Chapter 9
Holocene History of the Laptev Sea Continental Shelf[1]

M. L. HOLMES[2] AND J. S. CREAGER[2]

Abstract

The 400-km-wide, low gradient Laptev Sea continental shelf consists of flat terrace-like features at regular depth intervals from 10 to 40 m below present sea level. The five large submarine valleys traversing the shelf do not continuously grade seaward, but contain elongated, closed basins. These terraces and closed basins plus deltaic sediments associated with the submarine valleys quite possibly mark sea level stillstands, and enable reconstruction of the paleogeography of the Laptev Sea shore line at five periods during post-Wisconsin (Holocene) time.

Radiocarbon dates on the silty-clay to clayey-silt sediments from cores of the northeastern Laptev Sea indicate average sedimentation intensity of 2 to 15 mg/cm^2/yr. The presence of manganese nodules and crusts in surface samples from less than 55 m depths and a general decrease in total foraminiferal abundances with depth in the cores suggest that the present deposition rate is less than when sea level was lower. The main components of the shelf deposits are nearshore sediments which were spread over the shelf as Holocene sea level fluctuated and marine currents distributed modern fine sediment. Rare silty-sand layers and the coarser nuclei of the manganese crusts and nodules indicate ice rafting. However, this mechanism is probably only locally important as a significant transporting agent.

[1] Contribution no. 734, Department of Oceanography, University of Washington.

[2] Department of Oceanography, University of Washington, Seattle, Washington 98105, U.S.A.

Introduction

The Laptev Sea is one of three epicontinental seas lying along the northern coast of central Asiatic Russia (see Fig. 1, Naugler et al., this volume). Field work was carried out during July and August 1963, aboard the U.S. Coast Guard ice-breaker *Northwind.* Ninety-nine stations were occupied along approximately 4000 km of track, and bottom samples collected include 58 gravity cores and 62 grab samples (Fig. 1). This paper is concerned with the analysis of bathymetric data and the study of 14 cores from the northeastern Laptev Sea, and discusses sea-level history and paleogeography of coast lines of the Laptev Sea during Holocene (post-Wisconsin) time.

The climatic and physiographic features of the surrounding area are described by Suslov (1961, p. 125), and Naugler et al. (this volume). Sverdrup (1927), Suslov (1961, p. 162), and Codispoti (1965) discuss the physical oceanography of the Laptev Sea. The extent of various continental glaciations in Siberia are discussed by Flint and Dorsey (1945), Donn et al. (1962), and Flint (1971). At various times during the Pleistocene, continental ice sheets covered only the western shores and sea floor of the Laptev Sea, and did not extend east of the present-day Olenek River. A small thin ice sheet, approximately 250 km in diameter, spread out from the New Siberian Islands (Flint, 1971, p. 665). Saks (Samoilov, 1952,

Y. Herman (ed.), *Marine Geology and Oceanography of the Arctic Seas*

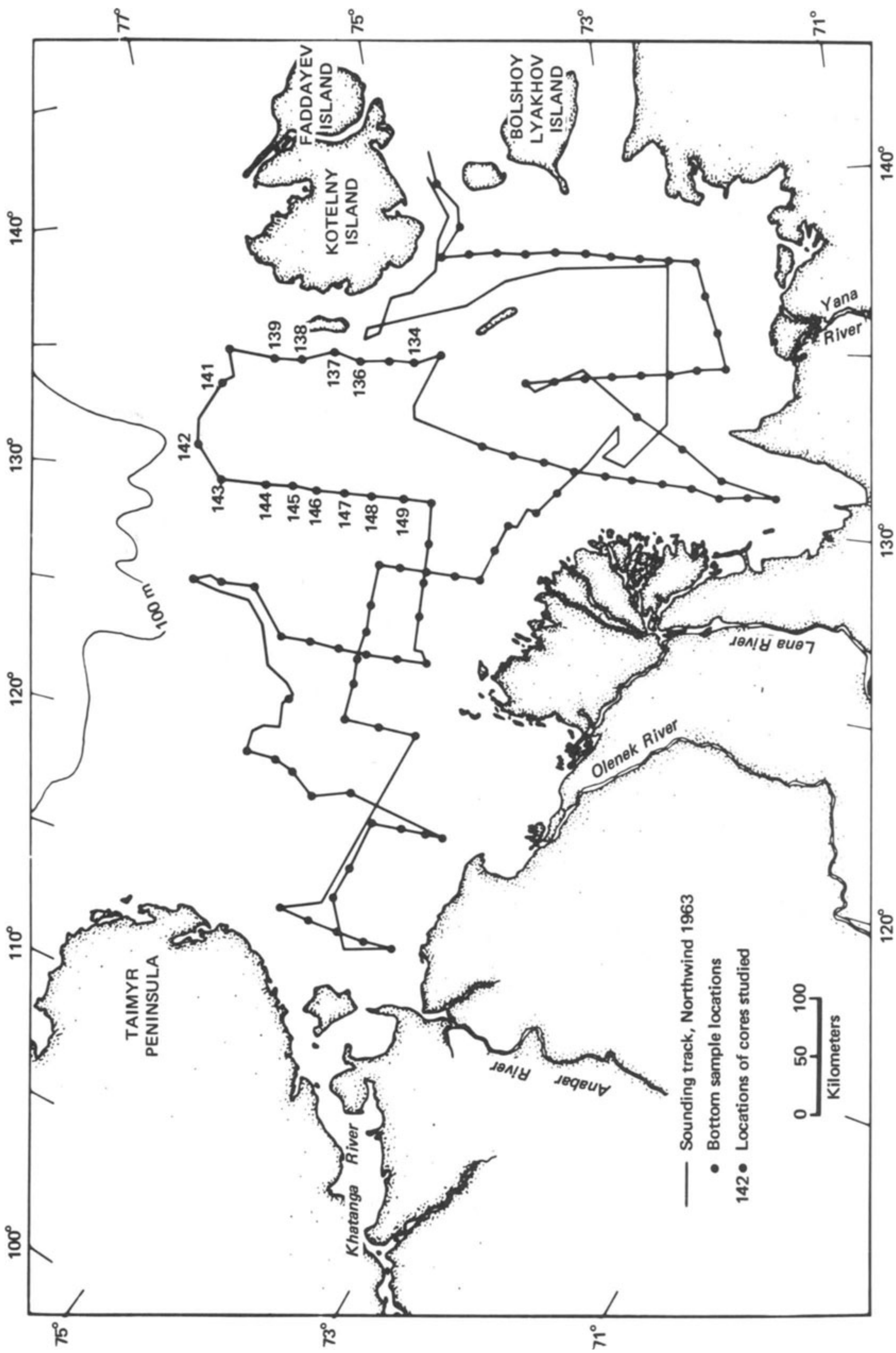

Fig. 1. Bottom sample locations and track chart, Laptev Sea.

