Distribution of Clay Minerals in the Suspended and Bottom Sediments from the Northern Bering Sea Shelf Area, Alaska

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By FREDRIKA C. MOSER and JAMES R. HEIN

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By Fredrika C. Moser *and* James R. Hein

ABSTRACT

Analysis of the clay mineralogy of bottom and suspended sediment from Norton Sound and the adjacent Bering Sea shelf and from the Yukon and Kuskokwim Rivers suggests possible source areas, dispersal routes, and current patterns. Source areas include the Yukon and Kuskokwim Rivers, and possibly sites to the south or west.

On June 20, 1975, clay mineralogy in the Yukon and Kuskokwim Rivers, respectively, averaged 50 and 52 percent illite, 48 and 48 percent chlorite+kaolinite, and 2 and 1 percent smectite. During the summer months of 1968-70 and 1976-77, the suspended sediment, which indicates short-term sediment supply, averaged 1 percent smectite, and the bottom sediment, which represents longer term deposition, averaged 21 percent smectite. Thus, smectite may be supplied to the northern shelf from a source to the south or west, perhaps the Aleutian Ridge or Chukotka Peninsula region of the U.S.S.R. In addition, the clay mineralogy of the Yukon River may change seasonally or annually; our sampling of the river represents only one moment in time. The detailed distribution of the clay minerals indicates that the dominant current in the Bering shelf is the north-flowing Alaska Coastal Water. This current distributes fine-grained sediment northward from the Kuskokwim River into the Chirikov Basin, primarily around the western end of St. Lawrence Island and into Norton Sound, where the sediment is mostly masked by the Yukon River clay-mineral suite. Yukon detritus moves primarily to the northwest and enters the Chukchi Sea through the Bering Strait, but some sediment moves around Norton Sound in a sluggish counterclockwise gyre.

Sediment-dispersal routes suggest that pollution in Norton Sound, such as an oil spill, could result in the rapid distribution of pollutants throughout the northern Bering Sea area. Because Norton Sound is shallow, resuspension of bottom sediments by tidal fluctuations and storm waves also could cause rapid distribution of pollutants.

INTRODUCTION

Analysis of clay minerals in bottom and suspended sediments from the Yukon and Kuskokwim Rivers and from the northern Bering Sea shelf off Alaska allowed determination of fine-grained sediment sources, sediment-dispersal routes, and inferred current patterns. Because of pending offshore oil development on the northern Bering shelf, this kind of information is invaluable for determining the possible dispersal routes of oil spills and the siting of offshore drilling platforms and pipelines.

ACKNOWLEDGMENTS

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REGIONAL SETTING

The area studied includes Norton Sound, Chirikov Basin, and the epicontinental shelf area of the Northern Bering Sea (fig. 1). We also studied samples from the area north of St. Lawrence Island and the southernmost part of the Bering Strait.

Bathymetry

The shelf area from the Yukon delta to the Bering Strait is relatively flat and shallow. The bottom topography (fig. 2) suggests that the Yukon River crossed the shelf and flowed into the Chukchi Sea prior to the Holocene transgression (McManus and others, 1974). Chirikov Basin displays a more complex, uneven topography, probably caused by Pleistocene glaciation (Moll, 1970). Between the Yukon delta and St. Lawrence Island are two linear depressions with an intervening ridge; all trend north-south (Knebel and Creager, 1973a, b). The topography in Norton Sound is smooth, with a gradual increase in depth from east to west and few depressions where sediment may be trapped.

Major Currents

A major north-trending current (water mass) is present off the western Alaska coast. This current is called the Alaska Coastal Water (ACW) where it borders the coast (Goodman and others, 1942; Coachman and Aagaard, 1966; Sharma and others, 1974; Nelson and others, 1975; Drake and others, 1980). The current moves northerly, parallel to the Alaskan coastline, swinging into the Bering Sea at the Yukon delta and then through the Bering Strait into the Chukchi Sea. At the Yukon delta the ACW bifurcates, with a sluggish branch moving into Norton Sound (Coachman and Aagaard, 1966). The ACW is normally present westward to a depth of 30 m (greater through the Bering Strait). Velocities range from 10 (bottom) to 20 (surface) cm/s in the seaward areas but increase to velocities of 30 to 40 cm/s within 30 km of the shoreline (Husby, 1969, 1971; McManus and Smyth, 1970; Fleming and Heggarty, 1976; see Drake and others, 1980 for a detailed discussion of currents and their velocities). In the Bering Strait, where the ACW is funneled into the Chukchi Sea, velocities reach a maximum of 180 cm/s.

A distinct counterclockwise gyre in Norton Sound is a manifestation of the sluggish branch of the ACW (fig. 2). After this gyre moves along the margin of Norton Sound, it rejoins the main branch of the ACW south of Port Clarence. The gyre is created in part by the interaction of the ACW with discharge from the Yukon River (Nelson and Creager, 1977; Drake and others, 1979, 1980).

Another northward-moving current flows from the Pribilof Islands to St. Lawrence Island through the western part of the study area. Just south of St. Lawrence Island the current bifurcates and joins the ACW to the east. The western arm flow is less clearly defined and may move northward through Anadyr Strait into the northern Bering Sea or southward (Knebel and Creager, 1973a, b; fig. 2).

Major Sources and Dispersal of Sediments

Two major fluvial systems contribute sediment to the study area—the Kuskokwim River to the southern Bering Sea and the Yukon River to southwestern Norton Sound (fig. 2). The Kuskokwim River does not flow in the winter because it freezes, but the Yukon maintains a small winter flow (Drake and others, 1979). Major discharge of sediment takes place in the summer months of June to October (Lisitsyn, 1966; Drake and others, 1980). Local streams along northern Norton Sound provide about 2 to 3×10^6 metric tons of sediment per year (Drake and others, 1980).

The Yukon River contributes annually between 40 and 100×10^6 metric tons of suspended and bedload sediment to the Bering Sea (Lisitsyn, 1966; Drake and others, 1980). The Yukon ranks 18th among the world's rivers in total annual sediment discharge, having a drainage area of about 8.5×10^5 km^2 (Lisitsyn, 1966; Inman and Nordstrom, 1971). Ninety percent of the river-borne sediment in the Bering Sea comes from the Yukon (Lisitsyn, 1966).

The Kuskokwim River also discharges sediment to the shelf. This sediment is transported northwest toward St. Lawrence Island and along the Alaskan coast by the ACW. The suspended-sediment concentration, determined from midchannel flow, ranges in the summer months from 100 to 200 mg/L (Carlson and others, 1975). The contribution of sediment to the shelf is considerably less than that from the Yukon River (Lisitsyn, 1966).

Sediment in Norton Sound is additionally distributed by resuspension due to storm activity and tidal fluctuations (Nelson and Creager, 1977; Drake and others, 1979, 1980; Cacchione and Drake, 1982). Shore-fast ice occurs in the winter in Norton Sound; the effects of ice rafting on sediment transportation and deposition are poorly known (Dupre, 1978).

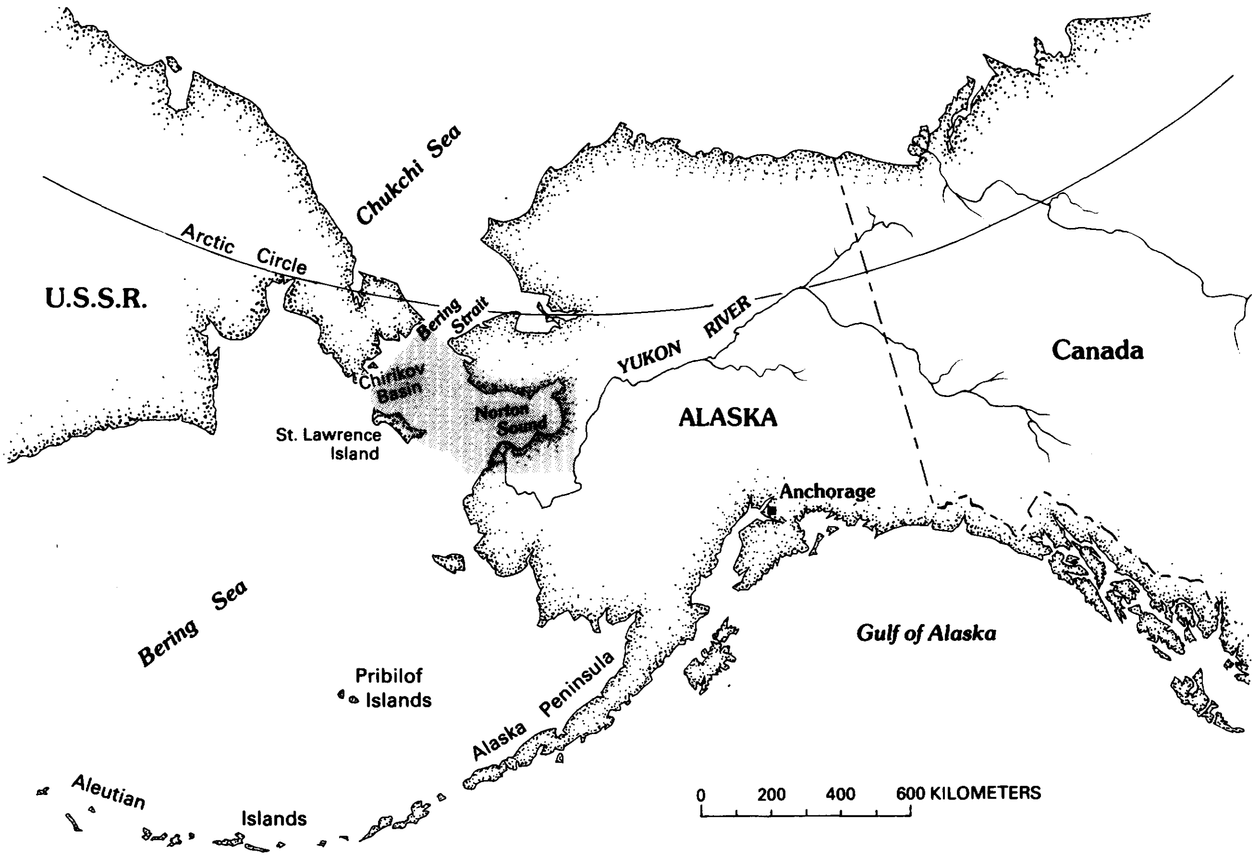

Figure 1. Location of study area (shaded) in the northern Bering Sea. Map from Howard and Nelson (1982).

Geology

Norton Sound is flanked on the north by the Seward Peninsula and on the east and south by the Yukon-Koyukuk province, which extends from the Brooks Range in the north to the Yukon delta. South of the delta the Yukon-Koyukuk province is bordered by the Yukon-Kuskokwim coastal lowland. Patton (1971) described the Yukon-Koyukuk province as a vast tract of Cretaceous rocks locally veneered by Quaternary alluvial deposits and volcanic rocks. The Cretaceous sequence consists of marine andesitic volcanic rocks, graywacke, mudstone,

