to 100 cm/see; average 40 cm/see) were reported to prevail in the central and outer continental shelf of the Beaufort Sea (Johnson, 1956; Hufford, 1973; Mountain, 1974). Conceivably therefore, clay size particles from the Colville Delta could be transported readily to the Alaskan sector of the Eastern Beaufort Sea. However, the isolated and discontinuous position relative to the Colville Delta strongly suggests that the deposit was relict. A possible source in the Mackenzie River was considered unlikely, for there are relatively high proportions of illite and low concentrations of expandable mineral phases in the Mackenzie bedload and also in the deltaic sediments off the river mouth (Naidu and Mowatt, 1982). In addition, the distribution pattern of illite (Fig. 21) does not support a significant westward flux of Mackenzie River clays.

In the coastal Alaskan part of the Beaufort Sea the lateral variations in clay mineral assemblages were shown by Naidu and Mowatt (1974, 1982) to reflect the differences in the clay mineral suites of the major rivers of the North Slope of Alaska and to show limits of westward littoral transport of the clays from the various fluvial outfalls. The presence of a net westward littoral drift in the above area was confirmed by investigations based on nearshore current measurements and experiments involving drifters (Wiseman et al., 1973; Dygas and Burrell, 1976; Barnes and Toimil, 1979; Matthews, 1981).

In attempting to explain the seaward decrease in expandable clay minerals relative to illite, we have considered possible authigenic and diagenetic changes in clay mineral suites resulting from changing salinities, particularly in light of the experimental data gathered by Whitehouse *et al.* (1960), in addition to our own studies on Colville River clays (Mowatt *et al.* , 1974).. Naidu and Mowatt (1975, 1982) suggested that the observed variations in the clay mineral assemblages of Colville Delta are largely due to "reconstitution" (Weaver, 1958a, 1958b) of some of the expandable material by K^+ adsorption by degraded (depotassicated) illites and/or by mixed-layered illite/smectite that had intercalated degraded illite phases. The proposed mineral reconstitution probably occurred through a process of halmyrolysis as some of the expandable clay minerals were passed from non-saline to the saline environment. This further seemed likely considering that a portion of the expandable minerals (other than the depotassicated illites) of the Colville River are predominantly well-defined smectite, derived principally from the Uniat Bentonite, thoroughly characterized by Anderson and Reynolds (1966). The conversion of such a smectite to illite in the contemporary marine environment is difficult to conceive, particularly in light of thermodynamic arguments (Eberl and Hewer, 1976), and the character of illites and mixed-layer illite/montmorillonites (Hewer and Mowatt, 1966).

In summary, our ability to fingerprint the clay mineral assemblages of the various fluvial systems of the North Slope offers a unique criterion to interpret the disposition of paleochannels, and also of paleocurrent directions? for the Beaufort Sea nearshore. Additionally, based on our studies, it would seem that dispersal patterns and depositional sites of any pollutants that would be scavenged by clay minerals and discharged from specific discharge points, can be predicted for the Beaufort Sea inner continental shelf.

SEDIMENT GEOCHEMISTRY

Organic Carbon and C/N Ratios: The average concentrations (by dry weight %) of organic carbon and nitrogen and the average C/N ratios of marine sediments for various environments of the North Alaskan Arctic are presented in Table VI. The distribution pattern of organic carbon in the Beaufort Sea and the Simpson Lagoon are shown in Figures 25 and 26 respectively. The C/N ratios of the arctic deltaic sediments are slightly higher than the 8 to 12 ratios that were reported as typical for the low-latitude deltaic sediments. A net decrease in the C/N ratios of sediments from the nearshore to deeper waters are recognized. It is surmised that the latter variations are most likely attributable to seaward decrease in the proportion of terrigenous organic detritus as opposed to marine detritus. This is consistent with the pattern of seaward variations in the stable isotope ratios ($\delta^{13}C$) of total organic carbon in continental margin sediments of Beaufort Sea (Gearing *et al.*, 1977).

Organic carbon in the particulate and dissolved phases of a few water samples were analyzed. The content of particulate organic carbon (POC) in the Colville River fresh-water regime was 0.54 mg ℓ^{-1}, whereas in the lower saline or brackish portion it was about 0.34 mg ℓ^{-1}. In the east Harrison Bay and Simpson Lagoon the POC values were 0.28 and 0.31 mg ℓ^{-1}, respectively. The dissolved organic carbon (DOC) in the Colville River and east Harrison Bay waters were 4.4 and 2.9 mg ℓ^{-1}, respectively.

TABLE VI

AVERAGE CONTENTS (BY DRY WT. %) OF ORGANIC CARBON AND NITROGEN, AND AVERAGE C/N RATIOS OF COASTAL TUNDRA PEAT, AND SURFICIAL SEDIMENTS OF THE CONTINENTAL MARGIN OF THE BEAUFORT SEA AND CANADA BASIN

Environment	Organic Carbon	Nitrogen	C/N Ratios
Harrison Bay	0.88	0.08	11.7
Simpson Lagoon	1.12	0.08	13.2
Open Beaufort Sea Shelf (21 m to 64m)	0.73	0.08	9.0
Continental Slope (64-1000 m)	0.89	0.12	7.0
Deep-Sea (>1000 m)	0.81	0.17	5.2
Coastal Tundra Peat*			19. 0*

*Average of C/N ratios of several samples provided by Dr. D. Schell (personal communication).

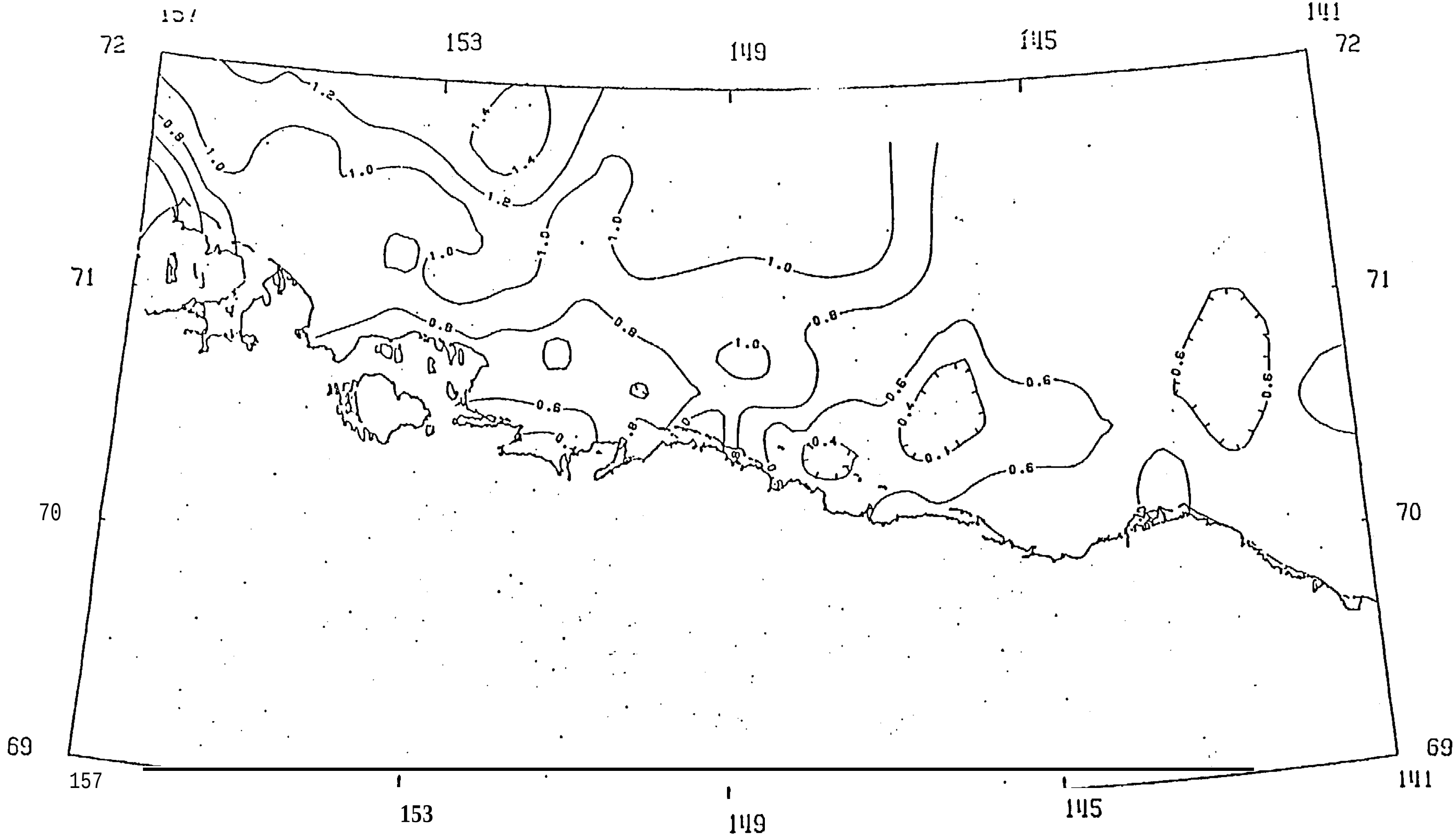

Figure 25. **Map of the Beaufort** Sea showing the distribution of organic **carbon** (wt. %) in **bottom** sediments.