p. 307) briefly describes the mouths of the Lena and Yana Rivers (Fig. 1) during the Quaternary. He states that during the Karginsky transgression (about 11,500 years B.P.) the Lena formed two branches near the area of its present delta. The mouth of one branch was 300 km northwest of the present delta, and a separate branch flowed northward. Saks (Samioilov, 1952, p. 307) also states that the mouth of the Yana River during this period was slightly more than 300 km north of its present position. Gusev (1959) discusses the evolution of the coastal plain during the Quaternary, but gives coast-line positions only for Wisconsin time and for an unspecified period during Neogene time.

Results and Discussion

Bathymetry

Sounding data from the *Northwind* cruise, supplemented by nearly 500 Soviet spot soundings, were used to compile the bathymetry of the Laptev Sea (Fig. 2). The bathymetry of the continental slope is from a chart by Gakkel' (1958). The continental shelf covers approximately 460,000 km^2, and varies in width from 300 km in the western part to over 500 km in the east. The shelf break occurs at 50 to 60 m depth, much shallower than the 200-m break mentioned by Suslov (1961, p. 261) and Eardley (1964) for this area. The shelf is very flat, with gradients ranging from undetectable, in some areas, to about 5 m/km. The bathymetry is more irregular in the northwestern area, probably due in part to the action of the continental ice sheet which covered portions of this region during part of the Pleistocene. An extensive shoal (called Stolbovoy Shoal in this paper), with depths less than 15 m, occupies the central area of the eastern Laptev Sea. The shoal is probably a primary structural feature representing the northward extension of the foothills of the Verkhoyansk Range. Numerous small banks, less than 5 m in depth, occurring on Stolbovoy Shoal were probably formed as a result of the melting of ice cores in small islands. This process has been documented in the case of Vasilevsky Bank by Grigorov (1946).

Five large submarine valleys cross the Laptev Sea shelf and are named after the rivers with which they seem to be associated. A conspicuous feature of all of these valleys is that they are not continuously graded seaward, but are marked by a series of linear depressions. The depressions in the Yana and eastern Lena valleys occur at depths of 25 and 40 m, while those of the Olenek, western Yana, and Anabar-Khatanga valleys exhibit closures at depths of 30 and 45 m. Similar depressions have been found along Hope valley in the Chukchi Sea (Creager and McManus, 1965) and in the Kolyma and Indigirka valleys of the East Siberian Sea (Naugler et al., this volume).

Extensive flat areas occur at remarkably regular depth intervals on the shelf. The greater part of Stolbovoy Shoal is between 10 and 15 m in depth, and in the western Laptev Sea between the Anabar River and the Lena Delta the 10- and 15-m isobaths are also very widely spaced. Northeast of Kotelny Island, the 20- and 25-m contours may delineate another large flat area, but the bathymetry here is based only on Soviet spot soundings. In the central area of the shelf north of the Lena Delta, two large plains are well developed at depths of 30 to 35 m and 40 to 45 m.

The subaerial portions of the Lena Delta do not extend very far seaward (Fig. 1). The Gulf of Bourkhaya and Oleneksky Bay probably represent delta flank depressions (Bates, 1953) which have been formed by a combination of wave and current action, local crustal downwarping, and compaction of fine-grained sediments with time.

The larger size of the Gulf of Bourkhaya, the distribution of delta channels, and the lack of barrier islands along the eastern edge of the delta (and their presence to the west) seem to indicate that most of the Lena River's sediment load is being deposited along the eastern flank of the delta at present.

The general circulation pattern of surface currents in the Laptev Sea is described by Suslov (1961, p. 162). A cold current sets southward along the eastern coast of the Taimyr Peninsula toward the Khatanga estuary, where it mixes with the waters of the Khatanga and Anabar Rivers and turns eastward. This current, reinforced by the outflow from the Lena River, then sets northeastward and bifurcates, one branch setting northward and the other eastward between Kotelny Island and the mainland (Fig. 2). The northern branch again divides, with the main portion proceeding northwestward into the Arctic drift, while the other branch sets eastward along the northern side of Kotelny Island (U.S. Navy Hy-