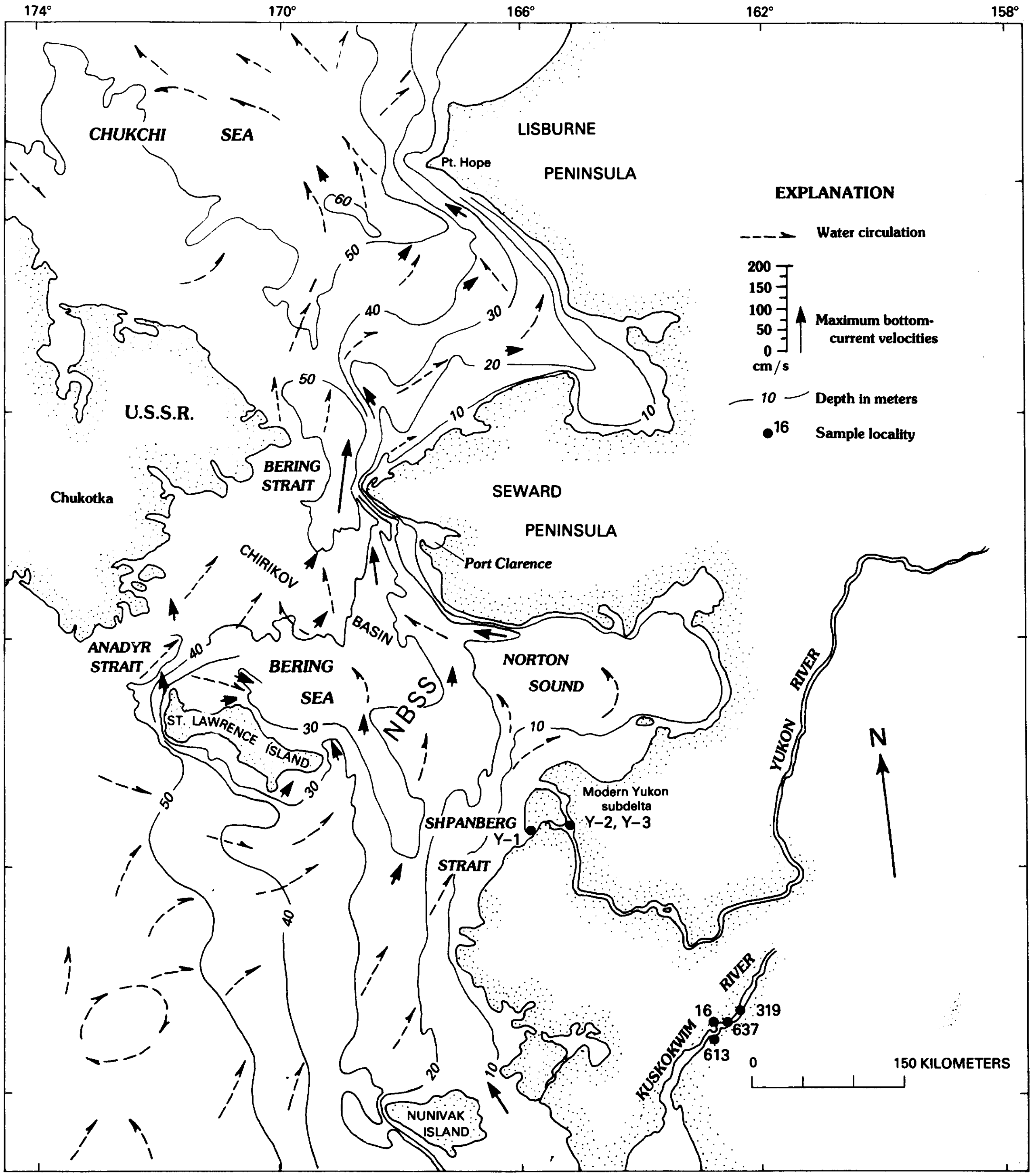

Figure 2. Northeastern Bering Sea and southern Chukchi Sea, showing water circulation, distribution of Alaska Coastal Water (arrows), measured bottom-current velocities, and bathymetry. NBSS is northern Bering Sea shallows. Figure from Nelson (1982).

and shallow marine to nonmarine beds. Cenozoic rocks are felsic volcanic rocks with underlying basalts.

The Seward Peninsula is predominately Precambrian sedimentary rocks and metamorphosed rocks; the latter include quartz schist, phyllite, argillite, dolomitic limestone, gneiss, and slate. Less extensive outcrops of Paleozoic marble, dolomite, and chert underlie Mesozoic felsic intrusive rocks.

METHODS

Both bottom and suspended sediment from Norton Sound and the adjacent shelf were collected during the summer (ice-free) months of 1968-70 and 1976-77. A total of 615 bottom and suspended samples were collected, of which 53 bottom samples and 54 suspended-sediment samples were used in this study. The distribution of offshore suspended-sediment samples is different from that for bottom-sediment samples (figs. 3, 6). In the summers of 1972 and 1975, 12 samples from bank and suspended sediment were collected in the Yukon and Kuskokwim Rivers.

Box cores were taken at each offshore bottom station. From the surface of the core an approximately 5- to 10-g sample of sediment was taken for clay-mineral analysis.

Suspended-sediment samples were collected in Norton Sound, in the northern Bering Sea shallows, northeast of the Bering Strait, and west of Port Clarence; suspended-sediment samples were not available from Chirikov Basin and north of St. Lawrence Island. Water samples of 1 L were collected in Van Dorn bottles. Samples were collected at various depths in the water column at each station. In Norton Sound, water was collected at 2- to 4- m intervals; in the outer shelf, where water depths are greater, the sampling interval ranged from 10 to 15 m through the water column. Each 1-L sample was passed through a Millipore filter with pore diameters of 0.4 m. The amount of suspended material collected on the filter paper usually weighed less than 6 mg, with a few ranging from 10 to 20 mg.

X-ray techniques used for clay mineralogy were described by Hein and others (1976). Sediment was treated to remove organic matter and $CaCO_3$,

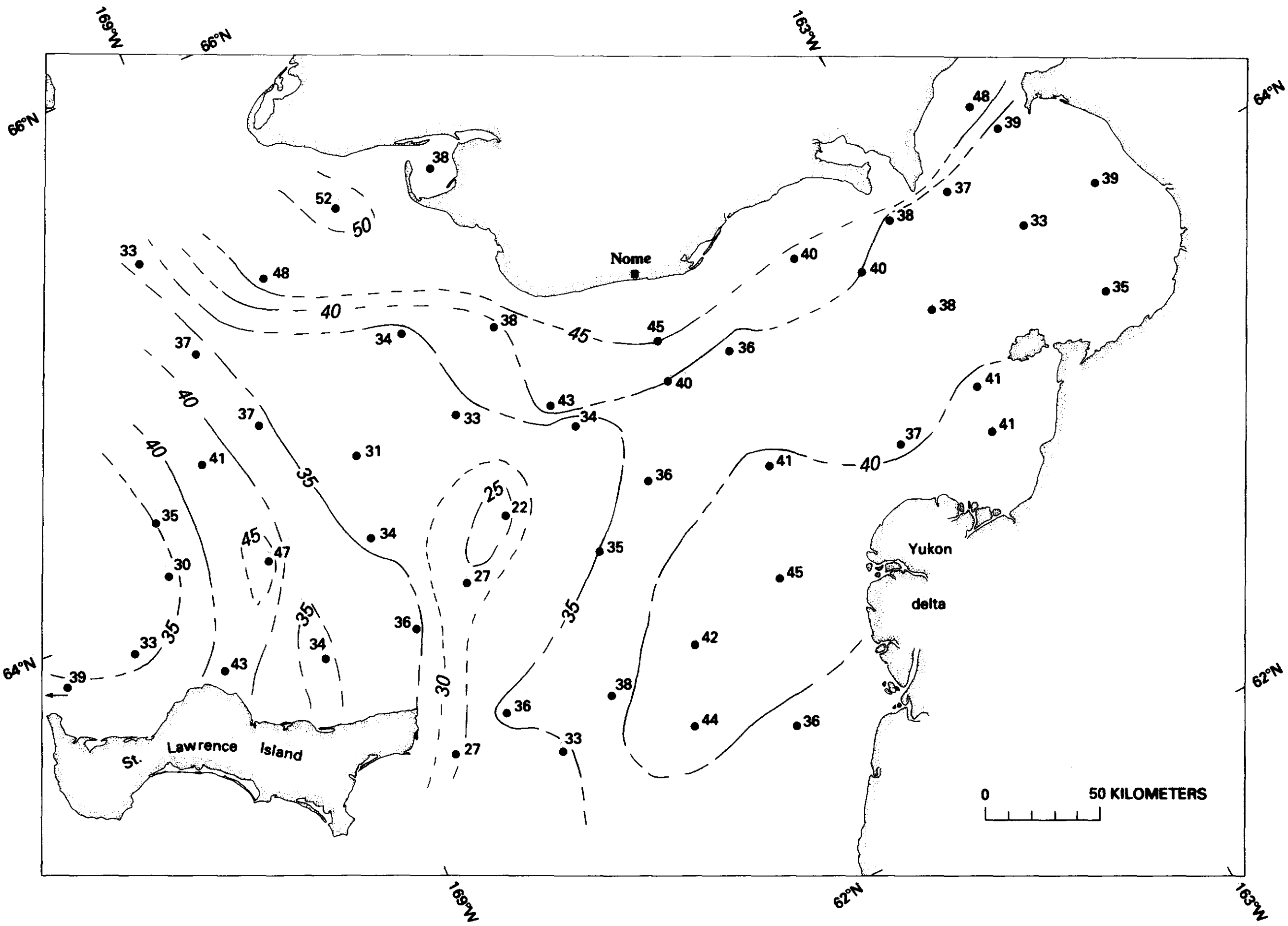

Figure 3. Distribution of chlorite+kaolinite in bottom sediment. Values are in percentage of chlorite+kaolinite in the clay-mineral suite and are contoured at a 5-percent interval. Arrow just north of western St. Lawrence Island indicates sample location is immediately west of the edge of the map. Contour lines dashed where approximately located.

respectively, using 30 percent hydrogen peroxide and Morgan's solution (sodium acetate plus glacial acetic acid diluted with distilled water). The samples were then washed repeatedly with additional Morgan's solution and centrifuged to isolate the 2- m size fraction. The 2- m fraction was saturated with $MgCl_2$ and X-rayed, then treated with ethelene glycol and X-rayed again. Peak areas rather than peak heights were measured, and the relative clay percentages were calculated from the weighted peak areas and were summed to equal 100. Biscaye's (1965) weighting factors were used: two, four, and one times the peak areas of kaolinite plus chlorite, illite, and smectite, respectively. Because kaolinite makes up a small fraction of the clay-mineral assemblage in the area studied and it is difficult to determine its relative abundance accurately when present in small amounts, the chlorite+kaolinite abundances were considered together. In this paper smectite is used as a general term to represent any mineral phases that expand to about 17 A when glycolated. The expandable minerals are most commonly smectite-group minerals but may also include degraded chlorite and illite or some mixed-layer clays (Naidu and others, 1982).

The techniques used to determine the clay mineralogy of the offshore bottom samples differ from the technique used for the offshore suspended-sediment samples. The small amounts of sediment trapped on the filters made it impossible to put the samples through the same chemical treatments and size segregations used for the bottom samples. Instead, the sediment-coated filter papers were washed with distilled water to remove the salts and the loose coarse-grained particles. The filter paper and sediment was then saturated with $MgCl_2$ for one-half hour and rinsed twice with distilled water. A section of filter paper was cut out, placed on a glass slide, and allowed to dry in a dessicator before being glycolated. X-ray diffractograms were taken of each sample as described above; reproducibility within a single sample of suspended sediment was always within seven percentage points. The results from the suspended sediment are presented in three ways: (1) the averages of the suspended sediment collected at all depths in the water column at a specific station (figs. 6-8), (2) the value of the suspended-sediment sample nearest the surface (figs. 9-11), and (3) the value of the suspended-sediment sample from nearest the sea floor (figs. 12-14).

Suspended-sediment samples from the Yukon and Kuskokwim Rivers were collected in liter bottles. All sediment was recovered by centrifugation; samples were not passed through Millipore filters. River suspended and bottom sediments were analyzed for clay mineralogy in the same way as offshore bottom samples.

Several drawbacks are inherent in the technique used for the analysis of the small amounts of offshore suspended sediment collected: (1) The analysis of offshore bottom sediments and all river sediments was of clay-sized debris only, whereas the offshore suspended-sediment samples were of varying and unknown size fractions, thus making the validity of any comparisons uncertain; however, from examinations of the sediment-laden filter paper under a stereoscopic microscope, it appears that the suspended sediment is mostly fine grained; (2) nonclay minerals present in the suspended-sediment samples decrease the quality of the diffractograms; (3) muscovite cannot be separated from illite by this technique, which causes anomalously high illite concentrations for some suspended sediments; (4) some clays (0.4 m), especially smectite, may have passed through the Millipore filter, although, certainly not all of the smectite would have passed through. Gibbs (1967, 1977) stated that smectite was the finest grained clay in the Amazon clay-mineral suite, with an average size of 0.4 m and a range of 0.9 to 0.1 m. However, Gibbs' results could also be interpreted as a density effect due to settling technique, inasmuch as smectite is the least dense of the clay minerals. Regardless, the possibility exists that some smectite was lost through the technique used to recover the offshore suspended sediments; river suspended sediments, however, were not passed through a filter.

DISTRIBUTION OF SEDIMENT

Bottom Sediment

On the basis of the distribution of clay minerals, the study area is divided into three parts (fig. 2): (1) Chirikov Basin, the western and central part of the northern Bering Sea, (2) Norton Sound, and (3) the northern Bering Sea shallows, defined by Moll (1970) as the narrow north-south strip of sea floor between Norton Sound and Chirikov Basin.

Norton Sound

Chlorite + kaolinite values (fig. 3) show the least amount of variation, with values mostly in the range of 35 to 40 percent. Chlorite+kaolinite is highest (40 to 45 percent) close to the Yukon delta and decreases to the east (35 to 40 percent) and north (35 to 40 percent) to as far as the central part of the sound, where it again increases toward the northern shore (40 to 50 percent). The distribution of illite (fig. 4) is similar to that of chlorite+kaolinite, with percentages near the Yukon delta ranging from 45 to 50 percent with concentrations decreasing slightly from 40 to 45 percent in the east-central parts of the sound. Adjacent to the northern Norton Sound coastline, illite is less abundant (30 to 40 percent) than chlorite+kaolinite. Smectite (fig. 5) is distributed in a distinct halo around the Yukon delta area, with concentrations increasing to the north and east (15 to 25 percent). Lower percentages (0 to 10 percent) occur adjacent to the northern and southern coasts.