Carbonate Contents: The distributional pattern of carbonate contents (dry weight %) in bottom sediments of the Beaufort Sea are illustrated in Figure 27. A net seaward decrease in carbonate contents is apparent.

Heavy Metal Geochemistry: The baseline average concentrations of eight metals (e.g., Fe, Mn, Cu, Co, Cr, Ni, V and Zn) in gross sediments and "readily" mobilized sediment fractions in four depositional facies (e.g., continental shelf, Harrison Bay, Simpson and Beaufort Lagoons) of the Beaufort Sea are compared in Table VII. More detailed fractionation patterns of the metals for six different Simpson Lagoon sediments are shown in Tables VIII to XIII. The distributional patterns of the eight metals surface sediments of Beaufort Sea are displayed in Figures 28 to 35.

An abbreviated reaction description, for data presented in Tables VIII to XIII, with the corresponding sediment constituent presumably under attack is shown for each treatment. The seven-step treatment scheme is similar to the scheme used by Gupta and Chen (1975, among many others), in basic form and rationale. The more easily leached metal phases (or the more "readily" mobilized fractions) are selectively removed first and the relatively more stable forms are attacked in successive steps.

The references for treatments adopted were:

Idealized Fraction	References
Exchangeable	Jackson, 1958
Carbonates	Sibbesen, 1977
Organic Complex	Giovannini and Sequi, 1976
Manganese and Easily Reducible Oxides	Daly and Binnie, 1974
Moderately Reducible and Crystalline Iron Oxides	Coffin, 1963
Remaining Nonsilicates, Sulfides and Organics	Agemian and Chau, 1977; Olade and Fletcher, 1974

TABLE VII

AVERAGE CONCENTRATIONS (μg/g, EXCEPT Fe WHICH IS IN 10 μg/g) OF SOME HEAVY METALS IN THE TOTAL (T) AND THE ACETIC ACID-HYDROXYLAMINE HYDROCHLORIDE EXTRACTS (E), WITH CALCULATED PERCENT EXTRACTABLE QUANTITIES (%E) FROM 54 SIMPSON LAGOON, 19 BEAUFORT LAGOON, 7 BEAUFORT SEA SHELF AND 7 HARRISON BAY SEDIMENTS

	v			Cr			Mn			Fe			co			Ni			Cu			Zn		
Environment	T	E	%E	T	E	%E	T	E	%E	T	E	%E	T	E	%E	T	E	%E	T	E	%E	T	E	%E
Simpson Lagoon	70	4	6	4 5	1	2	260	130	50	2.0	.22	11	8	2	25	23	3	14	17	3	18	76	13	17
Beaufort Lagoon	100	9	9	55	1.6	3	400	200	50	2.8	.,31	11	10	3.5	35	30	3	10	27	4	15	80	15	19
Beaufort Sea Shelf	140	10	17	85	1.6	2	560	230	40	4.1	.42	10	16	3.9	24	40	3.7	9	33	8	24	112	21	19
Harrison Bay	108	14	13	67	2.5	4	410	180	44	2.8	.57	20	10	2.5	25	28	4.5	16	30	7	23	80	22	28

TABLE VIII

AVERAGE CONCENTRATIONS (µg/g) OF SOME HEAVY METALS IN EXTRACTS FROM A SEVEN-STEP, TWO-STEP, AND SINGLE CHEMICAL TREATMENT, AS WELL AS TOTAL DISSOLUTION OF SL877-2 (SAND SEDIMENT, SIMPSON LAGOON)

EXTRACTION PROCEDURE	IDEALIZED FRACTION TARGET	V	Cr	Mn	Fe	Co	Ni	Cu	Zn
I. Seven-Step Treatment[b]									
1. 0.2 N $MgCl_2$ - triethanolamine; pH 8.1; 5 minutes	Exchangeable	0.13	0.02	9	3	0.02	0.07	0.23	
2. Cation exchange resin in nylon net bag; pH 5; 8 hours	Carbonates	0.12	0.12	20	40	0.18	0.5	0.6	2.5
3. Acetylacetone in benzene (5:95); 200 hours	Organic complex	0.2	0.03	15	200	0.15	0.03	1	
4. 0.1 N hydroxylamine-HCl in 0.01 M HNO_3 (pH 2); 30 minutes	Manganese and easily reducible oxides	0.2	0.03	15	100	0.2	0.2	0.37	2
5. 0.2 M acid ammonium oxalate; pH 3.3 buffered; 2 hours	Amorphous iron oxides	1.7	0.25	5	1,100	0.2	0.4	1	2
6. 5% sodium dithionite in 0.2 M citrate buffer (pH 4.8); 30 minutes; 50°C	Moderately reducible and crystalline iron oxides	2	0.5	12	2,100	0.8	0.8	0.3	
7. 2% $KClO_3$ in 0.5 N HCl; pH 0.3; 24 hours	Remaining nonsilicates; authigenic sulfides, organic complex	0.55	0.2	5	400	0.25	0.9	1	
Extractable Total		4.9	1.05	81	3,943	1.8	2.9	4.5	
Concentrated HF (48%) and HNO_3 (70%) digestion (1:1)[c]	Residual, resistant minerals	NA	16.35	35	5,000	NA	3.2	4.4	11.6
Sum Total			17.4	116	8,943		6.1	8.9	
II. Two-Step Treatment[d]									
1. 0.1 M hydroxylamine-HCl in 0.01 M HNO_3 (pH 2); 30 minutes	Exchangeable, carbonates, easily reducible oxides								
2. 0.5 N HCl; pH 0.3; 12 hours	Iron oxides, organic complex, authigenic sulfides								
Extractable Total									
III. Single Treatment[e]									
1 M hydroxylamine-HCl in 25% acetic acid; pH 1.5; 4 hours	Exchangeable, carbonates, manganese oxides, some iron oxides	2.0	0.44	80	1,100	0.66	1.0	1.1	3.0
IV. Single Total Dissolution									
Concentrated HF-HNO_3 digestion (1:1)	Entire sediment	36	21	146	9,500	3.6	11	11	28

[a] Temperature of 25°C unless otherwise specified.

[b] Sequence modified after Gupta and Chen, 1975 (see text for details).

[c] Rader and Grimaldi, 1961.

[d] As suggested in this study (see text for details).

[e] Chester and Hughes, 1967.

TABLE IX

AVERAGE CONCENTRATIONS (μg/g) OF SOME HEAVY METALS IN EXTRACTS FROM A SEVEN-STEP, TWO-STEP, AND SINGLE CHEMICAL TREATMENT, AS WELL AS TOTAL DISSOLUTION OF SL877-13 (SILT SEDIMENT, SIMPSON LAGOON)

EXTRACTION PROCEDURE[a]	IDEALIZED FRACTION TARGET	V	Cr	Mn	Fe	Co	Ni	Cu	Zn
I. Seven-Step Treatment[b]									
1. 0.2 N $MgCl_2$ - triethanolamine; PN 8.1; 5 minutes	Exchangeable	0.25	0.06	37	15	0.05	0.23	0.7	
2. Cation exchange resin in nylon net bag; pH 5; 8 hours	Carbonates	0.6	1	70	150	0.3	1.8	2.7	9
3. Acetylacetone in benzene (5:95); 200 hours	Organic complex	0.5	0.05	60	400	0.3	0.02	3	
4. 0.1 M hydroxylamine-HCl in 0.01 M HNO_3 (PH 2); 30 minutes	Manganese and easily reducible oxides	0.5	0.05	37	85	0.15	0.2	0.2	1.3
5. 0.2 M acid ammonium oxalate; pH 3.3 buffered: 2 hours	Amorphous iron oxides	4	1	28	4,500	0.8	2	4.5	8
6. 5% sodium dithionite in 0.2 M citrate buffer (pH 6.8); 30 minutes; 50°C	Moderately reducible and crystalline iron oxides	3.7	1	40	4,050	2	3.5	1.3	
7. 2% $KClO_3$ in 0.5 N HCl; pH 0.3; 24 hours	Remaining nonsilicates: authigenic sulfides, organic complex	3.45	3.5	28	3.000	1	4.5	2.6	
Extractable Total		13	6.66	300	12,200	4.6	12.25	15	
Concentrated HF (48%) and HNO_3 (70%) digestion (1:1)[c]	Residual, resistant minerals								
Sum Total									
II. Two-Step Treatment[d]									
1. 0.1 M hydroxylamine-HCl in 0.01 M HNO_3 (pH 2); 30 minutes	Exchangeable, carbonates, easily reducible oxides								
2. 0.5 N HCl; pH 0.3; 12 hours	Iron oxides, organic complex, authigenic sulfides								
Extractable Total									
III. Single Treatment[e]									
1 M hydroxylamine-HCl in 25% acetic acid; pH 1.5; 4 hours	Exchangeable, carbonates, manganese oxides, some iron oxides	5.1	1.8	300	3,700	3.0	5.0	3.5	18
IV. Single Total Dissolution[c]									
Concentrated HF-HNO_3 digestion (1:1)	Entire sediment	79	60	467	26,400	9.2	29	23	88

[a]Temperature of 25°C unless otherwise specified.

[b]Sequence modified after Gupta and Chen, 1975 (see text for details).

[c]Rader and Grimaldi, 1961.

[d]As Suggested in this study (see text for details).

[e]Chester and Hughes, 1967.