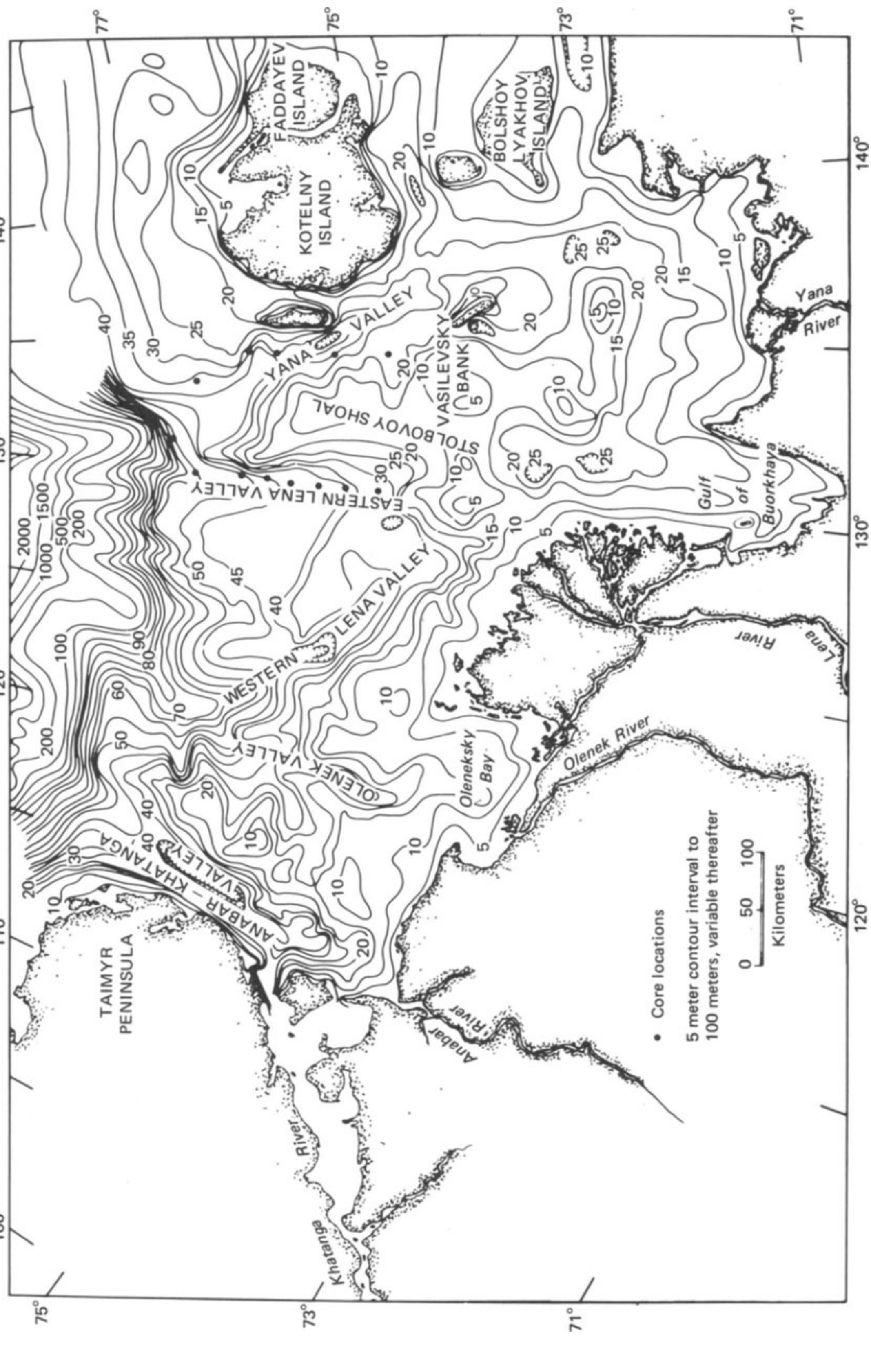

Fig. 2. Bathymetric chart of the Laptev Sea.

drographic Office, 1944). Currents generally do not exceed 10 cm/sec, although speeds of 25 to 50 cm/sec have been observed for the northward-flowing current in the eastern-central portion of the Laptev Sea.

Stolbovoy Shoal would have acted to control the location and magnitude of currents as the sea level rose and fell over the ridge during late Pleistocene and Holocene times. The configuration of the northwestern part of the shoal suggests that the bathymetry in this area may have been modified by current action. During times of lowered sea level, the shore line forming the northwestern bank of Stolbovoy Shoal may have acted to deflect the northward and northeastward flowing currents slightly to the northwest, resulting in a piling up of water and an increase in current speed. This current could have either prevented deposition or permitted the bypassing of finer sediments. The extreme northern tip (40-m isobath) of Stolbovoy Shoal may represent an extension of the shoal by deposition of suspended sediment from this current as it slowed while passing beyond the confining part of the bathymetric ridge. A similar process has apparently been responsible for the formation of Cape Prince of Wales Shoal and other smaller shoals downstream from promontories in the Chukchi Sea (McManus and Creager, 1963; Fleming and Heggarty, 1966; Creager and McManus, 1966; Holmes et al. 1968).

The continental slope north of the Laptev Sea exhibits gradients as steep as 95 m/km, and has several troughs and canyons incised into it. The largest of these, the Sadko Trough (Gakkel', 1958), appears to merge with the Yana and eastern Lena valleys on the shelf (Fig. 2).

Sediments

Fourteen cores (Fig. 1) from the vicinity of the Yana and eastern Lena valleys were selected for detailed study (Holmes, 1967). Where grab samples had been collected with the cores, they were examined for the presence of material coarser than sand size. The 80 subsamples collected were subjected to mechanical analysis to determine textural relations. The carbon content, average grain density, and mineralogy of selected samples were analyzed. Foraminiferal species were identified and six ^{14}C dates were obtained from four cores using the total organic carbon method.

The predominant sediment types are silty-clays and clayey-silts, with mean grain sizes from 7.5 to 8.5ø. With the exception of cores 136 and 143 (Fig. 1), they are quite uniform with respect to sediment type, mineralogy, and chemistry. Sediments below sharp unconformities, at 25 cm in core 136 and 18 cm in core 143, show many of the characteristics of deltaic sediments as described by Shepard (1960) from the Mississippi Delta. The silts and silty-sands in these zones are coarser than the overlying material, and plant fragments and fibers are abundant, as are ferruginous aggregates. No foraminifera were found in samples taken below the unconformities. Ferruginous aggregates also occur in cores 137, 138, and 139. High concentrations of organic matter are not present in these cores, but the presence of ferruginous aggregates below about 40 cm suggests that these sediments were deposited close to sea level, where they may have been subjected periodically to subaerial oxidation.

Manganese nodules were found in the surface grab samples from two stations in the eastern Lena valley (Fig. 2). One nodule, a small quartzite pebble (−4ø) with an iron-manganese crust, was found at station 145, while three smaller crusts were found at station 143 (Fig. 1). These latter crusts appear to have been formed around nuclei (−2 to −3ø) of highly altered basalts. The crusts contained about 10% manganese and 22% iron, and the total composition is very similar to that of manganese nodules from the North Pacific Ocean (Y. R. Nayudu, 1967, personal communication).

With the exception of the manganese nodule and crusts from cores 143 and 145, the eastern Laptev Sea sediments are very fine grained. Although silty-sands with mean grain diameter of 4.5 to 5.5ø occur in cores 143 and 146 (Fig. 1), over 70% of the samples have mean grain diameters finer than 7.0ø (very fine silt). Ninety-five percent of the samples are very poorly sorted, having sorting coefficients greater than 2.0ø units (Folk and Ward, 1957).