Northern Bering Sea Shallows and Chirikov Basin

Each clay mineral delineates concentration gradients trending northwest-southeast across the northern Bering Sea shallows that extend from just east of St. Lawrence Island to the Bering Strait (figs. 3-5). The gradients are generally less steep to the south but become very steep to the north, as they converge on the narrow Bering Strait. Both illite and chlorite+kaolinite are less concentrated at the center, flanked by increasing concentrations to both the east and west. Illite values are greatest to the northwest of St. Lawrence Island (55 percent), with a gradual decrease eastward to the center of the shallows (fig. 4). A reversal in the gradient of chlorite+kaolinite occurs to the northwest of St. Lawrence Island, where it decreases to 30 to 40 percent (fig. 3). The greatest concentration of smectite occurs midchannel in the shallows (fig. 5). Smectite decreases rapidly to the east and west of the channel. A deviation from this smooth-trending decrease of smectite is a slight increase of 5 percent just north of central St. Lawrence Island.

In summary, for bottom-sediment samples, high illite percentages generally dominate in both Norton Sound and the eastern section of the northern Bering shelf. It is only near the Bering Strait that chlorite+kaolinite dominates the clay-mineral suite, whereas smectite is dominant only in a few samples from the center of the northern Bering Sea shallows.

Suspended Sediment

The distribution of chlorite+kaolinite in the near-sea-floor suspended sediment, the near-sea-surface suspended sediment, and the average values through the water column at each station are similar, as might be expected (figs. 6, 9, 12). Chlorite+kaolinite values in the near-bottom suspended sediment (fig. 13) show a smooth gradient from low concentrations in northern Norton Sound to high concentrations in the south-central part of the sound; the trend then reverses and concentrations decrease to the south. Thus, chlorite+kaolinite values in the near-bottom suspended sediment define northwest-southeast-trending belts of similar concentrations that roughly parallel the northern coast, with the belt of highest concentration between belts of decreasing abundance on either side. The pattern for chlorite+kaolinite in near-surface suspended sediment (fig. 9) is more complex; it has two areas of high concentration—one trending northwest from the Yukon delta marking the western limit of the data points, and one in the south-central part of Norton Sound. In the northern part of the study area the reversing concentration gradients seen for the near-bottom sediment values are also seen for the near-surface suspended-sediment values. Because more data are available for the average chlorite+kaolinite values from the entire water column at each station, more detail in distributions can be determined (fig. 6); however, the overall pattern is the same as described above.

Illite distribution (figs. 7, 10, 13) generally follows the same pattern of northwest-southeast belts of nearly equal concentrations as that shown by chlorite+kaolinite. Two differences are evident, however, for both the near-surface and near-bottom suspended-sediment distributions: (1) they show steeper gradients across central Norton Sound, and (2) they show values that are lowest in the center, with belts of increasing concentration on either side. Illite abundance ranges from 50 to 70 percent. The concentrations just

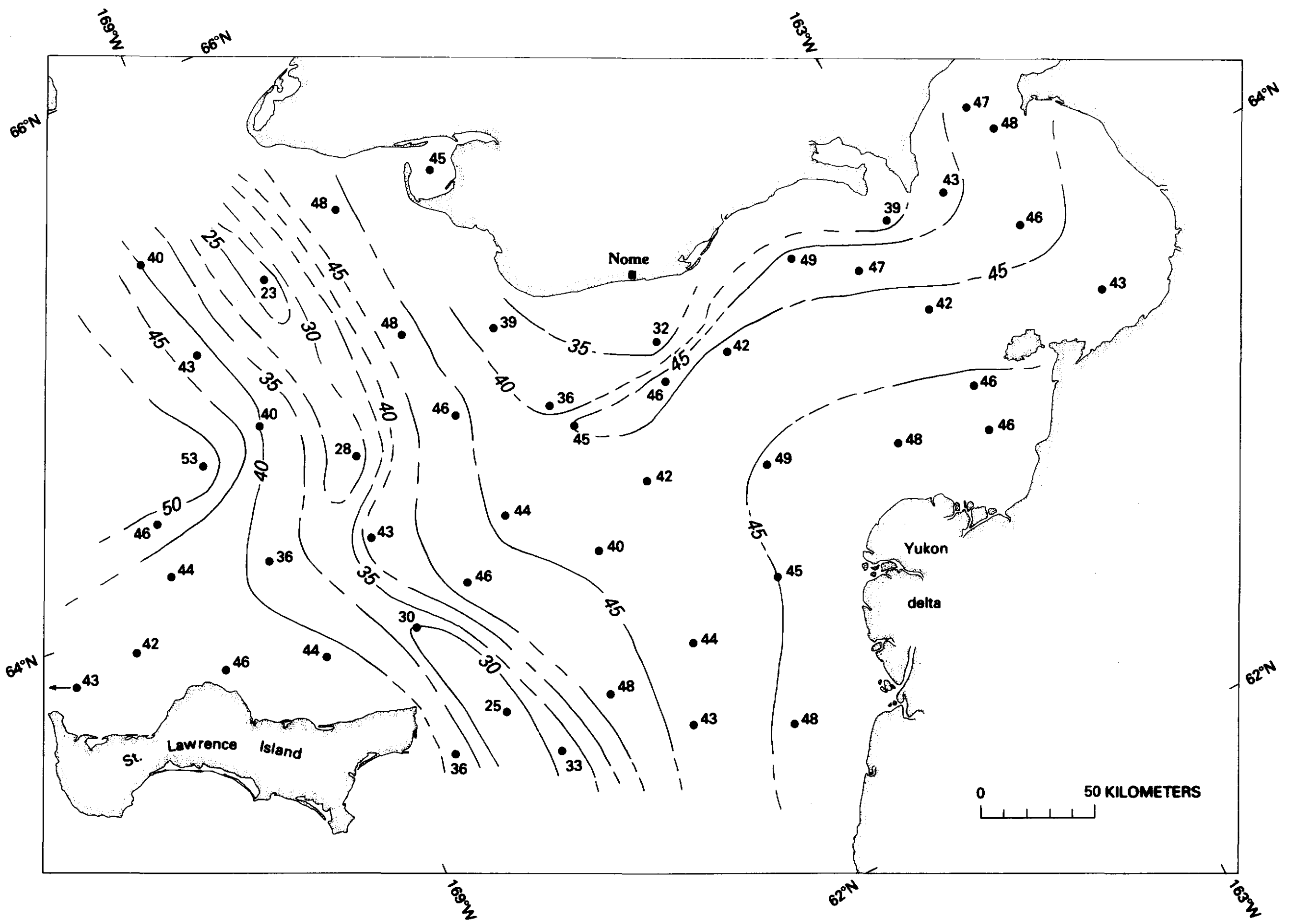

Figure 4. Distribution of illite in bottom sediment. Values are in percentage of illite in the clay-mineral suite and are contoured at a 5-percent interval. Symbols same as for figure 3.

south of the Bering Strait for near-bottom and near-surface suspended sediment range from 50 to 60 percent, showing less variation than suspended sediment farther to the south, in Norton Sound.

Smectite is present in only a few suspended-sediment samples (figs. 8, 11, 14). Areas that show smectite are over the Yukon prodelta and in a small belt along the north-central coast of Norton Sound (fig. 8). Smectite is minor in the Port Clarence-southern Bering Strait areas.

Overall the suspended-sediment clay-mineral suite is illite dominated, with chlorite+kaolinite slightly less both in Norton Sound and the Bering Strait. In near-surface suspended sediment both illite and chlorite+kaolinite increase from the Yukon prodelta seaward. However, in near-bottom suspended sediment illite and chlorite+kaolinite values differ in that illite percentages are high over the prodelta and in the northern sound (range 50 to 70 percent) (fig. 13), whereas chlorite+kaolinite percentages show minor change over the prodelta to the middle of Norton Sound (range 35-45 percent) (fig. 12).

Yukon River

The average clay-mineral percentages of the Yukon River bank sediment are 45, 51, and 4 percent for chlorite+kaolinite, illite, and smectite, respectively. The excellent diffractograms of the suspended sediment show averages of 50 percent chlorite+kaolinite, 50 percent illite, and no smectite (table 1). The concentration of illite in bank and river sediment is higher than that for most of the offshore study area exclusive of the midchannel of the northern Bering Sea shallows and the areas bordering the Yukon delta. The average chlorite+kaolinite value from the Yukon system is slightly higher (5 to 15 percent most commonly) than that for many offshore samples but, as might be expected, matches most closely the near-surface suspended-sediment data. Smectite shows markedly lower concentration in the Yukon system than in most offshore bottom deposits, but it also more closely matches offshore suspended sediment in concentration. Naidu and others (1982) reported that the Yukon River bottom sediment contains a 21 percent expandable phase (smectite as used here), but they do not clearly state the location or the time of year their six Yukon River samples were collected, so it is difficult to evaluate the possibilities for the difference in their 21 versus our 4 percent for bank and 0 percent for suspended sediment. In addition, Naidu and others (1982) measured 41 percent illite and 38 percent chlorite+kaolinite for the Yukon bottom sediment.

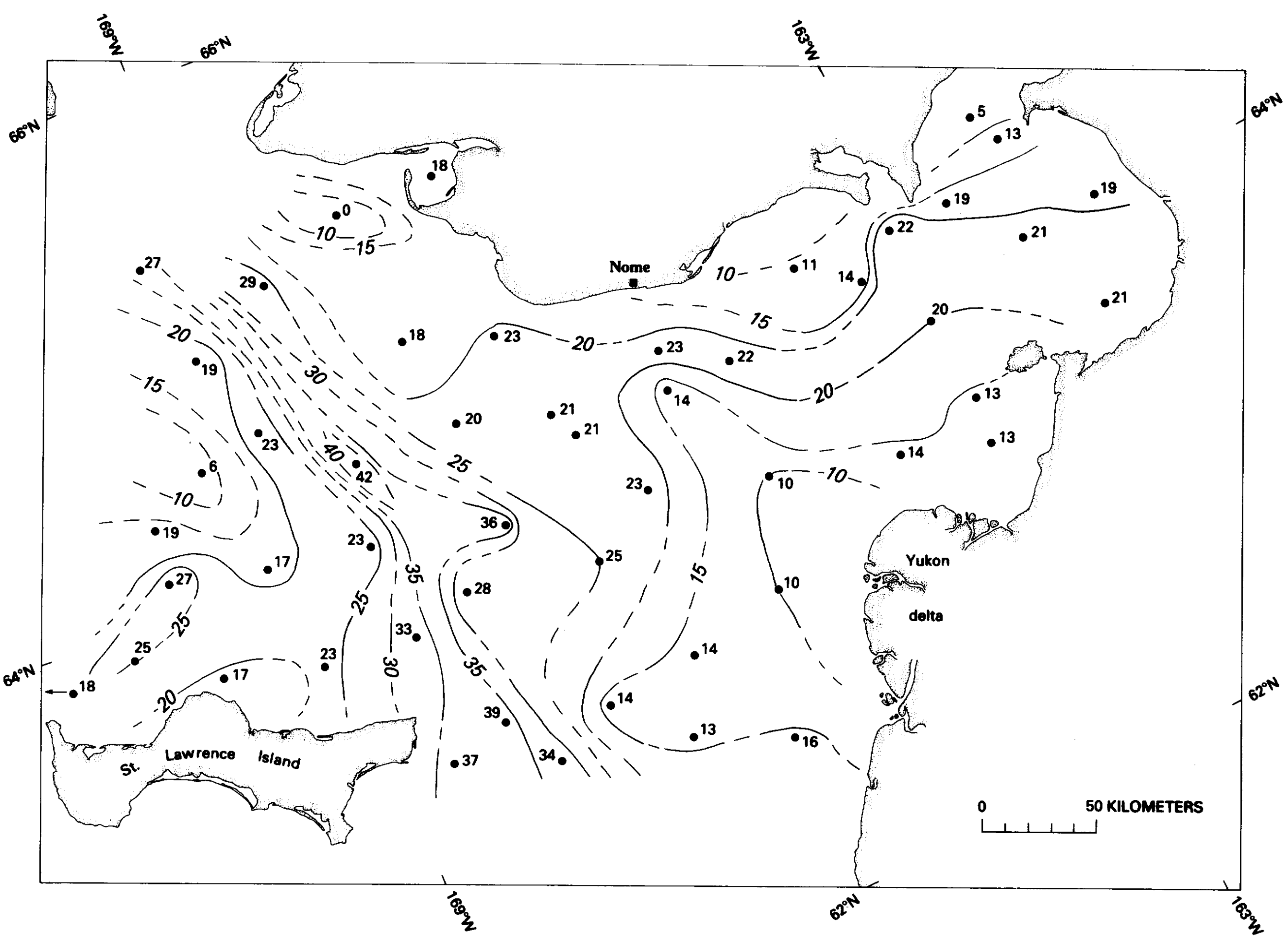

Figure 5. Distribution of smectite in bottom sediment. Values are in percentage of smectite in the clay-mineral suite and are contoured at a 5-percent interval. Symbols same as for figure 3.