TABLE X

AVERAGE CONCENTRATIONS (µg/g) OF SOME HEAVY METALS IN EXTRACTS FROM A SEVEN-STEP, TWO-STEP, AND SINGLE CHEMICAL TREATMENT, AS WELL AS TOTAL DISSOLUTION OF SL877-18 (PEATY, SILTY SAND SEDIMENT, SIMPSON LAGOON)

EXTRACTION PROCEDURE[a]	IDEALIZED FRACTION TARGET	V	Cr	Mn	Fe	Co	Ni	Cu	Zn
I. Seven-Step Treatment[b]									
1. 0.2 N $MgCl_2$ - triethanolamine; pH 8.1; 5 minutes	Exchangeable								
2. Cation exchange resin in nylon net bag; pH 5; 8 hours	Carbonates	3.7	0.14	16	660	1.2	2.5	3.4	10.5
3. Acetylacetone in benzene (5:95); 200 hours	Organic complex	1	0.06	1	1,000	0.35	0.05	4.7	
4. 0.1 M hydroxylamine-HCl in 0.01 M HNO_3 (pH 2); 30 minutes	Manganese and easily reducible oxides	1.3	0.1	12	250	0.3	0.7	0.2	2.5
5. 0.2 M acid ammonium oxalate; pH 3.3 buffered; 2 hours	Amorphous iron oxides	5	0.9	7	4,000	0.7	3	4.6	5
6. 5% sodium dithionite in 0.2 M citrate buffer (pH 6.8): 30 minutes; 50°C	Moderately reducible and crystalline iron oxides	1.3	0.9	10	1.500	1.4	1.7	0.7	
7. 2% $KClO_3$ in 0.5 N HCl; pH 0.3; 24 hours	Remaining nonsilicates; authigenic sulfides, organic complex	2	2	16	2,080	1.3	3.5	2.1	
Extractable Total		14.5	4.2	70	9,500	5.2	11.6	16	
Concentrated HF (48%) and HNO_3 (70%) digestion (1:1)[c]	Residual, resistant minerals								
Sum Total									
II. Two-Step Treatment[d]									
1. 0.1 M hydroxylamine-HCl in 0.01 M HNO_3 (pH 2): 30 minutes	Exchangeable, carbonates, easily reducible oxides	5	0.5	44	670	1.3	3	5	16
2. 0.5 N HCl; pH 0.3; 12 hours	Iron oxides, organic complex, authigenic sulfides	8	1.6	23	4,810	1.7	4	8.5	19
Extractable Total		13	2.1	67	5,480	3	7	13.5	35
III. Single Treatment[e]									
1 M hydroxylamine-HCl in 25% acetic acid; pH 1.5; 4 hours	Exchangeable, carbonates, manganese oxides, some iron oxides	6.7	1.7	60	4,100	3.1	6.1	2.3	22
IV. Single Total Dissolution[c]									
Concentrated HF-HNO_3 digestion (1:1)	Entire sediment	74	54	163	19.300	8.7	27	20	78

[a]Temperature of 25°C unless otherwise specified.

[b]Sequence modified after Gupta and Chen, 1975 (see text for details).

[c]Rader and Grimaldi, 1961.

[d]As suggested in this study (see text for details).

[e]Chester and Hughes, 1967.

TABLE X7

AVERAGE CONCENTRATIONS (µg/g) OF SOME HEAVY METALS IN EXTRACTS FROM A SEVEN-STEP, TWO-STEP, AND SINGLE CHEMICAL TREATMENT, AS WELL AS TOTAL DISSOLUTION OF SL377-23 (SANDY SILT SEDIMENT, SIMPSON LAGOON)

EXTRACTION PROCEDURE[a]	IDEALIZED FRACTION TARGET	V	Cr	Mn	Fe	Co	Ni	Cu	Zn
I. Seven-Step Treatment[b]									
1. 0.2 N $MgCl_2$ - triethanolamine; pH 8.1; 5 minutes	Exchangeable	0.4	0.2	20	10	0.03	0.2	0.8	
2. Cation exchange resin in nylon net bag; pH 5; 8 hours	carbonates	1.5	0.6	80	300	0.7	2.5	2.5	13
3. Acetylacetone in benzene (5:95): 200 hours	Organic complex	0.4	0.2	20	400	0.2	0.05	3.5	
4. 0.1 M hydroxylamine-HCl in 0.01 M HNO_3 (pH 2); 30 minutes	Manganese and easily reducible oxides	0.4	0.1	20	200	0.3	0.5	0.2	3.5
5. 0.2 M acid ammonium oxalate; PH 3.3 buffered; 2 hours	Amorphous iron oxides	4	1	20	4,000	1	2	5	6
6. 5% sodium dithionite in 0.2 M citrate buffer (pH 4.8); 30 minutes; 50°C	Moderately reducible and crystalline iron oxides	3	1	40	5,000	1.7	3	1.5	
7. 2% $KClO_3$ in 0.5 N HCl; pH 0.3; 24 hours	Remaining nonsilicates; authigenic sulfides, organic complex	1.5	2	20	1,800	0.7	3	2.5	
Extractable Total		11.2	5.1	220	11,710	4.6	11.3	16	
Concentrated HF (48%) and HNO_3 (70%) digestion (1:1)[c]	Residual, resistant minerals		60	80	13,000		15	5.5	37
Sum Total			65.1	300	24,710		26.3	21.5	
II. Two-Step Treatment[d]									
1. 0.1 M hydroxylamine-HCl in 0.01 N HNO_3 (PH 2); 30 minutes	Exchangeable, carbonates, easily reducible oxides	1.5	0.2	151	170	0.8	0.3	0	3.1
2. 0.5 N HCl; pH 0.3; 12 hours	Iron oxides, organic complex, authigenic sulfides	8.8	2.5	84	4,700	2.5	7	12.2	25.4
Extractable Total		10.3	2.7	235	4,870	3.3	7.3	12.2	28.5
III. Single Treatment[e]									
1 M hydroxylamine-HCl in 25% acetic acid; pH 1.5; 4 hours	Exchangeable, carbonates, manganese oxides, some iron oxides	4.4	1.2	215	2,480	2.7	4.7	2.7	15
IV. Single Total Dissolution[c]									
Concentrated HF-HNO_3 digestion (1:1)	Entire sediment	70	56	380	20,900	8.4	27	21	93

[a] Temperature of 25°C unless otherwise specified.

[b] Sequence modified after Gupta and Chen, 1975 (see text for details).

[c] Rader and Grimaldi, 1961.

[d] As suggested in this study (see text for details).

[e] Chester and Hughes, 1967.

TABLE XII

AVERAGE CONCENTRATIONS (µg/g) OF SOME HEAVY METALS IN EXTRACTS FROM A SEVEN-STEP, TWO-STEP, AND SINGLE CHEMICAL TREATMENT, AS WELL AS TOTAL DISSOLUTION OF SL877-28 (CLAYEY SILT SEDIMENT, SIMPSON LAGOON)

EXTRACTION PROCEDURE[a]	IDEALIZED FRACTION TARGET	V	Cr	Mn	Fe	Co	Ni	Cu	Zn
I. Seven-Step Treatment[b]									
1. 0.2 M $MgCl_2$ - triethanolamine; pH 8.1; 5 minutes	Exchangeable	0.3	0.07	10	7	0.03	0.2	0.7	
2. Cation exchange resin in nylon net bag; pH 5; 8 hours	Carbonates	1.3	0.3	30	300	0.42	3	4	s
3. Acetylacetone in benzene (5:95); 200 hours	Organic complex	1.3	0.06	5	600	0.15	0	4	
4. 0.1 M hydroxylamine-HCl in 0.01 M HNO_3 (pH 2); 30 minutes	Manganese and easily reducible oxides	1.8	0.04	20	83	0.10	0.2	0.2	L
5. 0.2 M acid ammonium oxalate; pH 3.3 buffered; 2 hours	Amorphous iron oxides	5	1	20	4,100	1.2	3.5	6	s
6. 5% sodium dithionite in 0.2 M citrate buffer (pH 4.8); 30 minutes; 50°C	Moderately reducible and crystalline iron oxides	4.3	0.7	45	4,900	2	3.5	1.2	
7. 2% $KClO_3$ in 0.5 N HCl; pH 0.3; 24 hours	Remaining nonsilicates: authigenic sulfides, organic complex	2.5	2	30	2,700	1	4	3.5	
Extractable Total		16.5	4.17	160	12,690	4.9	14.4	19.6	
Concentrated HF (48%) and HNO_3 (70%) digestion (1:1)[c]	Residual, resistant minerals								
Sum Total									
II. Two-Step Treatment[d]									
1. 0.1 M hydroxylamine-HCl in 0.01 M HNO_3 (pH 2); 30 minutes	Exchangeable, carbonates, easily reducible oxides								
2. 0.5 N HCl; pH 0.3; 12 hours	Iron oxides, organic complex, authigenic sulfides								
Extractable Total									
III. Single Treatment[e]									
1 M hydroxylamine-HCl in 25% acetic acid; pH 1.5; 4 hours	Exchangeable, carbonates, manganese oxides, some iron oxides	5.1	1.8	114	2,740	2.3	4.3	2.8	16
IV. Single Total Dissolution[c]									
Concentrated HF-HNO_3 digestion (1:1)	Entire sediment	93	62	290	26,700	9.3	32	23	100

[a]Temperature of 25° C unless otherwise specified.