These general sediment characteristics are the result of the combined effects of the soil forming processes, transporting agents, and depositional environment. The extensive permafrost areas of north-central Asia favor the development and subsequent erosion of fine-grained soils. The major rivers flowing into the Laptev Sea have very low gradients where they cross the normally wide coastal plain, and the coarsest materials transported from their upper reaches would be deposited here as the rivers rapidly lose competency. The deltas and nearshore areas then trap most of the sandy sediments (Suslov, 1961, p. 177; Samoilov, 1952, p. 309). Since wave heights rarely exceed 1 m and current speeds are generally less than 10 cm/sec (Suslov, 1961, p. 162), the wide shallow Laptev Sea represents a very low energy environment in which the suspended material carried to sea in the plumes of the rivers is allowed to settle with very little modification and reworking.

The manganese nodules and crusts from the surface sediment of stations 143 and 145 represent one of the shallowest known occurrences of such material (45 to 55 m). The quartzite and altered basalt fragments forming the nuclei of these nodules and crusts were probably transported into the area by ice rafting from the southern or southwestern shores of the Laptev Sea prior to the formation of the rather fragile iron-manganese encrustations. The average rate of nodule growth is thought by Mero to be about 1 mm/1000 yr (Shepard, 1963, p. 405), and the 2 to 3 mm thickness of the Laptev Sea crusts would represent a time of accumulation of 2000 to 3000 years. Similar manganese crusts recovered from British Columbia fjords in water 70 m deep appear to have been deposited more rapidly than this, however (J. Murray, 1967, personal communication).

Sedimentation Intensities and Depositional Rates

Six radiocarbon dates from four cores (137, 143, 144, and 147; Fig. 1) were determined, using the total organic carbon method. Table 1 lists the dates, sampling intervals, and average sedimentation intensities (Koczy, 1951) for each of the cores. In discussing these dates, the ages will be applied to the mid-point of the sampling interval. In the cases of cores 143 and 147, a surface interval date of 6000 years B.P. was assumed. This is the age of the upper interval from core 144, which is located between these cores along the axis of the eastern Lena valley, and is probably a satisfactory approximation. The sedimentation intensities range from 2 to 15 mg/cm^2/yr, and values from cores in the eastern Lena valley show a distinct decrease northward.

The apparently anomalous old age of the surface sediments in core 137 is due to contamination by inactive carbon. Small black macroscopic particles, believed to be coal fragments, were observed in cores 137 and 141 (Fig. 1). In core 137 these particles were well dispersed above 40 cm, but increased noticeably and became more patchy below that level. In core 141 the fragments occurred in two separate zones at 21 and 38 cm and in much lower concentrations than in core 137. As a test for coal, two samples (at 12 and 71 cm) from core 137 were subjected to the Wakely-Black analysis (Jackson, 1958, p. 213). The test was positive, and indicated that 17 and 52% of the total carbon at 12 and 71 cm, respectively, was due to the presence of coal. Allowing for the 17% coal contamination, which was found in the surface interval of core 137, would result in a corrected age of 6500 years B.P., using the curves of Olson and Broecker (1958).

This is very close to the surface interval date from core 144, in which there was no apparent coal contamination. It is therefore probably safe to assume that the date for the surface interval of core 144 is actually 6050 years B.P. This is considerably older than the surface sediments (4350 years B.P.) in the Chukchi Sea (Creager and McManus, 1965). This can be explained by lower depositional rates in the Laptev Sea and by the fact that a large interval and thus a wide span of ages was covered in the dated sample.

Of the ages for subsurface intervals of the cores, only that from core 137 appears to be in error. The coal content in the section of the core from which the radiocarbon date was obtained appeared to be the same as the sample at 71 cm. If one assumes a 50 to 60% contamination for the dated interval, this would result in an actual age of 11,500 to 12,000 years B.P., and a corrected

Table 1 Carbon-14 Dates and Sedimentation Intensities

Core	Depth in core (cm)	Radiocarbon age (years B.P.)	Average sedimentation intensity (mg/cm^2/yr)[1]
137	3–17	8410 ± 230	
			9
	103–117	18,400 ± 540	
143	24–32	14,200 ± 370	2[2]
144	3–20	6050 ± 200	
			5
	44–64	15,000 ± 460	
147	89–102	11,040 ± 310	15[2]

[1] Based on elapsed time between dates.
[2] Assumed surface interval (3 to 20 cm) date 6000 yr B.P. See text.

sedimentation intensity since that time of about 25 mg/cm^2/yr.

The dated interval from core 143 was taken from a section (17 to 36 cm) containing large amounts of wood fragments and fibers. Because of the unique and uniform lithology of this zone, the date can probably be applied to the entire section. This, coupled with the sharp boundary between this portion and the surface interval, would indicate that the core may not represent continuous deposition, and the calculated average sedimentation intensity should be regarded as a maximum.

The combined annual discharge of suspended sediment from the Lena and Yana Rivers is 15×10^6 metric tons (Samoilov, 1952, pp. 310, 312). The area of that portion of the Laptev Sea east of 125°E is approximately 200,000 km^2. It is characterized in the summer by less than $\frac{7}{10}$ ice cover, and probably represents the greatest area over which the plumes of the Lena and Yana spread. If it is assumed that all of the suspended sediment discharged annually by these two rivers is deposited uniformly over this area, the present sedimentation intensity would be about 7 mg/cm^2/yr. To a first approximation, this agrees well with the average intensities determined from the radiocarbon dates.

The small manganese nodule and manganese crusts found in the surface grab samples from stations 143 and 145 indicated that the present rate of sediment accumulation is less than the average sedimentation intensities (2 and 5 mg/cm^2/yr, respectively) would indicate (Y. R. Nayudu, 1967, personal communication). Even if these shallow-water crusts were growing much more rapidly than deep-sea crusts, their presence would still indicate a very slow accumulation of detrital material (J. Murray, 1967, personal communication). The foraminifera number (test/gram of sediment) shows a general decrease with depth in all studied cores. These data, with the old surface interval dates, support the interpretation that present depositional rates are actually lower than those inferred from lapsed time between dates in the cores.