Kuskokwim River

The Kuskokwim River averages 53 and 50 percent illite for the bottom and suspended sediment, respectively (table 1); thus, slightly more illite is found in the river than in suspended and bottom sediment in Norton Sound and the western Bering shelf. However, similar illite concentrations occur in bottom sediment from the eastern Bering Sea-Chirikov Basin area. Chlorite+kaolinite values in the Kuskokwim River bottom (47 percent) and suspended-sediment samples (50 percent) are higher than for most of the bottom sediment in the offshore study area (table 2). A similarly chlorite-rich suite is found, however, along the Norton Sound coast and just south of the Bering Strait.

Less than 1 percent smectite is present in bottom and suspended sediment from the Kuskokwim River, a dramatically lower concentration than in Norton Sound and Bering shelf bottom sediments (table 2). Low smectite concentrations (0 to 10 percent) in offshore bottom deposits are found only near the Yukon delta and in the northwestern Bering Sea. The suspended-sediment clay-mineral suite from the Kuskokwim River correlates well with the suite in Norton Sound and the southern Bering Sea. Naidu and others (1982) measured 60 percent illite, 40 percent chlorite+kaolinite, and trace smectite for the clay mineralogy of the Kuskokwim River, results comparable to ours.

SEDIMENT SOURCES AND DISPERSAL ROUTES

Biscaye (1965) and Hein and others (1976, 1979) are among several workers who have shown that source areas and sediment-dispersal routes can be determined by the study of clay mineralogy. From delineation of sediment-dispersal routes, oceanic current patterns can be inferred (Hein and others, 1979). In this study, the Kuskokwim and Yukon Rivers are the major fluvial sources that contribute clay minerals to the area under consideration. Analysis of the river clay-mineral suites enables evaluation of the rivers as potential sources for offshore clay-mineral suites. From this evaluation, possible transportation routes can be determined.

Examination of offshore suspended and offshore bottom sediment allows a three-dimensional view of sediment dispersal. Correlation of suspended sediment with bottom sediment in this study, however, is restricted by the considerations discussed in the methods section. A further consideration is that bottom-sediment samples represent an average of several hundred years of

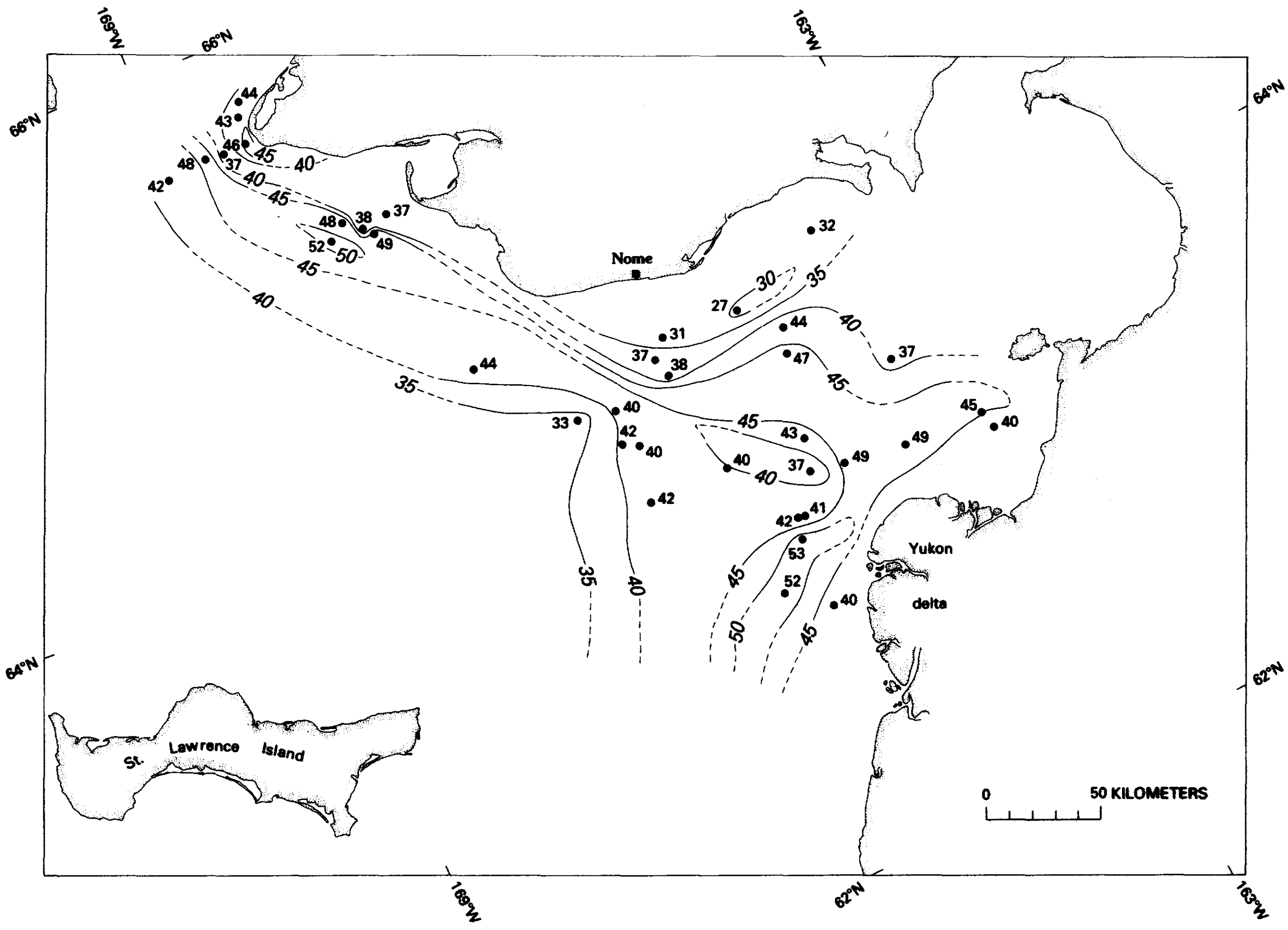

Figure 6. Distribution of chlorite+kaolinite in the clay-mineral suite in suspended sediment. Values are the average percentage of chlorite+kaolinite for all depths in the water column and are contoured at a 5-percent interval; contours dashed where approximately located.

sedimentation in contrast to offshore and river suspended sediments, which represent only daily or weekly sediment averages. Thus, the two data sets must be compared with these facts in mind.

Bottom Sediment

The Yukon River is unquestionably a primary source of Holocene sediment for Norton Sound and the northwestern Bering Sea (Moll, 1970; Carlson and others, 1975; fig. 15). The thickness of Holocene sediment decreases away from the Yukon River mouth (fig. 15). To the south, the Kuskokwim River also supplies significant amounts of sediment to the west-central Alaskan coast; from here the sediment is distributed north by currents (Knebel and Creager, 1973). The Yukon plume diverges from the southwest main distributary transporting fine-grained sediment to the north and also eastward along the coast of Norton Sound (Carlson and others, 1975). There is also minor southward flow from the Yukon delta (Carlson and others, 1975; Drake and others, 1980). A thick accumulation of Yukon-derived Holocene sand occurs along the margins of southern and south-central Norton Sound, composing the Yukon prodelta. Evidence for a northwestward-moving plume is supported by the patterns of the fine-grained bottom deposits as determined in this paper. All three clay minerals indicate a northwestward distribution trend from the delta, as well as possible distribution by a counterclockwise gyre in central Norton Sound. As would be expected, the distinct plume-shaped distribution of clay-mineral concentrations away from the Yukon River indicates the presence of a clay-mineral suite immediately offshore similar to that found in the Yukon River. The slight decrease (5 percent) in the concentrations of chlorite+kaolinite and illite directly northwest from the delta suggests rapid current removal of fine-grained sediment, an influx of clay minerals from another source that mixes with the Yukon clay-mineral suite, or a different clay-mineral suite being delivered by the Yukon during the year the offshore suspended sediment was collected. Yukon suspended sediment may in part be "stored" in Norton Sound prior to movement along the north coast and then farther north into the Bering Strait (see also Drake and others, 1979). This temporary holding period in the sound would allow time for some fine-grained sedimentation to occur (Moll, 1970). Both chlorite+kaolinite and illite abundances can be mapped in broad bands to the northeast of the Yukon delta, which may indicate that these minerals are widely

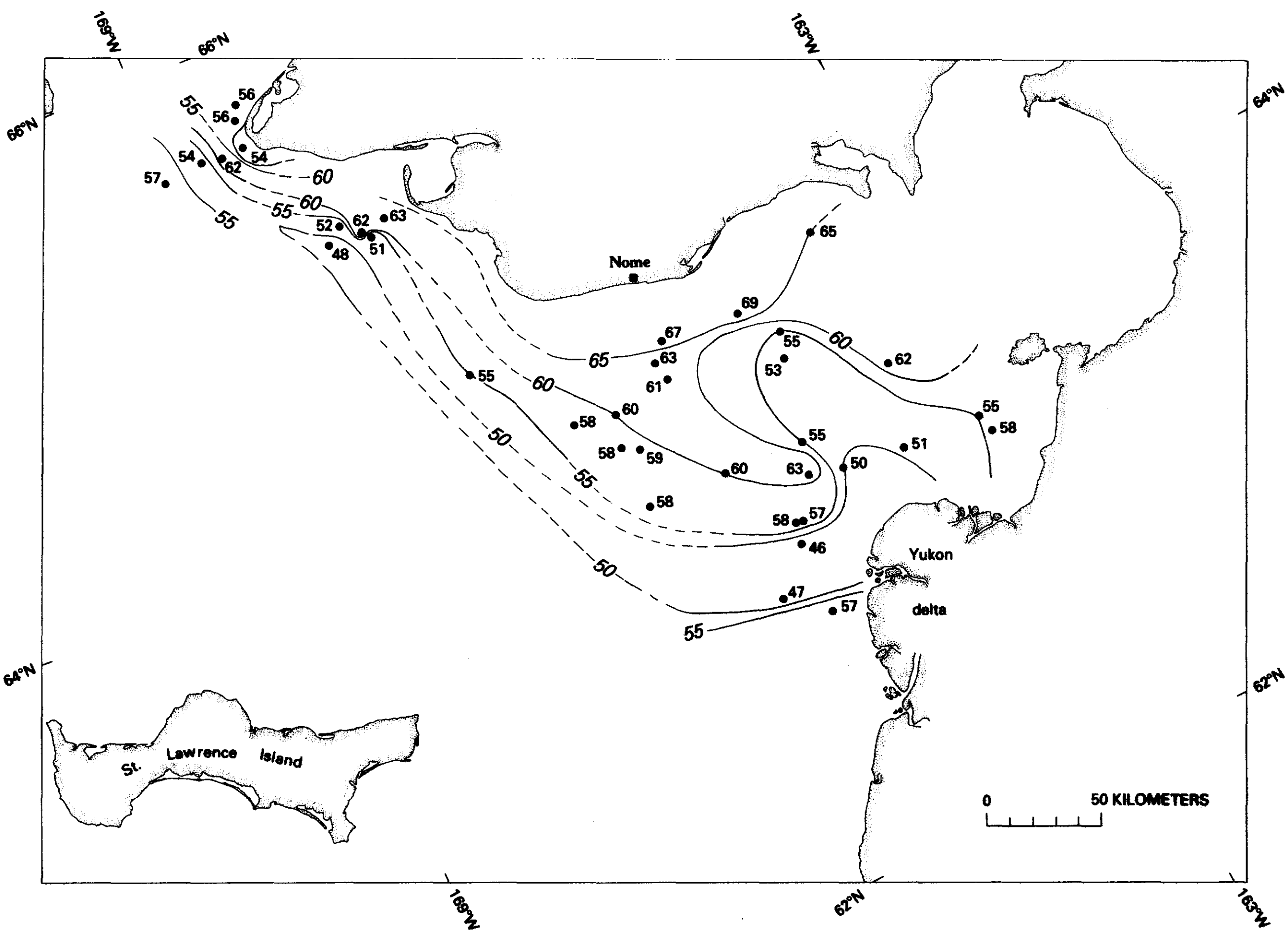

Figure. 7. Distribution of illite in the clay-mineral suite in suspended sediment. Values are the average percentage of illite for all depths in the water column and are contoured at a 5-percent interval; contours dashed where approximately located.

dispersed in Norton Sound by settling from the sluggish counterclockwise gyre. Clay minerals that form a belt parallel to the northern coast of Norton Sound are probably derived locally from coastal erosion and runoff from small coastal streams; however, clays in the northern sound might be a mixture of locally derived clay minerals and Yukon clay minerals brought around in the counterclockwise gyre. Nelson and Creager (1977) showed that relict sands occur in the northern Bering Sea shallows and that very little clay-sized debris is present. Yet, this small amount of clay minerals is probably not relict but contemporary—a condition similar to that found in Cook Inlet, Alaska (Hein and others, 1979).