[b]Sequence modified after Gupta and Chen, 1975 (see text for details).

[c]Rader and Grimaldi, 1961.

[d]As suggested in this study (see text for details).

[e]Chester and Hughes, 1967.

TABLE X [11

AVERAGE CONCENTRATIONS (µg/g) OF SOME HEAVY METALS IN EXTRACTS FROM A SEVEN-STEP, TWO-STEP, AND SINGLE CHEMICAL TREATMENT, AS WELL AS TOTAL DISSOLUTION OF UG-1 (PEATY, CLAYEY-SILT SAND SEDIMENT, SIMPSON LAGOON)

EXTRACTION PROCEDURE[a]	IDEALIZED FRACTION TARGET	V	Cr	Mn	Fe	Co	Ni	Cu	Zn
I. Seven-Step Treatment[b]									
1. 0.2 M $MgCl_2$ - triethanolamine; pH 8.1; 5 minutes	Exchangeable	0.4	0.05	17	30	0.03	0.25	0.55	
2. Cation exchange resin in nylon net bag; pH 5; 5 hours	Carbonates	1	0.5	34	220	0.47	4.3	2.5	12
3. Acetylacetone in benzene (5:95); 200 hours	Organic complex	0.4	0.05	10	200	0.1	0.05	2	
4. 0.1 M hydroxylamine-HCl in 0.01 M HNO_3 (pH 2); 30 minutes	Manganese and easily reducible oxides	0.4	0.05	11	170	0.2	0.7	0.05	2.5
5. 0.2 M acid ammonium oxalate; pH 3.3 buffered; 2 hours	Amorphous iron oxides	2.6	0.85	7	3,000	0.5	2	3.5	6
6. 5% sodium dithionite in 0.2 M citrate buffer (pH 4.8); 30 minutes; 50°C	Moderately reducible and crystalline iron oxides	4	1.5	26	3,700	1.7	2.7	1.2	
7. 2% $KClO_3$ in 0.5 N HCl; pH 0.3; 24 hours	Remaining nonsilicates; authigenic sulfides, organic complex	2	2.2	12	1,400	0.5	3	2	
Extractable Total		10.8	5.2	117	8.720	3.5	13	11.8	
Concentrated HF (48%) and HNO_3 (70%) digestion (1:1)[c]	Residual, resistant minerals								
Sum Total									
II. Two-Step Treatment[d]									
1. 0.1 M hydroxylamine-HCl in 0.01 M HNO_3 (pH 2); 30 minutes	Exchangeable, carbonates, easily reducible oxides								
2. 0.5 N HCl; pH 0.3; 12 hours	Iron oxides, organic complex, authigenic sulfides								
Extractable Total									
III. Single Treatment.[e]									
1 M hydroxylamine-HCl in 25.2 acetic acid; pH 1.5; 4 hours	Exchangeable, carbonates, manganese oxides, some iron oxides	3.5	0.7	90	1,500	2.1	4	0.4	12
IV. Single Total Dissolution[c]									
Concentrated $HF-HNO_3$ digestion (1:1)	Entire sediment	56	46	211	16,500	6	21	16	65

[a]Temperature of 25°C unless otherwise specified.

[b]Sequence modified after Gupta and Chen, 1975 (see text for details).

[c]Rader and Grimaldi, 1961.

[d]As suggested in this study (see text for details).

[e]Chester and Hughes, 1967.

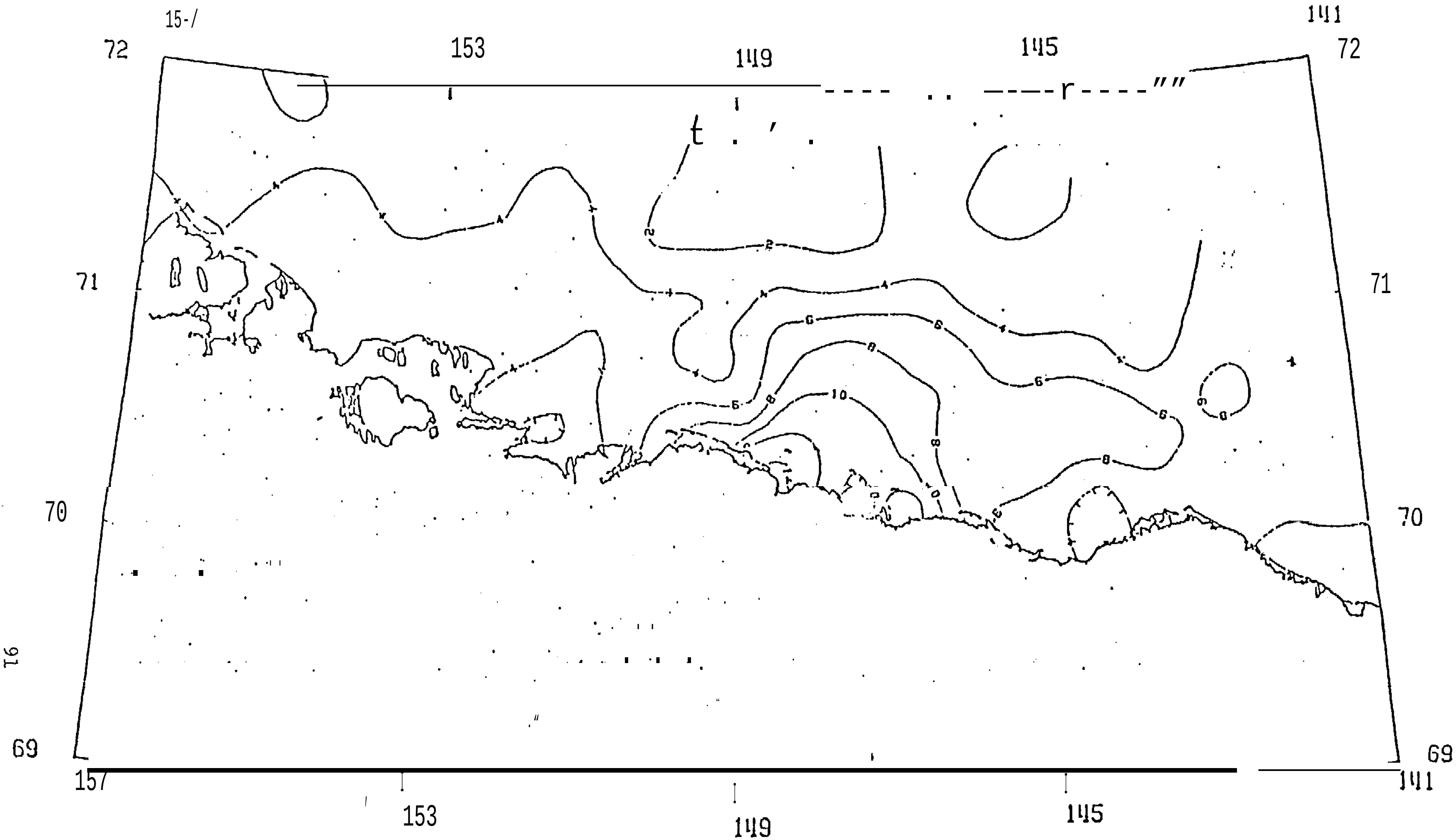

Figure 27. Map of the Beaufort Sea showing the distribution of carbonate (wt. %) in bottom sediments.