Sea-level Fluctuations

A potential difficulty in recognizing ancient stillstands of sea level in the Laptev Sea and correlating them with stillstands documented from other areas is the fact that the region is currently tectonically active. The only definite quantitative evidence cited in the literature (Suslov, 1961, p. 173) of the amount of possible post-Pleistocene uplift are the 3- to 5-m terraces on Bolshoy Lyakhov Island (Fig. 2). The change in river mouth configuration from estuaries in the west to deltas in the east indicates that the region may have undergone tilting during late Pleistocene or Holocene time, although this apparent regional tilt could also be the result of crustal depression by ice loading (Flint, 1971, p. 366, 662).

Certain bathymetric features also suggest an uplift of the eastern portion of the Laptev Sea relative to the western part. The series of depressions along the axes of the submarine valleys occur at two different depths. The basins in the Yana and eastern Lena valleys exhibit closures at 25 and 40 m, whereas those in the western Lena, Olenek, and Anabar–Khatanga valleys occur at 30 and 45 m. Although this supports other evidence for the relative emergence of the eastern Laptev Sea, it would be very difficult to determine if the uplift occurred during one brief period or rather slowly and uniformly throughout most of late Pleistocene and Holocene times. Therefore, no effort will be made to correct features discussed in the following stillstand discussion for the amount of uplift which may have occurred after they were formed. Most of these features would require a water depth of 2 to 4 m for their formation, and a correction for this would merely cancel that for subsequent tectonic effects.

The well-developed shoals and benches with depths from 10 to 15 m (Fig. 2) were probably formed by thermal erosion (Larionova, 1959) and other nearshore processes at a time of lowered sea level. A bathymetric chart of the East Siberian Sea (Naugler et al., this volume) also shows extensive flat areas between 10 and 15 m. Fairbridge (1961, p. 147) indicates a stillstand at -10 m during the period from 7500 to 6700 years B.P. (Fig. 3). No cores from these flat areas were studied or dated, and so any correlation with Fairbridge's -10-m stillstand must be based solely on the similarity of depths.

The configuration of the 20- and 25-m isobaths northeast of Kotelny Island (Fig. 2) may give similar evidence for a stillstand of sea level at about -20 m. This bench-like feature is more weakly developed than the one at -10 m, and its existence is based only on Soviet soundings. Fairbridge (1961, p. 147) lists limits of -15 to -24 m for a stillstand during the period 10,300 to 8900 years B.P. (Fig. 3). The sea-level curves of

Curray (1960, 1961, 1965) show two stillstands within these same depth limits, one at about 9600 years B.P. and a later one at 8100 years B.P. Mörner (1971) also shows a stillstand at −20 m during the period from 8700 to 7900 years B.P. (Fig. 3). Again, because no actual dates are available from the Laptev Sea feature, correlation must be on the basis of bathymetry only, and it could thus be the result of two −15 to −24 m stillstands at different times (9600 and 8100 years B.P.).

Another well-developed terrace with depths from −30 to −35 m occurs north of the Lena River Delta. This large flat area is cut by both the eastern and western Lena valleys, but can be easily recognized in spite of its dissected nature. Naugler et al. (this volume) also found a well-developed terrace at these depths in the East Siberian Sea.

The linear depressions or basins which interrupt the grade of the submarine valleys on the Laptev Sea shelf could have been formed at times of lowered sea level. Similar depressions are found in present-day estuaries and may be the result of tidal and river current scour or nondeposition. If this is the case, the depressions indicated by closures of the 30-m isobath in the Olenek valley (Fig. 2) and the 25-m isobaths in branches of the Yana valley would have been formed when sea level was approximately 25 to 30 m below its present position.

Shepard (1960) lists criteria for recognition of ancient deltas. He stated that deltaic sediments would include abundant land plant remains and ferruginous aggregates. Invertebrate remains would be scarce and if found, should show little diversity of species. These characteristics are well shown by the sediments in the lower portion (below 25 cm) of core 136 (Fig. 1). Plant matter, wood fragments, and ferruginous aggregates are present in the sediments, and only one foraminifera test was found in the two samples from this zone. It is therefore possible that these sediments represent an ancient delta of the Yana River. The present depth of water at station 136 is 29 m, indicating that the stillstand during which the delta might have formed was at this depth or only slightly shallower.

The sea-level curve of Curray (1960, 1961) in Fig. 3 shows a low stillstand of sea level at −27 to −37 m at about 8700 years B.P. The bathymetric and sedimentary features from the Laptev Sea