Bottom sediment in Chirikov Basin is similar to that of the northern Bering Sea shallows in that it is primarily relict sand, mostly glacial debris (Moll, 1970). Chlorite+kaolinite and illite abundances in Chirikov Basin are similar to their abundances in the Yukon and Kuskokwim Rivers. Perhaps the Kuskokwim River is a likely source for Chirikov Basin illite and chlorite+kaolinite, which were transported north and around the western end of St. Lawrence Island. This possibility supports Knebel and Creager's (1973a) suggestion that currents carrying Kuskokwim-derived sediment flow northwest through Anadyr Strait. Additional support for the Kuskokwim input is seen in the smectite distribution. Both the Kuskokwim and Yukon samples we analyzed have little smectite. Similarly low smectite values occur only in the western Chirikov Basin and in the Yukon plume, although the Yukon may have

Table 1. Clay-mineral percentages in sediment from the Yukon and Kuskokwim Rivers as determined by X-ray diffraction.
[See fig. 2 for location of samples. Suspended samples collected June 20, 1975; water discharge was 17,641 m^3/s]

Sample	Chlorite	Kaolinite	Chlorite+Kaolinite	Illite	Smectite
YUKON RIVER BANK SEDIMENT					
Y-1--------	33	8	41	50	9
Y-2--------	34	13	47	51	3
Y-3B-------	32	16	48	51	1
YUKON RIVER SUSPENDED SEDIMENT					
Y-3-14-----	36	14	51	49	1
Y-3-18-----	40	11	50	50	0
Y-3-21-----	37	13	50	50	0
Y-3-24-----	39	13	52	48	0
Y-3-27-----	36	13	49	51	0
KUSKOKWIM RIVER BOTTOM SEDIMENT					
16---------	36	7	43	56	1
613--------	45	12	57	43	0
637--------	30	11	40	60	<1
KUSKOKWIM RIVER SUSPENDED SEDIMENT					
319--------	42	8	50	50	0

Y-1 is mud exposed in bank 2 mi (3.2 km) from coast along Kwigaki Pass.
Y-2 is silt/mud near junction of Kwikpak and Kawanak passes.
Y-3B is bank sample at Pilot Station.
Y-3 is at Pilot Station, lat 61°56'04" N. and long 162°52'50" W.: 14 is near left bank, 18 is between midchannel and left bank, 21 is midchannel, 24 is between midchannel and right bank, 27 is near right bank. Each value (14, 18, 21, 24, 27) is an average of the lower half and upper half of the water column; each station had essentially the same mineralogy.

greater amounts of smectite at different times of the year (see following paragraph). In contrast to these data, Moll's (1970) sparse data show a decrease in illite toward the east and in Chirikov Basin, which is opposite to the trend we observe.

One of the most significant aspects of this study is the remarkably high concentrations of smectite in marine bottom deposits as compared to the rivers. The greatest concentration occurs in the northern Bering Sea shallows following the northwest-southeast trend apparently established by the Alaska Coastal Water. Four explanations are possible for this discrepancy between marine and river compositions: (1) A smectite-rich suite may be derived from sediment adjacent to the Aleutian Island arc and brought north by the major current systems. Smectite-rich clay-mineral suites are known to occur in sediment adjacent to the Aleutian Ridge (Hein and others, 1976). Smectite could be further concentrated relative to illite and chlorite in the north-flowing currents by segregation according to varying size or density, as occurs off the Amazon River mouth (Gibbs, 1967, 1977). (2) Erosion of volcaniclastic and volcanic rocks on Chukotka Peninsula and adjacent areas in Siberia could produce smectite-rich clays that are brought eastward by currents. Current patterns may have been different during glacial periods than now, with increasing sediment contributions from areas different from those that dominate today. (3) Erosion of local bedrock outcrops on the northern Bering Sea shelf may provide smectite-rich clays. High concentrations of smectite on the Gulf of Alaska shelf are directly correlative with bedrock exposures of the shelf itself (Molnia and Hein, 1982); however, very few bedrock outcrops exist on the northern Bering Sea shelf. (4) The clay-mineral composition of the Yukon River may change from year to year or from season to season. Although changes in the mineralogy of major rivers like the Yukon have not been reported, such a change is supported by the different clay-mineral suites obtained in this study compared to those obtained by Naidu and others (1982). These differences in composition are greater than can be explained by analytical errors or differences in techniques of clay-mineral analysis. In contrast, the clay-mineral suites determined for the Kuskokwim River in this study and for Naidu and others' study are similar, suggesting a greater constancy in the composition of the Kuskokwim. Combinations of suggestions 1, 2, and 4 may explain the greater amount of smectite in bottom sediments versus the rivers.

In summary, smectite concentrations in Norton Sound are considerably higher (10 to 25 percent) than concentrations for the Yukon (2 percent) or Kuskokwim (less than 1 percent) Rivers and also much higher in places than measured for the Yukon (21 percent) by Naidu and others (1982). Interestingly, the concentration percentages of the the clay-mineral suite that Naidu and others (1982) determined for their Yukon River sediment are identical to the average values we obtained for all our offshore bottom sediments, whereas the average values for all the offshore suspended-sediment samples are the same as those determined for the clay-mineral suite of the Kuskokwim River. It is not known which conditions control the clay-mineral composition of the Yukon River. Clearly, the times at which and places where the Yukon was sampled by Naidu and others (1982) are more typical of what the river has delivered to the shelf than are the samples we analyzed, which were collected on June 20, 1975, at Pilot Station, about 60 km from the river mouth. The flow rate during our sampling was 17,641 m^3/s, only slightly less than the maximum flow of nearly 20,000 m^3/s that most commonly occurs after ice breakup in late May or early June (Drake and others, 1980). Perhaps much of the clay-sized material was flushed out of the system during onset of the spring thaw. Summer suspended-sediment samples from the Yukon contain less than 10 percent clay-sized material (Drake and others, 1980). The higher smectite concentration in Norton Sound versus values we obtained for the Yukon River is probably due to seasonal variations in the composition of the Yukon and to transport of smectite by the north-flowing ACW or by current flow from eastern Siberia during glacial periods.

Suspended Sediment

The distribution of suspended sediment is delineated by a northwesterly trend in the clay-mineral concentrations from the Yukon delta to the Bering Strait

Table 2. Average and range of clay mineral percentages of bottom- and suspended-sediment samples from Norton Sound and adjacent Bering shelf.

	Chlorite	Kaolinite	Chlorite+Kaolinite	Illite	Smectite
BOTTOM SEDIMENT					
Average----	28	10	38	42	21
Range------	18-36	0-17	22-52	23-53	0-48
SUSPENDED SEDIMENT					
Average----	33	9	42	57	<1
Range------	15-54	1-19	21-59	41-79	0-4

(figs. 6-14). The clay-mineral suite adjacent to the Yukon River is very similar to that of the Yukon River itself (figs. 6-8). Kuskokwim-type clay-mineral suites may be traceable into the northern Bering Sea shallows, suggesting transportation from the south in a current that diverges slightly around the Yukon delta in its northwesterly movement. The illite-rich suite along the northern coast of Norton Sound may be derived partly from the gyre in Norton Sound which carries sediment from the Kuskokwim or from farther south (figs. 6, 7) and partly from clays supplied locally as described for the bottom sediments. Both Kuskokwim- and Yukon-like clay suites are discernable at the southern entrance of the Bering Strait. If these suites are in fact from the two rivers, then both rivers supply sediment that is funneled directly into the Chukchi Sea through the Bering Strait (see also Naidu and others, 1982).

Near-surface suspended-sediment values are nearly the same as the average values for suspended sediment in the water column (figs. 9, 10). However, as described previously, clay-mineral-concentration gradients of the near-surface suspended sediment are slightly steeper than gradients of the near-bottom suspended-sediment concentrations (figs. 12, 13). The near-bottom clay-mineral suites show a more uniform gradient, which may indicate less mixing from different sources for bottom deposits (Figs. 12, 13). Although the concentration of smectite in the water column during the summer months does not help explain the enigmatic concentrations in bottom sediment, it is an excellent indicator of short-term summer sources. The percentage of smectite in bottom sediment in the Kuskokwim River (¼1 percent) supports the interpretation that it is a source of fine-grained sediment in Norton Sound and the Bering Strait. Since the Yukon can apparently have varying amounts of smectite in the suspended sediment and minor smectite in bank samples, the minor smectite in suspended sediment over the Yukon prodelta is probably derived from the river and from resuspension of bottom material by storm waves or tidal fluctuations. Smectite also seems to be a good indicator of movement along the north shore of Norton Sound. Percentages here range from 3 to 4 in near-bottom sediment, also suggesting resuspension of bottom deposits.

In summary, assuming that the smectite contents of the offshore suspended-sediment samples are not an anomaly of the filtration process, the Kuskokwim sediment is apparently represented in many areas of the Norton Sound and the adjacent shelf. In contrast, the Yukon clay-mineral suite is most clearly identified in

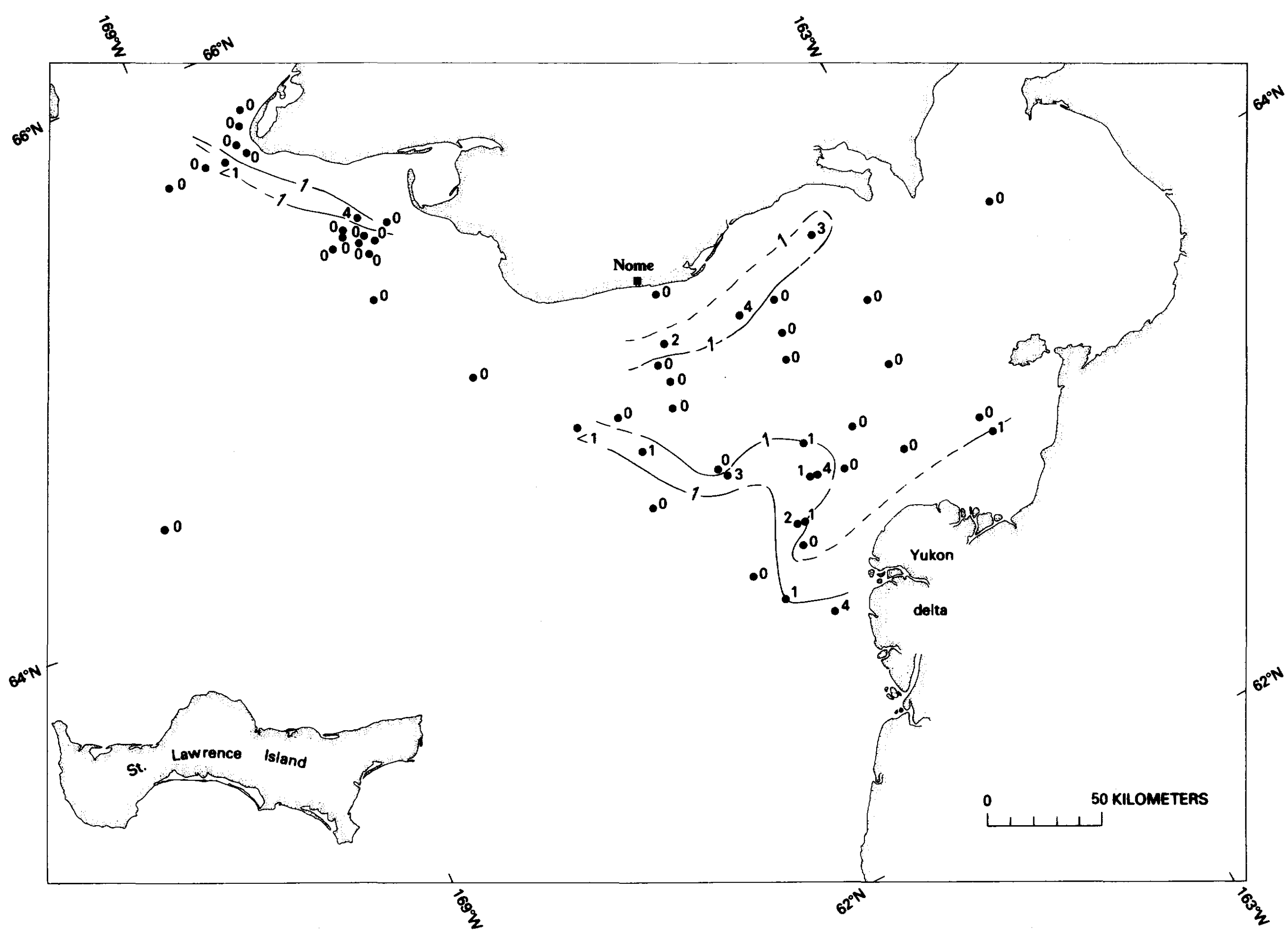

Figure 8. Distribution of smectite in the clay-mineral suite in suspended sediment. Values are the average percentage of smectite for all depths in the water column and are contoured at a 5-percent interval; contours dashed where approximately located.

suspended sediment that occupies a narrow band that stretches from the river mouth to the Bering Strait.