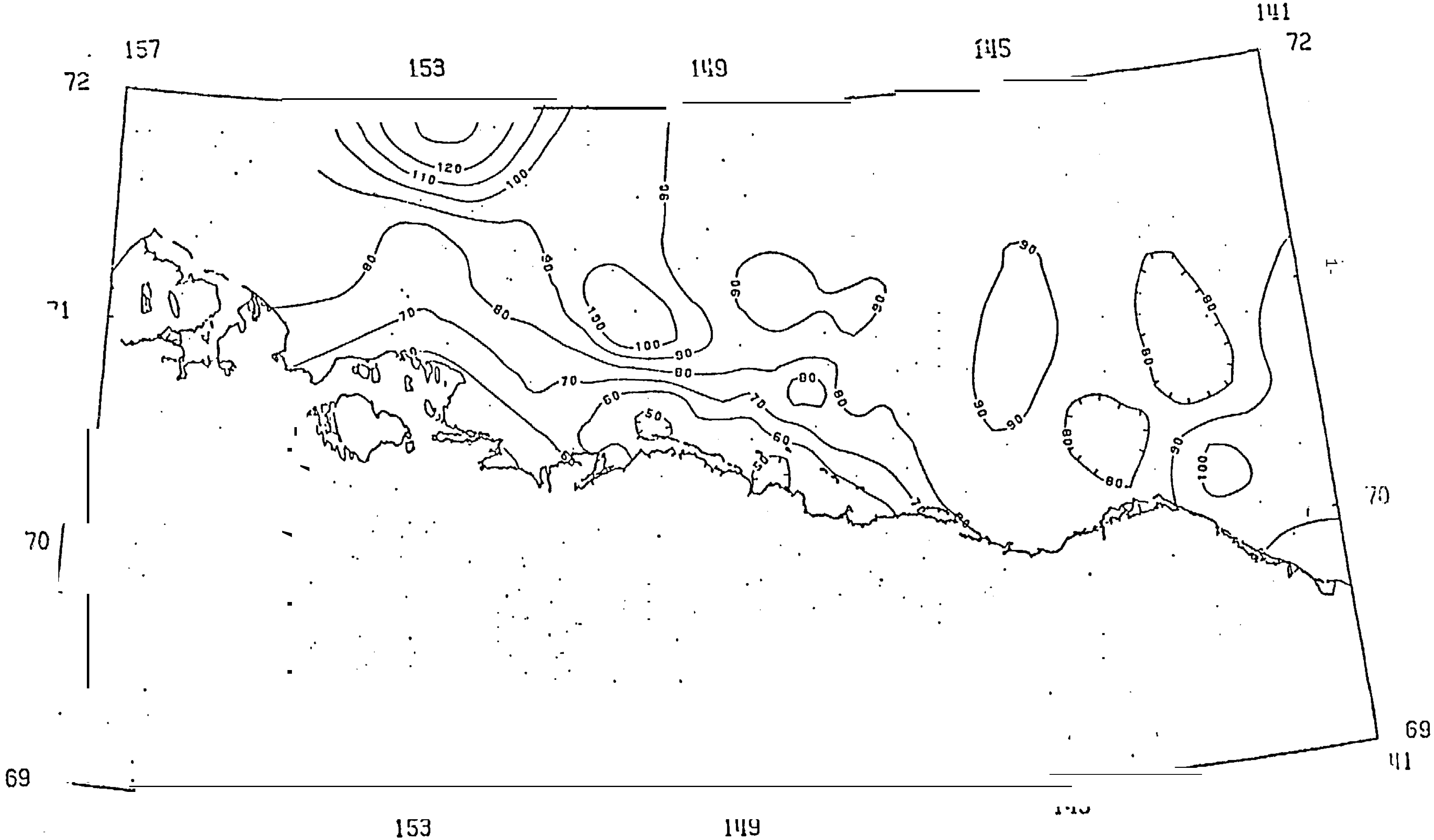

Figure 28. Map of the Beaufort Sea showing the variations in the concentrations (μg/g) of chromium in bottom sediments.

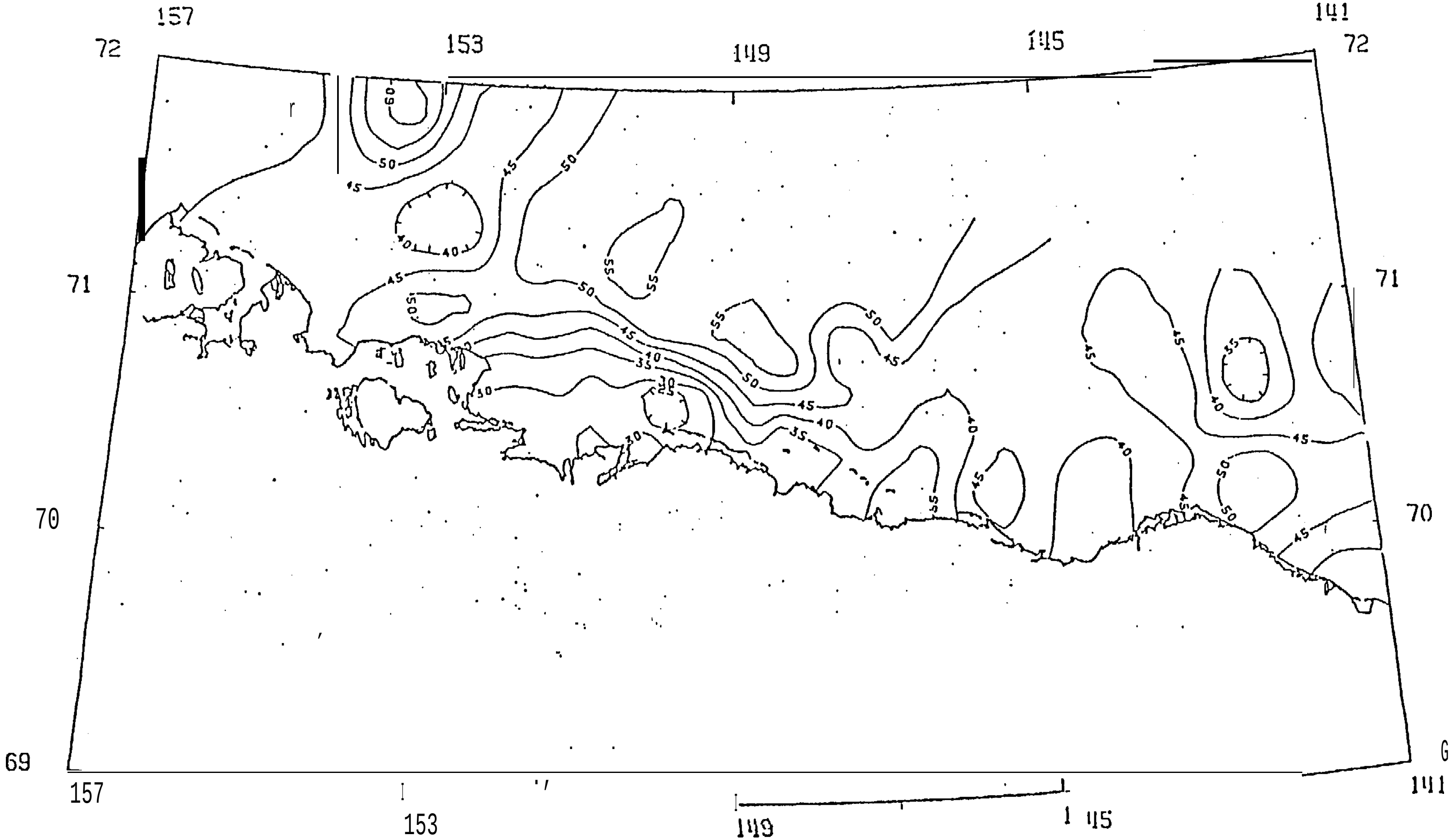

Figure 29. Map of the Beaufort Sea showing the variation in the concentrations (µg/g) of nickel in bottom sediments.

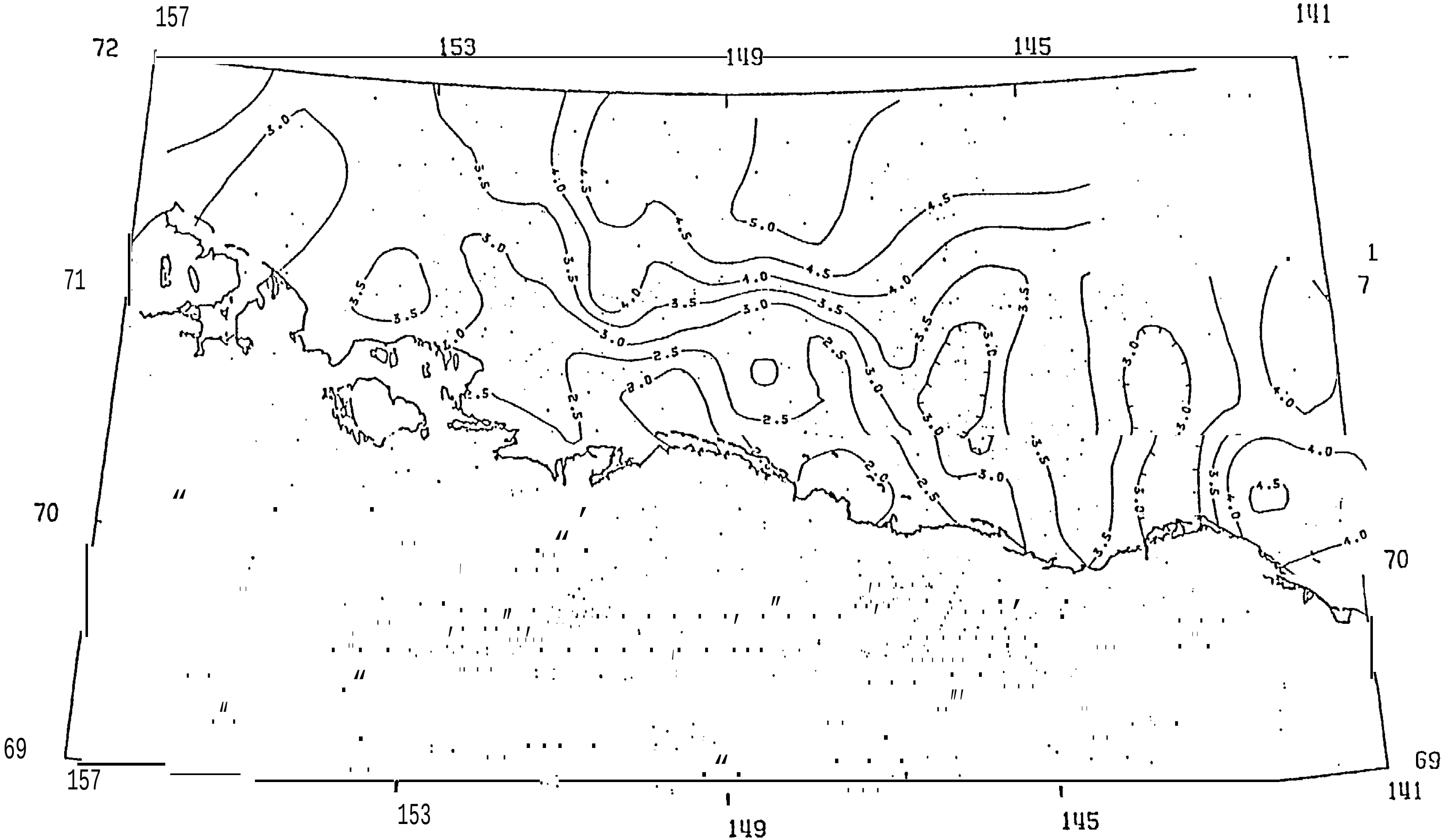

Figure 30. Map of the Beaufort Sea showing the variation of the concentrations (10^4 xµg/g) of iron in bottom sediments.