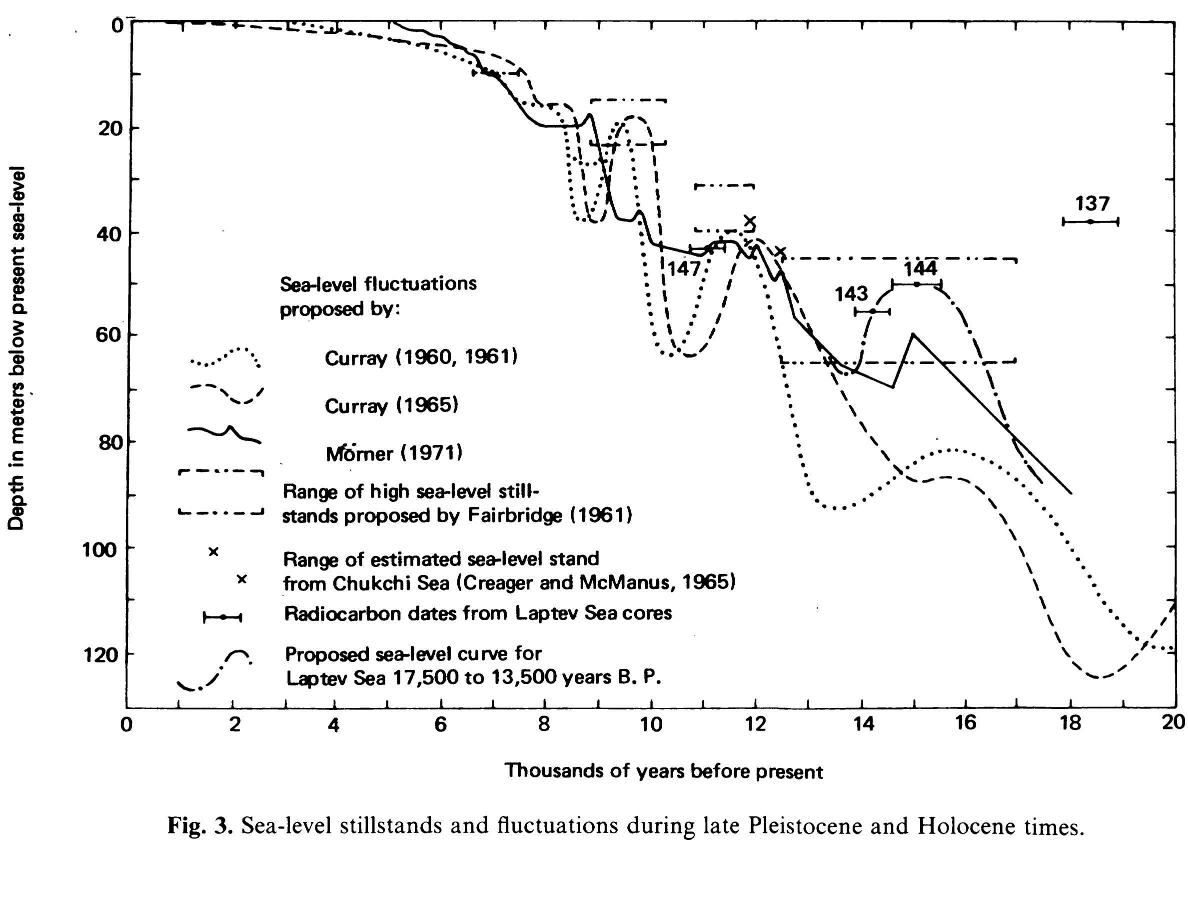

Fig. 3. Sea-level stillstands and fluctuations during late Pleistocene and Holocene times.

indicate a stillstand at −25 to −35 m, and although no dates are available, this could represent a low sea-level stand which was contemporary with Curray's.

An extensive terrace or bench 40 to 45 m deep is situated in the central portion of the Laptev Sea. Flat areas occurring at the same depths were cited by Naugler et al. (this volume) as possible evidence for a stillstand of sea level. Linear basins with closures at 45 m occur in the western Lena and Anabar–Khatanga valleys (Fig. 2). In the Yana valley a depression formed by a 40-m isobath closure may be seen. Following the assumptions concerning the origin of similar basins at 25 and 30 m, these might indicate a sea-level stillstand at −40 to −45 m.

Ferruginous aggregates occur in cores 137 to 139 (Fig. 1). High concentrations of organic matter are not present in these cores, and the foraminiferal population is not significantly smaller than that from the other cores. This excludes the possibility of these sediments being classified as deltaic using Shepard's (1960) criteria, but the presence of the ferruginous aggregates would still seem to indicate that the sediments from the lower portions of the cores were deposited very close to sea level, where they may have been subjected periodically to subaerial oxidation.

The radiocarbon dates (Table 1) from the lower intervals of cores 137, 143, 144, and 147 are plotted in Fig. 3. The occurrence of marine sediments with these ages places a lower limit on the position of sea level during these times. Curray's (1960, 1961, 1965) sea-level curves (Fig. 3) show a high sea-level stillstand at −40 to −41 m 12,000 to 11,600 years B.P., and Fairbridge (1961, p. 147) indicates a stillstand at −32 to −40 m during the period from 12,000 to 10,800 years B.P. The sea-level curve of Mörner (1971) also shows a high stand at −42 m during this same time interval. Figure 3 shows the dates (corrected for possible coal contamination) for a section of ancient deltaic sediments from the Chukchi Sea (Creager and McManus, 1965). The date from core 147 falls very close to the position of this previously documented stillstand, and strongly supports evidence from bathymetry and the sediments that sea level in the Laptev Sea stood at −37 to −45 m between 12,000 and 11,000 years B.P.

In the preceding section on sedimentation intensities it was stated that the average age of the lower interval of core 137 appeared to be in error due to contamination by coal. In Fig. 3 this date is well displaced from the sea-level curves and limits of Curray (1965) and Fairbridge (1961). If the contamination by inactive carbon is 50 to 60 percent, as indicated by the single coal analysis at 71 cm, the corrected age for that interval would be about 12,000 years B.P. This would place the date very close to those for the stillstand recognized by Curray (1960, 1961, 1965), Fairbridge (1961, p. 147), Creager and McManus (1965), and Mörner (1971).

Evidence for a stillstand at −50 to −55 m depths is provided by the subsurface dates of cores 143 and 144 (Fig. 3), and the character of the sediments in the lower half of core 143 (18 to 36 cm). These sediments contain large amounts of wood material and plant fibers, and no foraminifera were detected in the samples from this interval. Ferruginous material such as that found in cores 136 through 139 does not occur, but instead large concentrations of pyrite aggregates and pyritized wood fragments are present. The pyrite aggregates were probably produced by a reduction of original ferruginous granules under the anoxic conditions which apparently existed during or after deposition of this part of the core. Thus the sediments of this interval, like those in the lower portion of core 136, probably represent ancient deltaic deposits and give evidence for a sea-level stillstand at about −55 m.

The dates from this interval in core 143 and the lower portion of core 144 fall within the limits which Fairbridge (1961) proposed for a stillstand at −45 to −65 m from 17,000 to 12,500 years B.P. (Fig. 3). Creager and McManus (1965) found bathymetric evidence for a stillstand at −53 m in the Chukchi Sea, and concluded that it had probably occurred between 17,000 and 12,000 years B.P. Mörner (1971) also cites evidence for a high stand of sea level at about −60 m during this time (15,000 years B.P.). It would therefore appear that the stillstand of sea level during this period was considerably higher than the −81 to −86 m shown by Curray (1960, 1961, 1965). The stillstand date from the Laptev and Chukchi Seas (Creager and McManus, 1965) would modify the curve as shown in Fig. 3, supporting the view of Fairbridge (1961, p. 147) that there was a stillstand at this depth.