Inferred Current Patterns

On the basis of the bottom- and suspended-sediment data and previous studies, several distinct current patterns are indicated: (1) The Alaska Coastal Water (ACW) coming from the south and diverging at the Yukon delta northwest toward the Bering Strait and east into Norton Sound—this current also bifurcates and moves around the west side of St. Lawrence Island; (2) a counterclockwise gyre in central Norton Sound; and (3) a current moving along the north shoreline of Norton Sound, either influenced to some degree by movement of the ACW or wholly by local tidal action stimulating longshore drift.

The ACW, the major distributor of sediment, transports Kuskokwim as well as Yukon sediment. Yukon sediment is dispersed in two directions—a predominant flow to the northwest, indicated by steep gradients in the contoured clay-mineral data (figs. 6-8), and a more diffuse flow of fine-grained sediment eastward into most of Norton Sound. The clay mineralogy also indicates movement along the north shore of the sound. The existence of both the ACW and the slower current in Norton Sound is also supported by temperature and salinity studies (Carlson and others, 1975; Nelson and Creager, 1977).

Clay suites in Chirikov Basin and the westernmost part of the northern Bering Sea shelf suggest current transport from the south around the western end of St. Lawrence Island through Anadyr Strait. This current merges with the ACW just south of the Bering Strait. Clearly, currents from both Norton Sound and Chirikov Basin converge with the main branch of ACW in the northern part of the Bering shelf before passing through the Bering Strait.

ENVIRONMENTAL CONSIDERATIONS

Oil spilled within the rapidly northward moving ACW is likely to be transported northward and into the Chukchi Sea, as is the fine-grained sediment. Consequently, although spills could be removed from Norton Sound, an important fishing area, they could still be widely distributed to the north. It is unclear how much oil would be carried eastward past the ACW into Norton Sound and dispersed by the counterclockwise gyre and the longshore drift that occurs off the northern

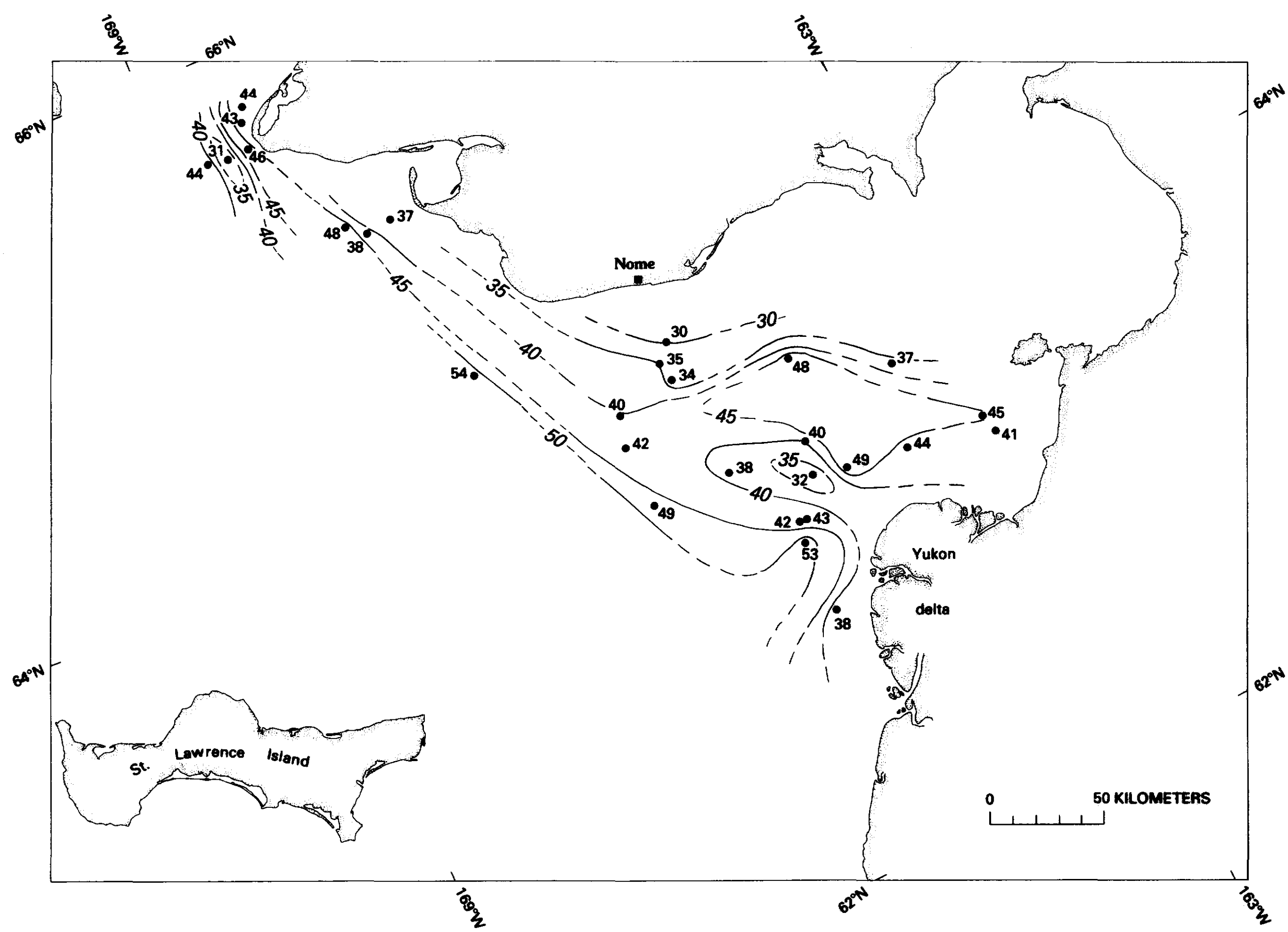

Figure 9. Distribution of chlorite+kaolinite in near-surface suspended sediment. Values are the percentage of chlorite+kaolinite in the clay-mineral suite and are contoured at a 5-percent interval; contours dashed where approximately located.

coast. Potentially a spill could have a devastating effect on the coastal areas, especially where fine-grained sediment occurs in bays and fjords. The shallow waters throughout Norton Sound pose a special problem regarding oil pollution—resuspension of bottom sediments by storm wave and tidal fluctuation. Such resuspension could disperse pollutants that had accumulated in the bottom sediment throughout the water column.

Another important pollution consideration is oil absorption into and adsorption onto clay minerals, especially smectites. Smectite is an expandable clay mineral which can accommodate large organic molecules (for instance, hydrocarbons) in its crystallographic interlayer spaces. This results in retention of oil in smectite-rich bottom and suspended deposits and has been suggested as a specific problem for suspended sediment in Lower Cook Inlet, Alaska (Hein and others, 1979). However, in central Norton Sound, where smectite is abundant in bottom sediment and minor in suspended sediment, the clay-sized fraction constitutes only a small part of the total sediment. Thus, the potential detrimental effect due to absorption of oil by clay minerals in bottom and suspended sediment may be negligible, except in the shallow bays and fjords that line Norton Sound, where muds predominate.

REFERENCES

Biscaye, P. E., 1965, Mineralogy and sedimentation of recent deep-sea clay in the Atlantic Ocean and adjacent seas and oceans: Geological Society of America Bulletin, v. 76, no. 7, p. 803-832.

Cacchione, D. A., and Drake, D. E., 1982, Measurements of storm-generated bottom stresses on the continental shelf: Journal of Geophysical Research, v. 87, no. C3, p. 1952-1960.

Carlson, P. R., Conomos, T. J., Janda, R. J., and Peterson, D. H., 1975, Principal sources and dispersal patterns of suspended particulate matter in nearshore surface waters of the northeast Pacific Ocean: Greenbelt, Maryland, Goddard Space Flight Center, NASA Contractors Final Report No. CR-142641, National Technological Information Service, p. 26-39.

Coachman, L. K., and Aagaard, K., 1966, On the water exchange through the Bering Strait: Limnology and Oceanography, v. 11, p. 44-59.

Drake, D. E., Cacchione, D. A., Muench, R. D., and Nelson, C. H., 1980, Sediment transport in Norton Sound, Alaska: Marine Geology, v. 36, p. 97-126.

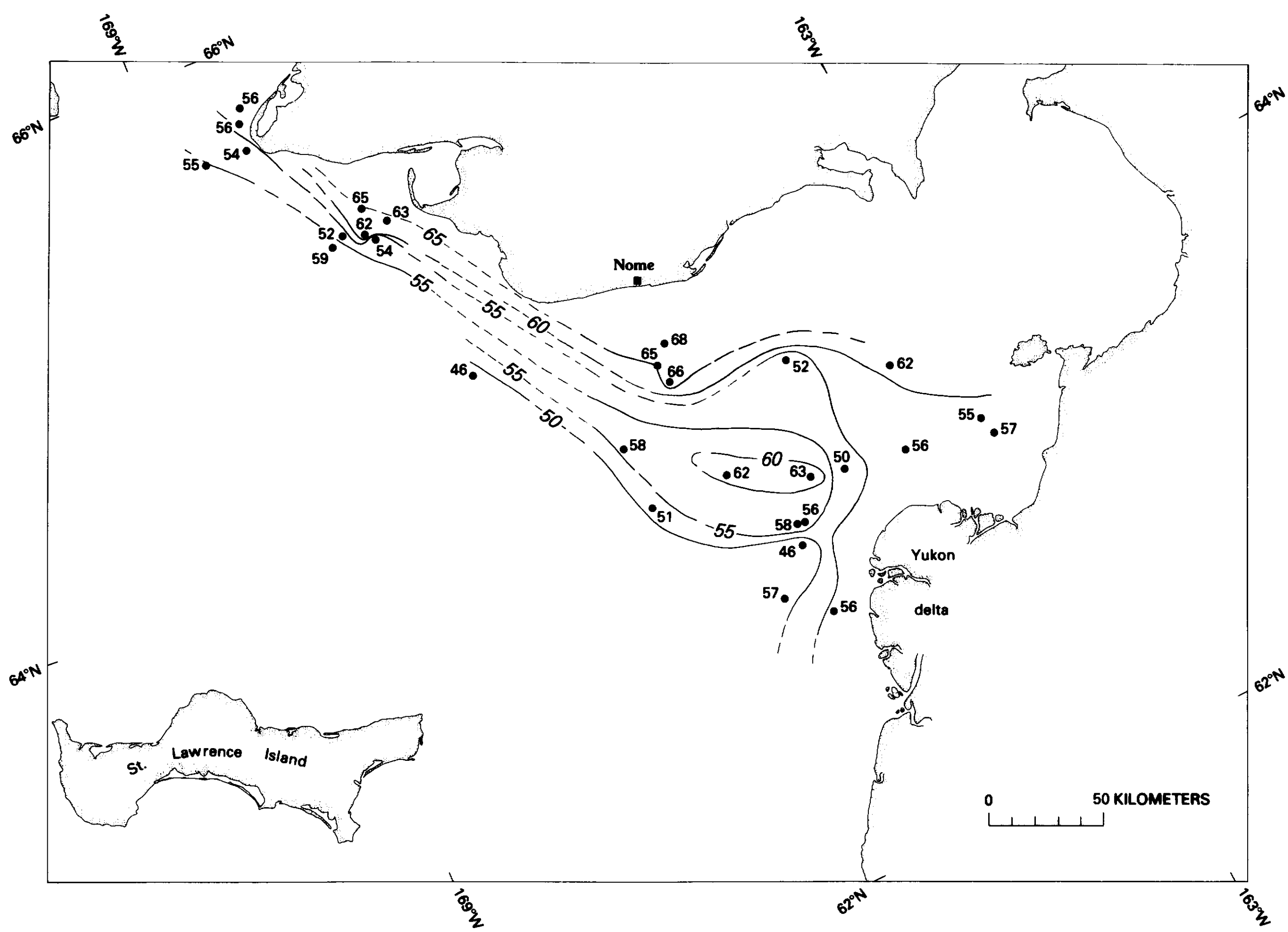

Figure 10. Distribution of illite in near-surface suspended sediment. Values are the percentage of illite in the clay-mineral suite and are contoured at a 5-percent interval; contours dashed where approximately located.

Drake, D. E., Totman, C. E., and Wiberg, P. L., 1979, Sediment transport during the winter on the Yukon prodelta, Norton Sound, Alaska: Journal of Sedimentary Petrology, v. 49, p. 1171-1180.

Dupre, W. R., 1978, Yukon Delta coastal processes study, in Assessment of the Alaskan Continental Shelf: U.S. National Oceanographic and Atmospheric Administration and Bureau of Land Management Principal Investigators Report for year ending March 1978, p. 384-446.