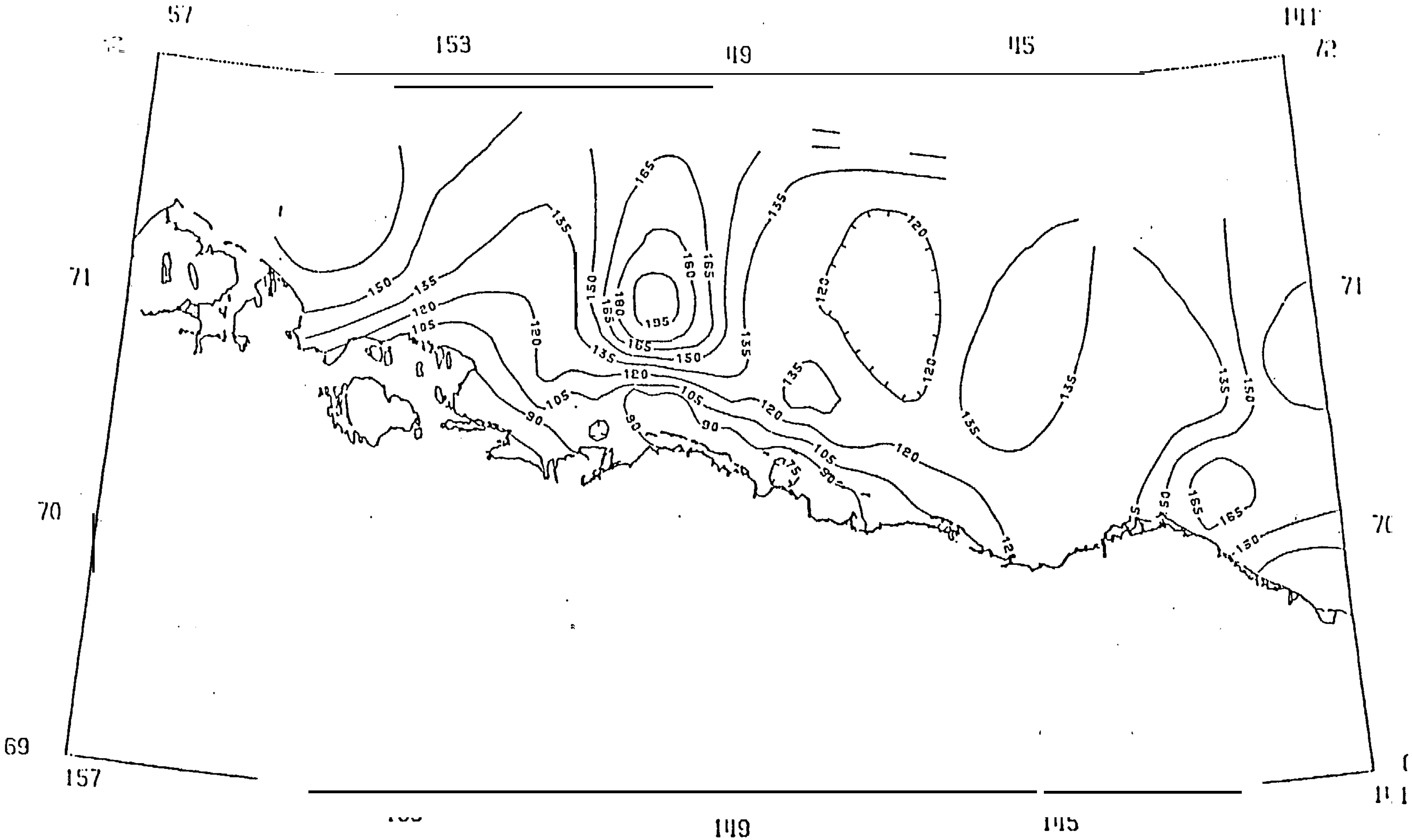

Figure 31. Map of the Beaufort Sea showing variation in the concentrations (µg/g) of vanadium in bottom sediments.

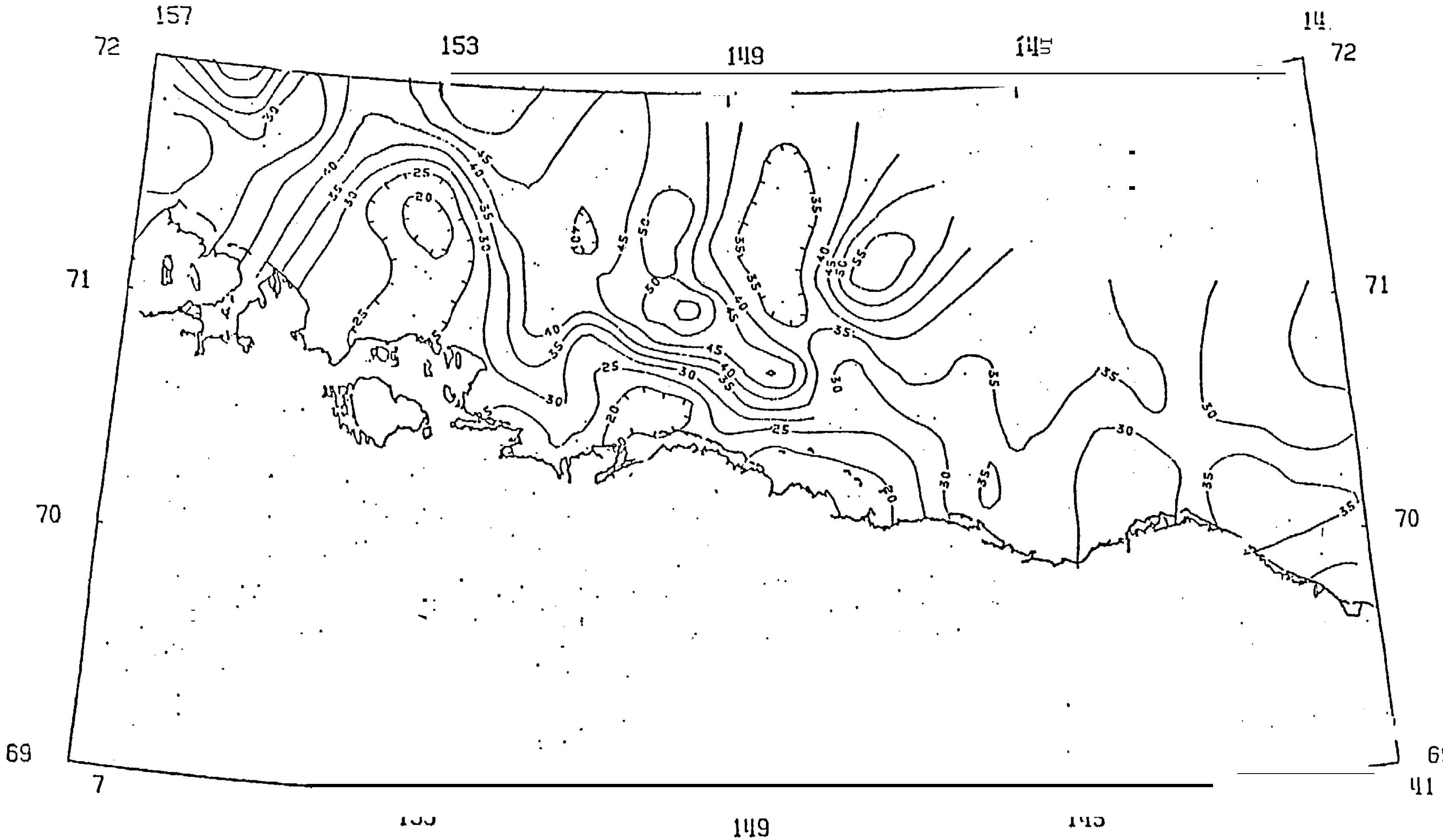

Figure 32. Map of the Beaufort Sea showing variation in the concentrations (μg/g) of copper in bottom sediments.