Paleogeography

Using the sea-level stillstand data from the preceding sections, a series of paleogeographic

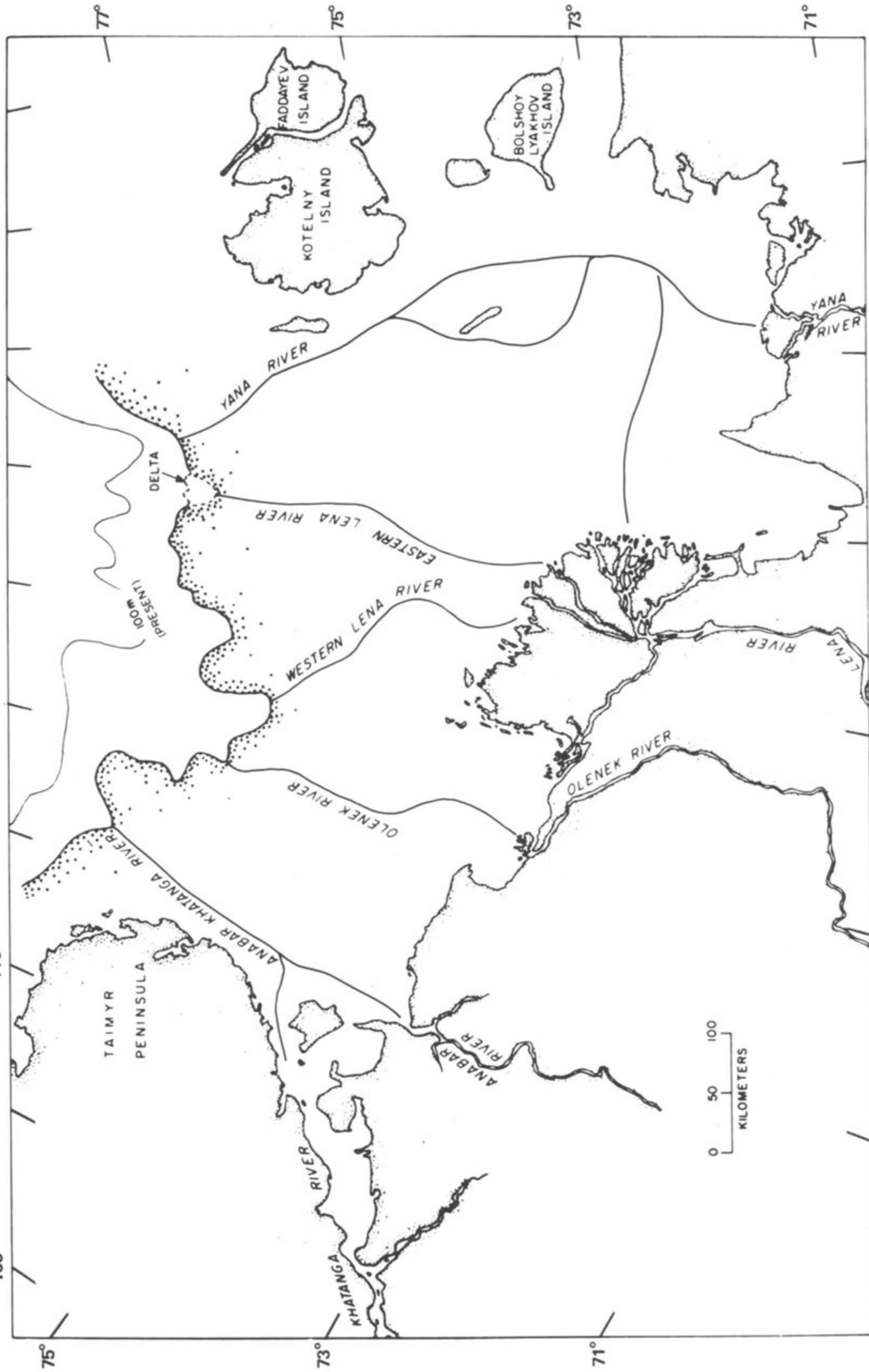

Fig. 4. Paleogeography of the Laptev Sea at about 15,000 years B.P.