Fleming, R. H., and Heggarty, D., 1976, Oceanography of the southeastern Chukchi Sea, in Wilimovsky, N. J., and Wolfe, J., eds., Environment of the Cape Thompson region, Alaska: U.S. Atomic Energy Commission, Division of Technical Information, PNE-481, p. 697-754.

Gibbs, R. J., 1967, The geochemistry of the Amazon River system; Part 1, The factors that control the salinity and the composition and concentration of the suspended solids: Geological Society of America Bulletin, v. 78, no. 10, p. 1203-1232.

_____ 1977, Clay mineral segregation in the marine environment: Journal of Sedimentary Petrology, v. 47, no. 1, p. 237-243.

Goodman, J. R., Lincoln, J. H., Thompson, T. G., and Zevsler, F. A., 1942, Physical and chemical investigations: Bering Sea, Bering Strait, Chukchi Sea during the summers of 1937 and 1938: Pullman, Washington, University of Washington Publication in Oceanography, v. 3, no. 4, p. 105-169, and Appendix, p. 1-117.

Hein, J. R., Bouma, A. H., Hampton, M. A., and Ross, R. C., 1979, Clay mineralogy, fine-grained sediment dispersal, and inferred current patterns, lower Cook Inlet and Kodiak Shelf, Alaska: Sedimentary Geology., v. 24, p. 291-306.

Hein, J. R., Scholl, D. W., and Gutmacher, C. E., 1976, Neogene clay minerals of the far northwest Pacific and southern Bering Sea: Sedimentation and diagenesis, in Bailey, S. W., ed. Proceedings of the 1975 International Clay Conference, Willmette, Illinois, Applied Publication Limited, p. 71-80.

Howard, J. D., and Nelson, C. H., 1982, Sedimentary structures on delta-influenced shallow shelf, Norton Sound, Alaska, in Nelson, C. H. and Nio, S. D., eds., The northeastern Bering Shelf: New perspectives of epicontinental shelf processes and depositional products: Geologie en Mijnbouw, v. 61, p. 29-36.

Husby, D. M., 1969, Report of oceanographic cruise U.S.C.G.C. Northwind, northern Bering Sea - Bering Strait - Chukchi Sea, July 1969: U.S. Coast Guard Oceanographic Report 24, 75 p.

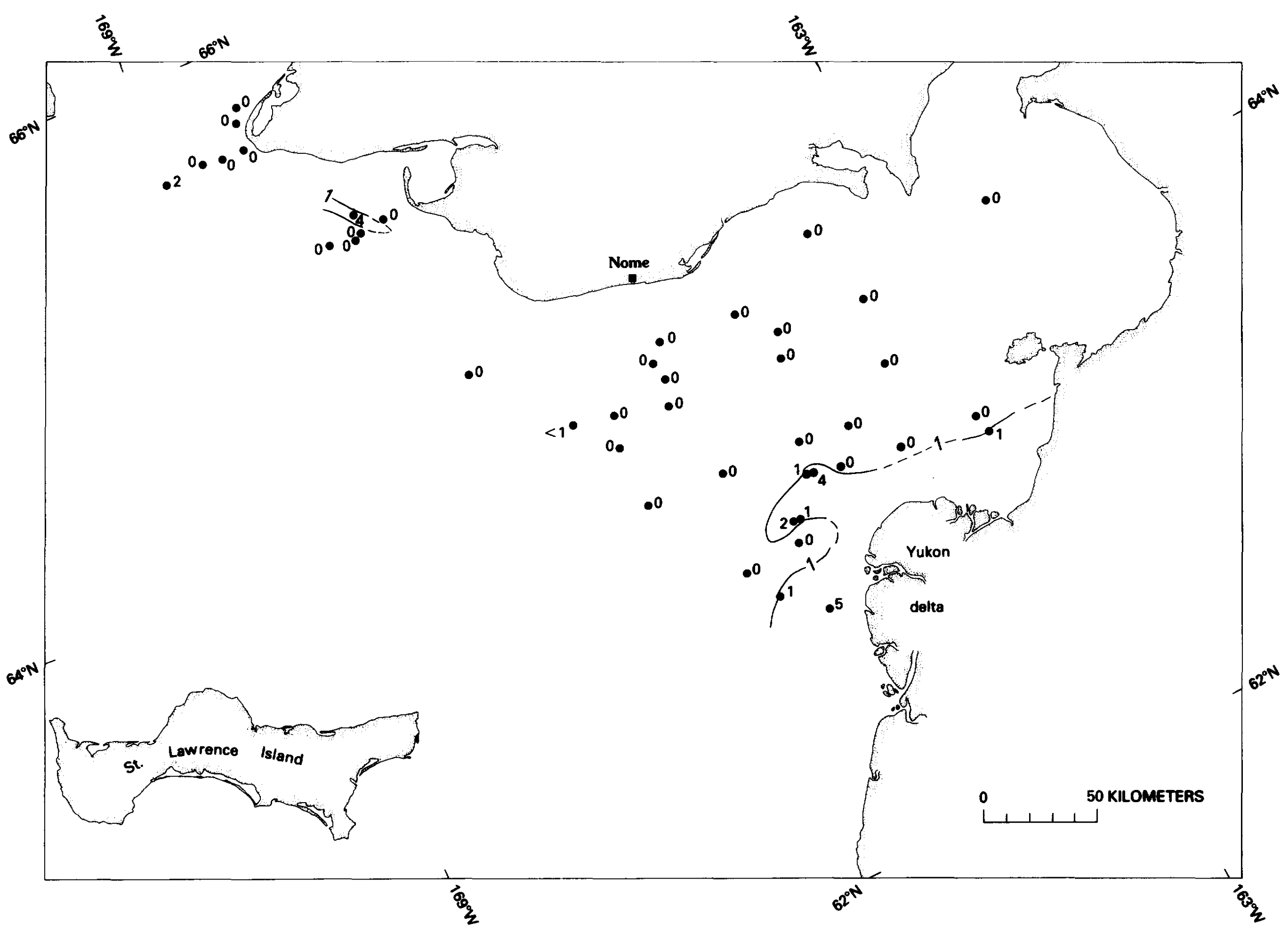

Figure 11. Distribution of smectite in near-surface suspended sediment. Values are in percentage of smectite in the clay-mineral suite and are contoured at a 5-percent interval; contours dashed where approximately located.

_____ 1971, Oceanographic investigations in the northern Bering Sea and Bering Strait, June-July 1969: U.S. Coast Guard Oceanographic Report 40, 50 p.

Inman, D. L., and Nordstrom, C. E., 1971, On the tectonic and morphologic classification of coasts: Jounal of Geology, v. 79, p. 1-21.

Knebel, H. J., and Creager J. S., 1973a, Sedimentary environments of the east-central Bering Sea continental shelf: Marine Geology, v. 15, p. 25-45.

_____ 1973b, Yukon River: Evidence for extensive migration during the Holocene transgression: Science, v. 179, p. 1230-1232.

Lisitsyn, A. P., 1966, Recent sedimentation in the Bering Sea (Protessy sovre mennogo osdkoobrazovaniya v Beringovom more): Akademiia Nauk (Doklady), U.S.S.R., Moscow (English translation, 1969, Israel Program for Scientific Translations), U.S. Department of Commerce, Clearing House for Federal Scientific and Technical Information, Springfield, Virginia, 614 p.

McManus, D. A., and Smyth, C. S., 1970, Turbid bottom water on the continental shelf of northern Bering Sea: Journal of Sedimentary Petrology, v. 40, no. 3, p. 869-877.

McManus, D. A., Venkatarathnam, K., Hopkins, D. M., and Nelson, H. C., 1974, Yukon River sediment on the northernmost Bering Sea Shelf: Journal of Sedimentary Petrology, v. 44, no. 4, p. 1052-1060.

Moll, R. F., 1970, Clay mineralogy of the north Bering Sea shallows: Los Angeles, Calif., University of Southern California, M. A. thesis (Report No. USC Geol. 70-2), 101 p.

Molnia, B. F., and Hein J. R., 1982, Clay mineralogy of a glacially dominated, subarctic continental shelf: Northeastern Gulf of Alaska: Journal of Sedimentary Petrology, v. 52, no. 2, p. 515-527.

Naidu, A. S., Creager, J. S., and Mowatt, T. C., 1982, Clay mineral dispersal patterns in the North Bering and Chukchi Seas: Marine Geology, v. 47, p. 1-15.

Nelson, C. H., 1982, Late Pleistocene-Holocene transgressive sedimentation in deltaic and non-deltaic areas of the northeastern Bering epicontinental shelf, in Nelson, C. H., and Nio, S. D., eds., The northeastern Bering Shelf: New perspectives of epicontinental shelf processes and depositional products: Geologie en Mijnbouw, v. 61, p. 5-18.

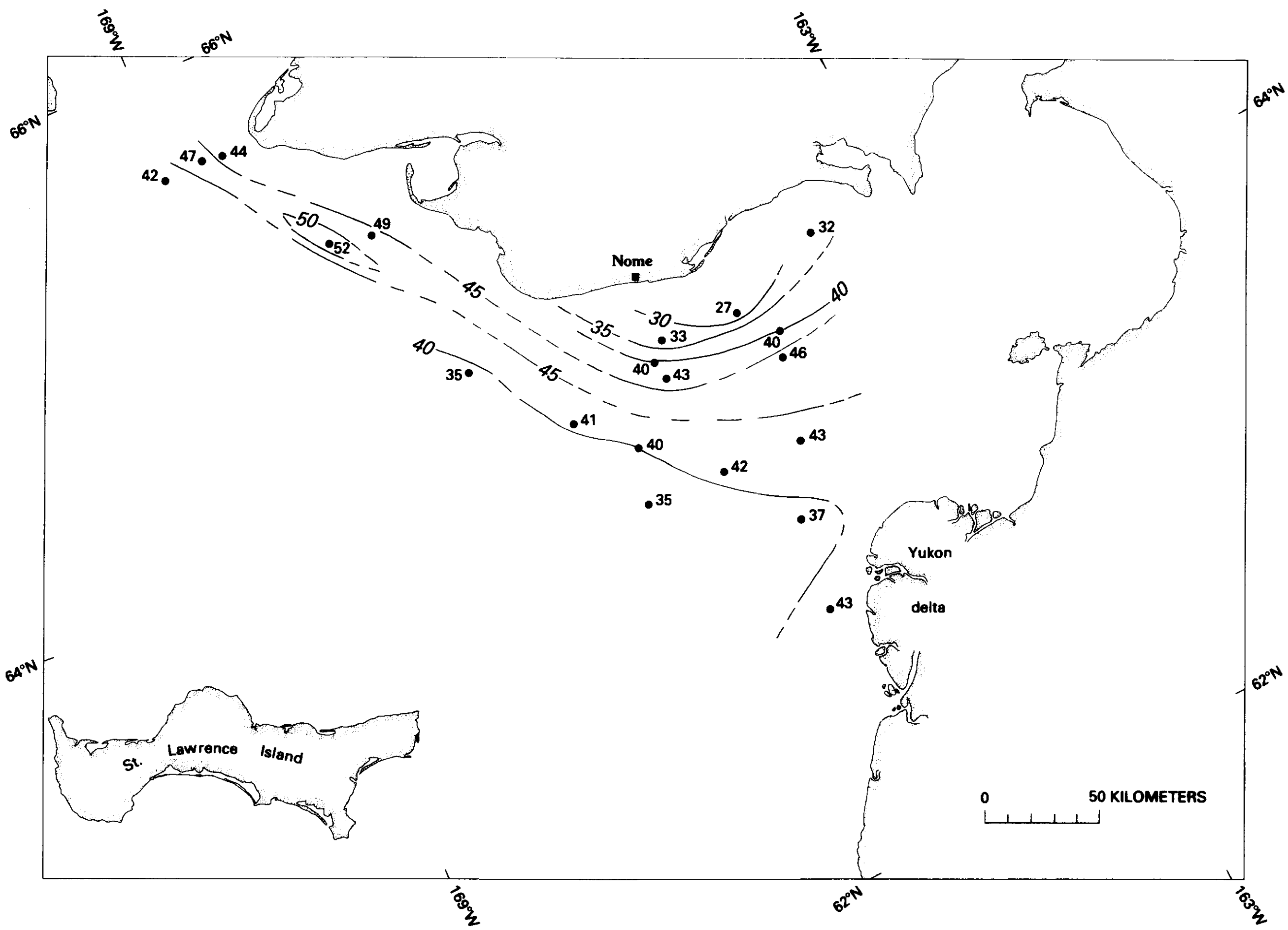

Figure 12. Distribution of chlorite+kaolinite in near-bottom suspended sediment. Values are in percentage of chlorite+kaolinite in the clay-mineral suite and are contoured at a 5-percent interval; contours dashed where approximately located.

Nelson, C. H., and Creager, J. S., 1977, Displacement of Yukon-derived sediment from Bering Strait to Chukchi Sea during Holocene time: Geology, v. 5, no. 3, p. 141-146.