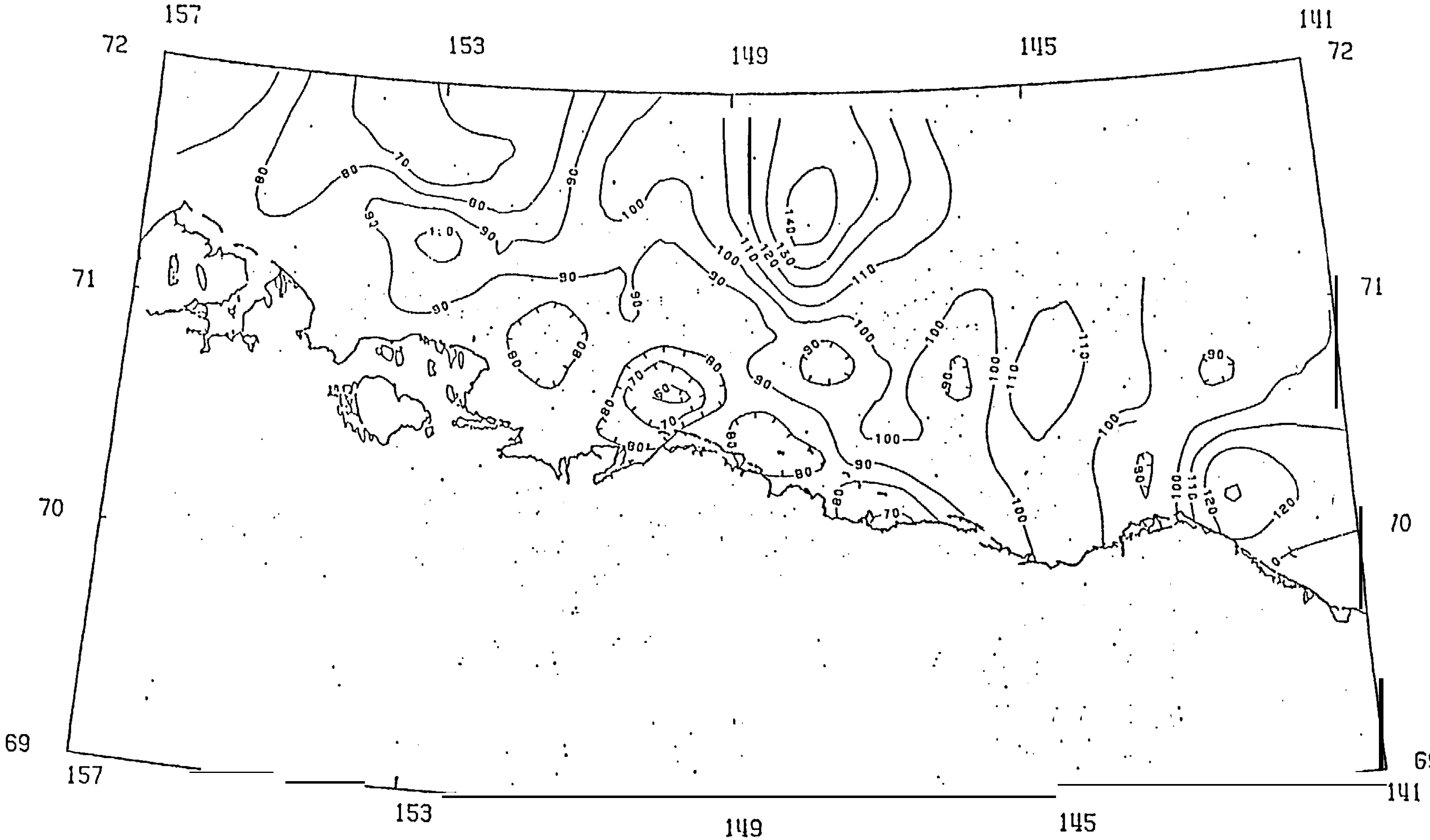

Figure 33. Map of the Beaufort Sea showing variation in the concentrations of zinc in the bottom sediments.

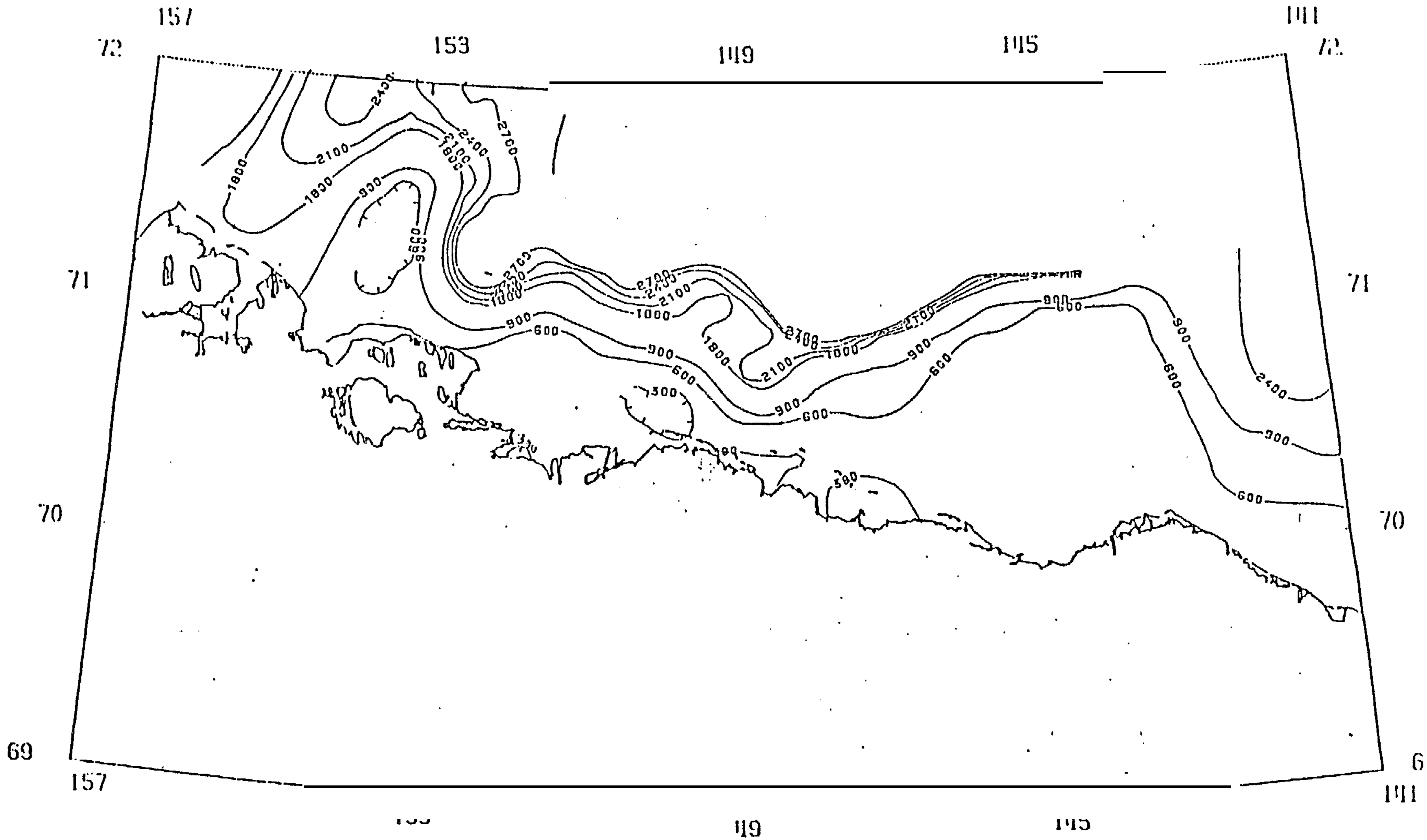

Figure 34. Map of the Beaufort Sea showing variation in the concentrations of manganese in bottom sediments.