Nelson, C. H., Pierce, D. E., Leong, K. W., and Wang, F. H., 1975, Mercury distribution in ancient and modern sediment of northeastern Bering Sea: Marine Geology, v. 18, p. 91-104.

Patton, W. W., 1971, Petroleum possibilities of Yukon-Koyukuk Province, Alaska, in Cram, I. H., ed., Future petroleum provinces of the U.S.--their geology and potential: American Association of Petroleum Geologists Memoir 15, v. 1, p. 100-104.

Sharma, G. D., Wright, F. F., Burns, J. J., and Burbank, D. C., 1974, Sea-surface circulation, sediment transport, and marine mammal distribution, Alaska continental shelf: Greenbelt, Maryland, Goddard Space Flight Center, NASA Contractors Final Report No. CR-139544, National Technology Information Service, NASA Contractor Report No. CR-139544, 77 p.

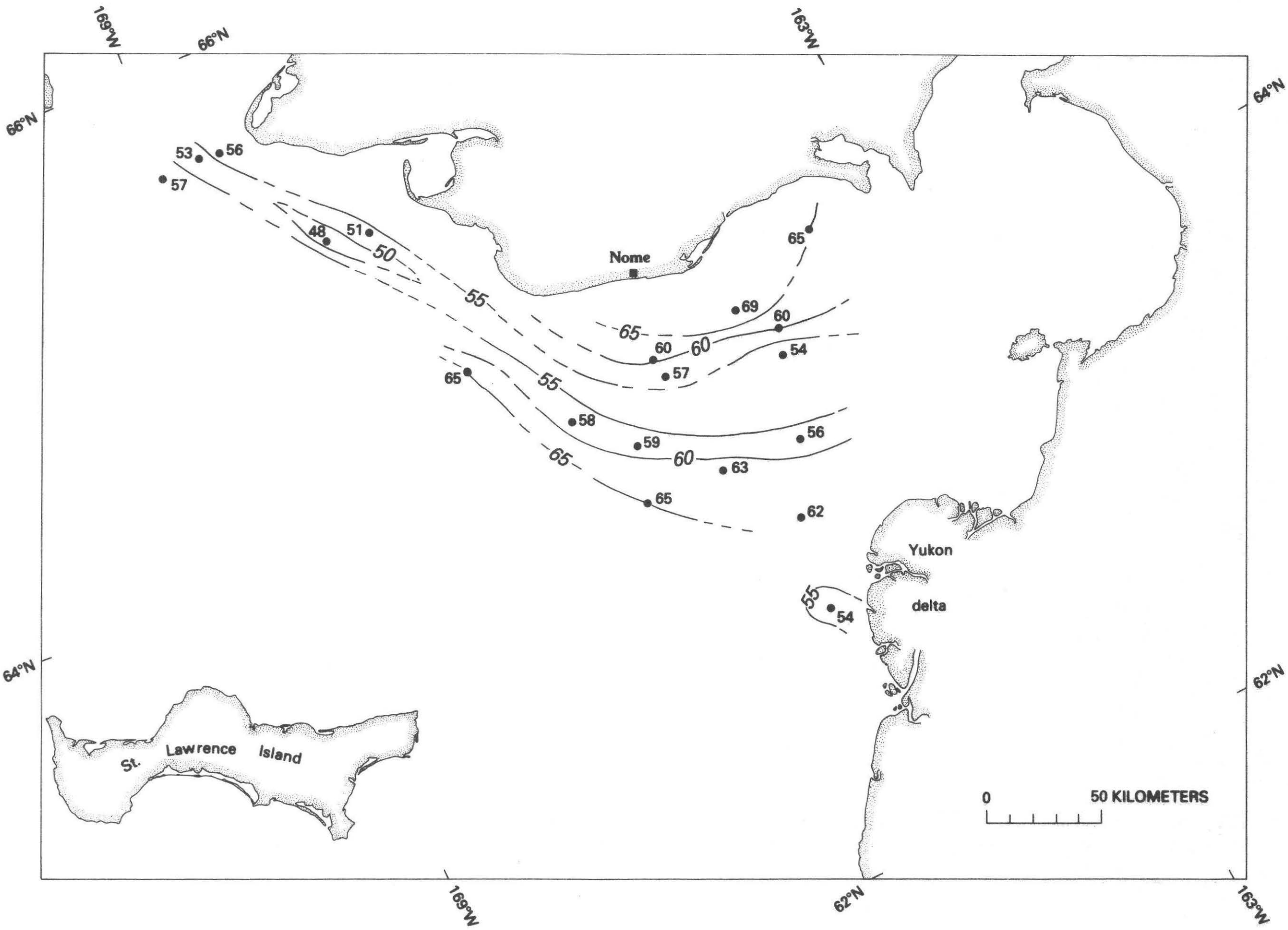

Figure 13. Distribution of illite in near-bottom suspended sediment. Values are in percentage of illite in the clay-mineral suite and are contoured at a 5-percent interval; contours dashed where approximately located.

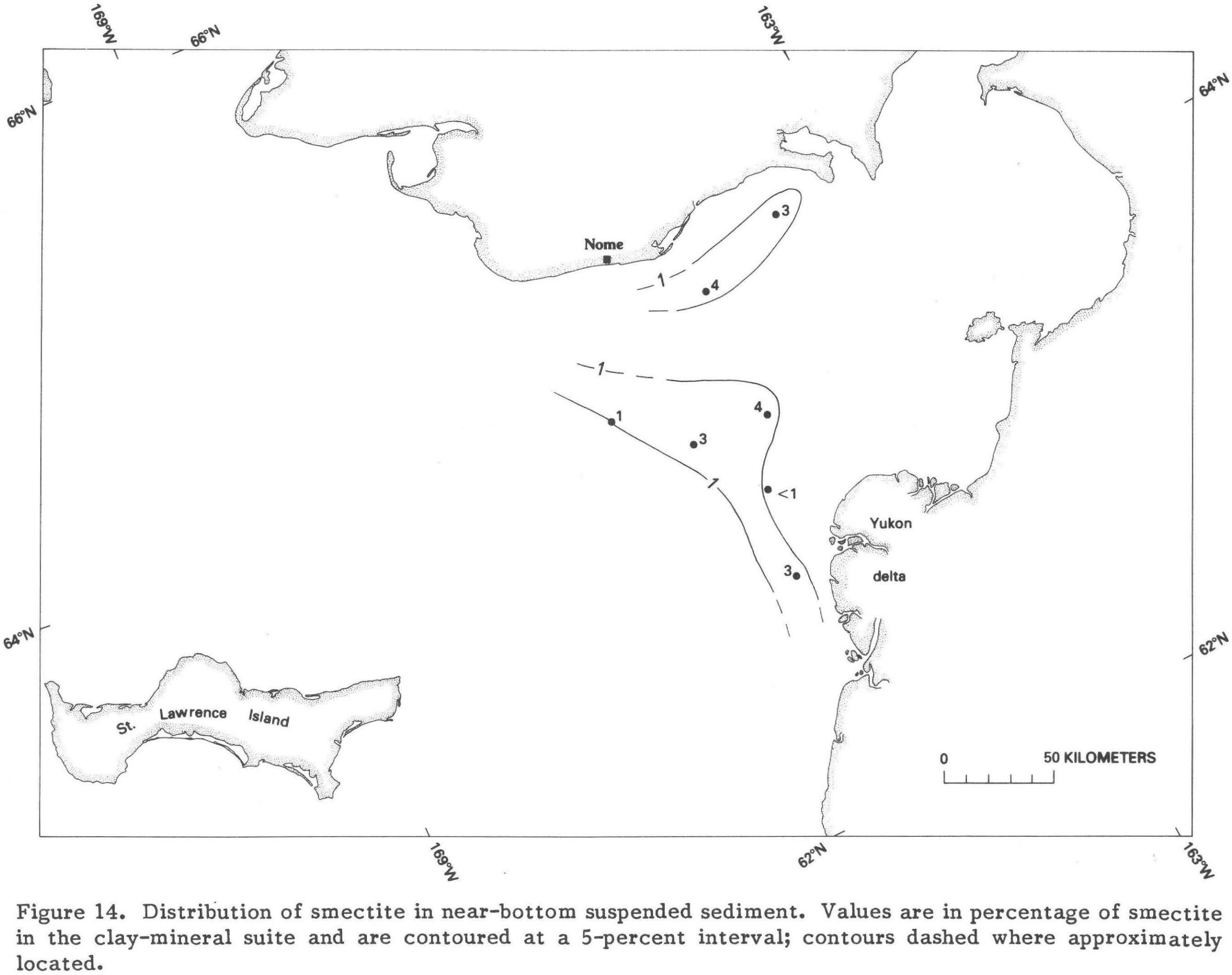

Figure 14. Distribution of smectite in near-bottom suspended sediment. Values are in percentage of smectite in the clay-mineral suite and are contoured at a 5-percent interval; contours dashed where approximately located.

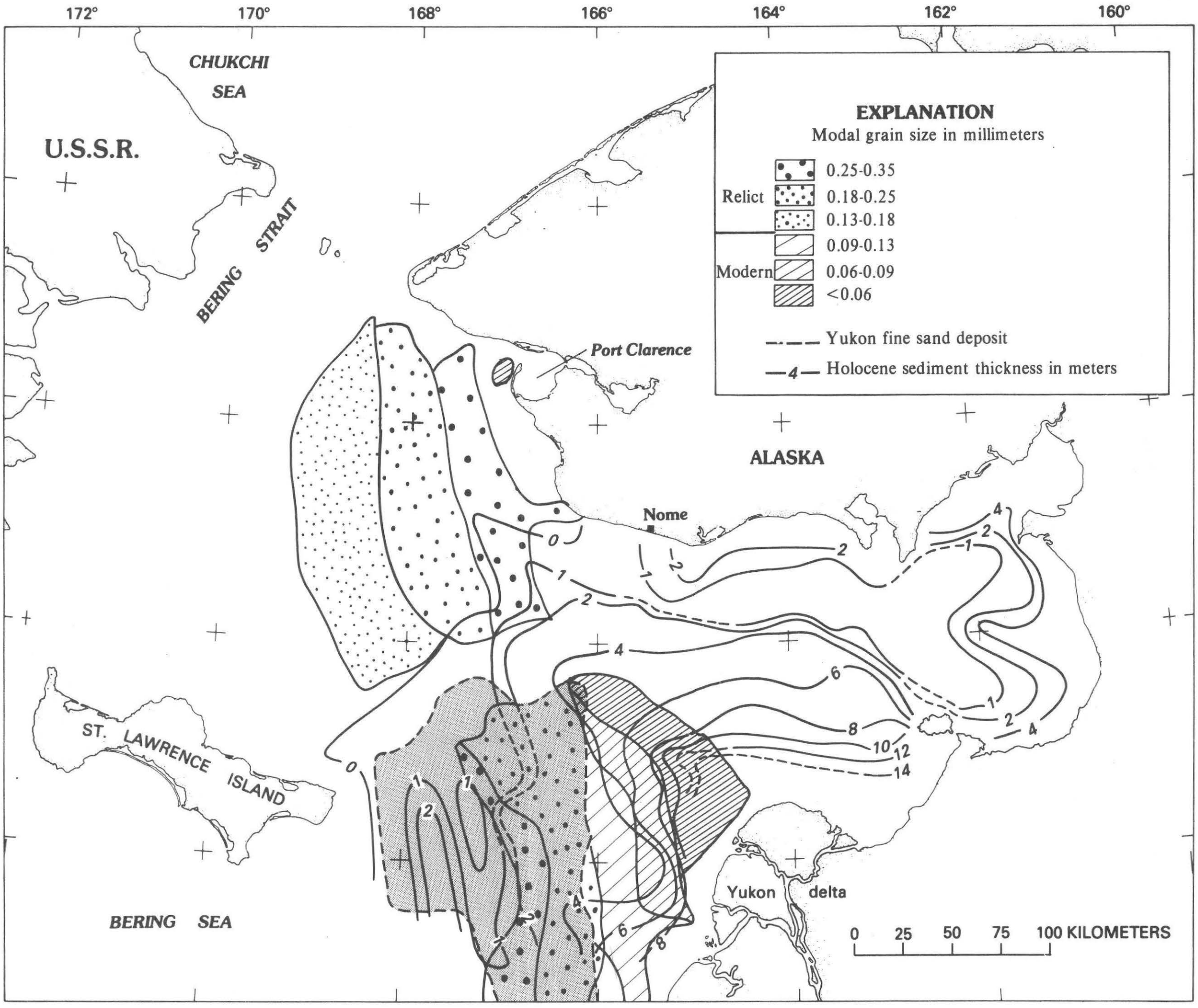

Figure 15. Isopach map of Holocene marine sediment in Norton Sound and the adjacent shelf area, based on core data and high-resolution seismic data. Figure from Nelson (1982).

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