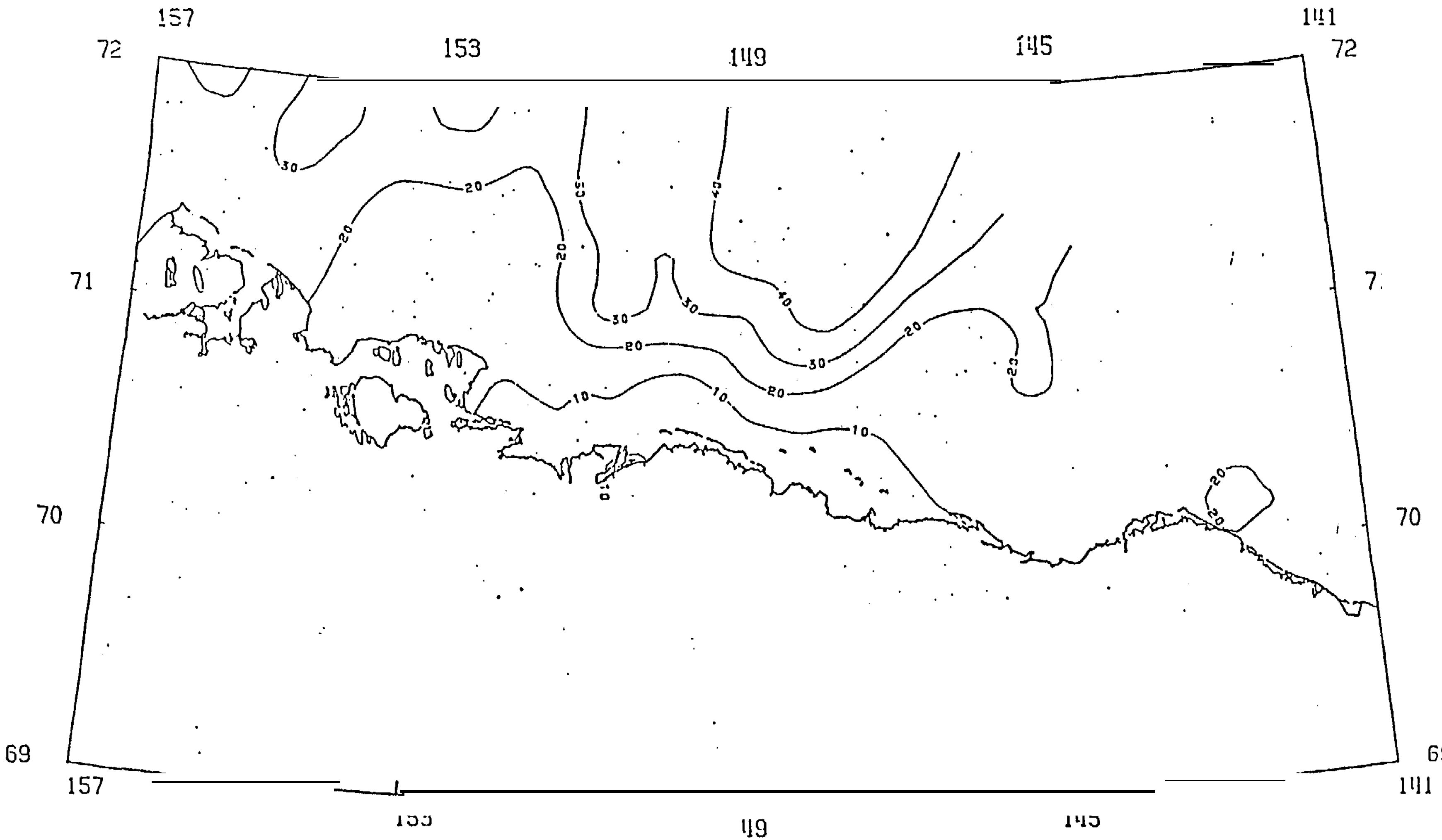

Figure 35. Map of the Beaufort Sea showing the variation in the concentrations (μg/g) of cobalt in bottom sediments.

A two-step abridgement of the above six steps is also shown for two of the six samples. Here, the very complex sediment assemblage was simplified into two categories: easily leachable and moderately leachable.

The single treatment was the familiar hydroxylamine hydrochloride-acetic acid procedure of Chester and Hughes (1967).

The foregoing laboratory investigations, and the interelement and the elemental-lithological correlation matrix (Table IX) have assisted in understanding the partitioning of the eight metals in the sediments.

The bulk of the iron occurred in the last steps of the sequential scheme, i.e., oxalate, dithionite, HCl, and $HF-HNO_3$ treatments. Approximately half of the total iron was non-residual, i.e. , removed into the seven extractions. The oxalate, dithionite, and HCl steps account for 90% of the non-residual iron. Therefore, most of the available iron required a moderate to strong chemical attack to be released from the sediment. While the remaining elements showed great variation in the proportion of residual to non-residual partitioning, they generally followed iron's non-residual distribution pattern among the various leachates.

Iron oxides appeared to account for a large share of the nonsilicate metal partitioning. Note, however, the abundance of metals removed by step 2 (cation exchange resin). This implies that a significant amount of the metals can be released from sediments merely by a small lowering of the pH of the environment.

Copper displayed the most distinctive extraction behaviour of all the trace elements. It showed the least association with oxides phases. Relatively more copper was removed by the weaker treatments and it had the highest non-residual proportion of the eight metals studied (up to 80%).

TABLE XIV

CORRELATION COEFFICIENTS[a] FOR CHEMICAL AND TEXTURAL COMPOSITIONS[b] OF 54 SIMPSON LAGOON SEDIMENTS, ARCTIC COAST OF NORTHERN ALASKA

	D	Sd	St	Cl	Mu	CO_3	OC	NE Fe	E Fe	NE Mn	E Mn	NE Zn
D												
Sd	-0.630											
St	0.638	-0.987										
Cl	0.465	-0.829	0.762									
Mu	0.630	-1.000	0.987	0.829								
CO_3	0.490	-0.843	0.829	0.712	0.843							
OC	0.249*	-0.546	0.520	0.587	0.546	0.413						
NE Fe	0.676	-0.944	0.917	0.841	0.944	0.776	0.520					
E Fe	0.513	-0,841	0.820	0.767	0.841	0.687	0.600	0.844				
NE Mn	0.647	-0.887	0.874	0.793	0.887	0.709	0.546	0.934	0.839			
E Mn	0.353*	-0.696	0.682	0.613	0.696	0.671	0.499	0.680	0.744	0.709		
NE Zn	0.655	-0.817	0.783	0.771	0.817	0.705	0.473	0.847	0.720	0.817	0.580	
E Zn	0.405	-0.813	0.761	0.886	0.813	0.745	0.603	0.776	0.814	0.692	0.598	0.704
NE V	0.585	-0.876	0.835	0.897	0.876	0.785	0.569	0.916	0.771	0.815	0.608	0.846
E V	0.465	-0.853	0.816	0.882	0.853	0.670	0.575	0.846	0.899	0.794	0.631	0.726
NE Cr	0.596	-0.924	0.889	0.908	0.924	0.727	0.568	0.937	0.829	0.8921	0.617	0.827
E Cr	0.399	-0.796	0.774	0.724	0.796	0.716	0.531	0.737	0.863	0.744	0.717	0.661
NE Ni	0.587	-0.929	0.894	0.898	0.929	0.788	0.552	0.933	0.817	0.888	0.659	0,821
E Ni	0.313*	-0.755	0.726	0.750	0.755	0.656	0.667	0.709	0.792	0.664	0.732	0.589
NE Cu	0.301*	-0.680	0.653	0.721	0.680	0.585	0.618	0.674	0.709	0.718	0.574	0.635
E Cu	0.482	-0.694	0.652	0.701	0.694	0.659	0.284*	0.749	0.634	0.673	0.561	0.660
NE Co	0.453	-0.717	0.692	0.675	0.717	0.623	0.439	0.757	0.548	0.676	0.433	0.557
E Co	0.468	-0.778	0.759	0.709	0.778	0.626	0.635	0.777	0.866	0.753	0.772	0.671

	E Zn	NE V	E V	NE Cr	E Cr	NE Ni	E Ni	NE Cu	E Cu	NE Co	E Co
NE V	0.852										
E V	0.892	0.832									
NE Cr	0.843	0.918	0.914								
E Cr	0.764	0.683	0.825	0.726							
NE Ni	0.824	0.908	0.882	0.950	0.756						
E Ni	0.806	0.729	0.798	0.746	0.811	0.732					
NE Cu	0.764	0.693	0.709	0.723	0.616	0.701	0.684				
E Cu	0.754	0.698	0.704	0.724	0.579	0.736	0.498	0.579			
NE Co	0.585	0.730	0.628	0.736	0.473	0.728	0.474	0.588	0.607		
E Co	0.763	0.729	0.815	0.770	0.797	0.754	0.901	0.649	0.56[illegible]	0.47[illegible]	

[a] Spearman nonparametric correlation problem. All coefficients are significant at or above the 99.9% confidence level.

* These coefficients are significant only at the 95% confidence level.

[b] The prefix "E" to the heavy metals connotes the amount of the metal extractable by an hydroxylamine hydrochloride-acetic acid leaching procedure (Chester & Hughes, 1967). The prefix "NE" connotes the amount of the metal not extracted by the same reagent, D, Sd, St, Cl, Mu, CO3, and OC are abbreviations for depth, sand + gravel, silt, clay, mud, carbonate, and organic carbon, respectively.

A comparison of the two-step with the seven-step treatment results revealed the additive effect of several chemical attacks on the sediment particles: The seven-step sum was greater for every element except manganese. Also, was observed that the number of steps, the severity and duration of treatments, would modify the amount of metals leached. There was no firm leachable value, it was relative to the scheme and treatments employed.

Relevance of the Geochemical Studies on Metal Pollutant Behaviour

The foregoing sequential extraction data may be used as a potential means to estimate the proportion of each of the eight metals that can be mobilized into the seawater of the Beaufort Sea by changing the pH and oxidation-reduction potential of the sedimentary environment. Whether the perturbation is an oil spill or dredge spoil dispersed in the nearshore arctic environment, it would appear that only a minor portion of the total metal content in the marine substrate would be potentially available for release into the water column. Most likely, the direct physical and chemical effects of an oil spill and/or dredge spoil (e.g., water turbidity change, sedimentation rate change, etc.) to the environment would be far more important than any small increases in dissolved metallic species mobilized from the natural bottom material. The rate of release of the metals and their concentration gradient between the sediment and the entire water column, the nature of the metal species released, and the circulation characteristics, as well as turbulence, to diffuse and remove the supplementary metal must be understood before one can realize the relationship of the total released metal to the overall variations of dissolved metals in time and space.

The current fluxes of the eight metals into the Simpson Lagoon are listed in Table XV. The metal inventories, their partitioning patterns and fluxes would provide a bench mark to monitoring of pollution in the Beaufort Sea shelf and adjacent coastal areas.

TABLE XV

AVERAGE FLUXES (μg $cm^{-2} yr^{-1}$, EXCEPT Fe WHICH IS IN 10^4 μg $cm^{-2} yr^{-1}$), FOR TOTAL (T) AND ACETIC ACID-HYDROXYLAMINE HYDROCHLORIDE EXTRACTABLE (E) HEAVY METALS IN SIMPSON LAGOON SEDIMENTS

V		Cr		Mn		Fe		Co		Ni		Cu		Zn	
T	E	T	E	T	E	T	E	T	E	T	E	T	E	T	E
90	5.6	60	1.2	340	165	2.6	.29	9.6	2.5	30	4.2	22	4.0	100	17

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