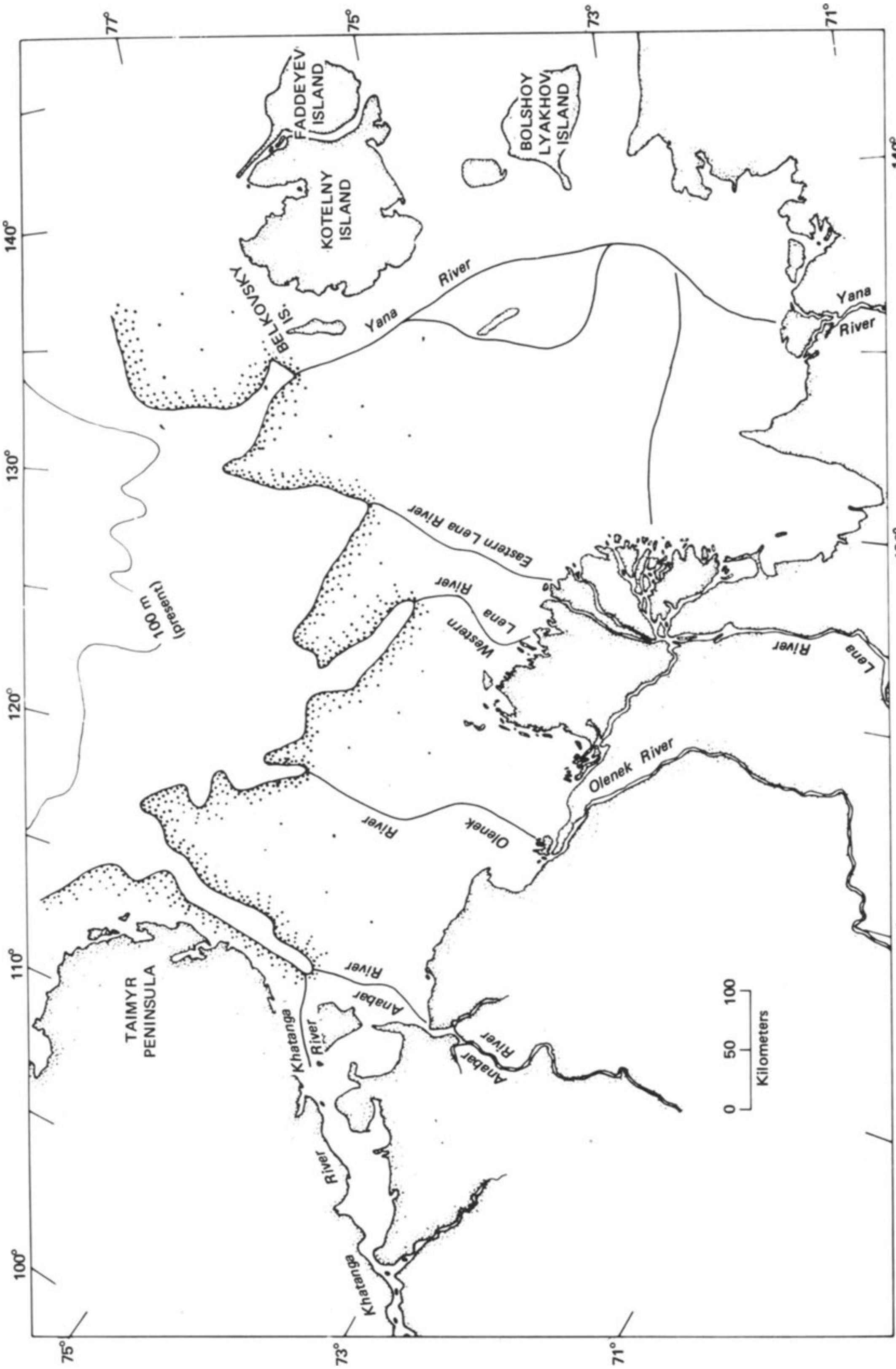

Fig. 5. Paleogeography of the Laptev Sea at about 11,500 years B.P.

charts were prepared (Figs. 4 through 8). They are numbered in order of decreasing age, and show the fluctuations of shore line and river valley locations on the Laptev Sea shelf during the late Pleistocene and Holocene transgressions and regressions (Fig. 3).

The high stillstand at -50 to -55 m would correspond to the Masurian Submergence about 15,000 years B.P. (Fairbridge, 1961). Figure 4 shows that the shore line of the Laptev Sea at this time was very close to the present shelf break. Gusev (1959) described an ancient coast occupying the same position, but dated it only as Neogene. The Lena River probably sent three distributaries across the shelf. The Western Lena and Olenek Rivers entered a large embayment about 200 km northwest of the present Lena Delta, and the mouths of the Yana and eastern Lena Rivers were within 100 km of each other northwest of the New Siberian Islands. The Khatanga and Anabar Rivers entered the Arctic Ocean through a common river valley.

Saks (Samoilov, 1952, p. 307) stated that during the Karginsky Submergence about 11,500 years B.P. (Fig. 5) the Lena River branched near the present delta and that the mouth of the western branch was 300 km to the northwest. He also stated that the mouth of the Yana River was a little more than 300 km north of its present position. The paleogeographic chart for the -37 to -45 m stillstand (Fig. 5) shows that although Saks' figure for the Yana River mouth was quite good, the locations of the mouths of the Lena River branches were approximately 200 km north of the present delta. The Anabar and Khatanga Rivers entered a long narrow estuary along the eastern coast of the Taimyr Peninsula, and the Yana flowed into a similar feature near present-day Belkovsky Island.

Fig. 6 shows the paleogeography for the -20-m-high stands of sea level during the Yoldia Submergence at about 9600 yr B.P. and the Ancylus Emergence about 8100 yr B.P. (Fairbridge, 1961). The configuration of the shore line is quite complex, with many embayments, peninsulas, and well-developed estuaries. The main flow of the Lena had probably shifted from the northward-flowing channels to those flowing east into the system of straits formed by present-day Stolbovoy Shoal and Stolbovoy Island.

During the Post-Yoldia Emergence (8700 years B.P.) sea level fell to approximately -25 to -30 m (Fig. 7). The rivers again flowed out across the shelf, and the mouths of all but the Lena entered the heads of long narrow estuaries. The Lena River, whose main outflow had probably shifted to the north once again, flowed into a large bay north of its present delta. The shallow channel trending eastward from the Lena Delta may have carried some of the Lena's discharge into the Yana River valley. This coastal configuration closely resembles one which Gusev (1959) described as lying along the present 25-m isobath, but he dates the shore line only as second half of the upper Quaternary.

Gusev (1959) also states that at the end of the Age of Mammoths the coast of the Laptev Sea followed the 15-m isobath. This may correspond to the shore line during the Hydrobia Submergence (-10 m) approximately 7000 years B.P., as shown in Fig. 8. The river mouths were very close to their present locations, and active modern delta formation probably began at this time. Many large islands were produced as a result of the partial flooding of the large shoal areas in the southeastern and western portions of the Laptev Sea.

Ice As a Geological Agent

Several writers (Tarr, 1897; Kindle, 1924; and Lisitsyn, 1957; and Hume and Schalk, 1967) discussed the importance of Arctic sea ice as an agent of erosion, transportation, and deposition of sediments. There seems to be little agreement as to the criteria for recognizing ice-borne sediments unless the material in question is noticeably coarser than the associated sediments. Opinions as to the actual importance of rafting by floe ice vary considerably also.

One of the most widely accepted methods by which floe ice acquires sediment is that of bottom accretion and progressive upward migration. Ice floes which scrape or freeze to the bottom pick up sediment which then makes its way upward as the surface ice melts and new ice forms on the bottom of the floe. This process undoubtedly occurs, and it may be illustrated in Fig. 9. The dark band near the sea surface in the ice floes may represent a layer of sediment slowly working its way upward. Another process which would be more effective in transporting large amounts of material involves fast ice which has frozen to the bottom near the river mouths and high coastal cliffs. The river ice tends to be broken up by the spring floods prior to the melting of the fast ice near shore. The rivers

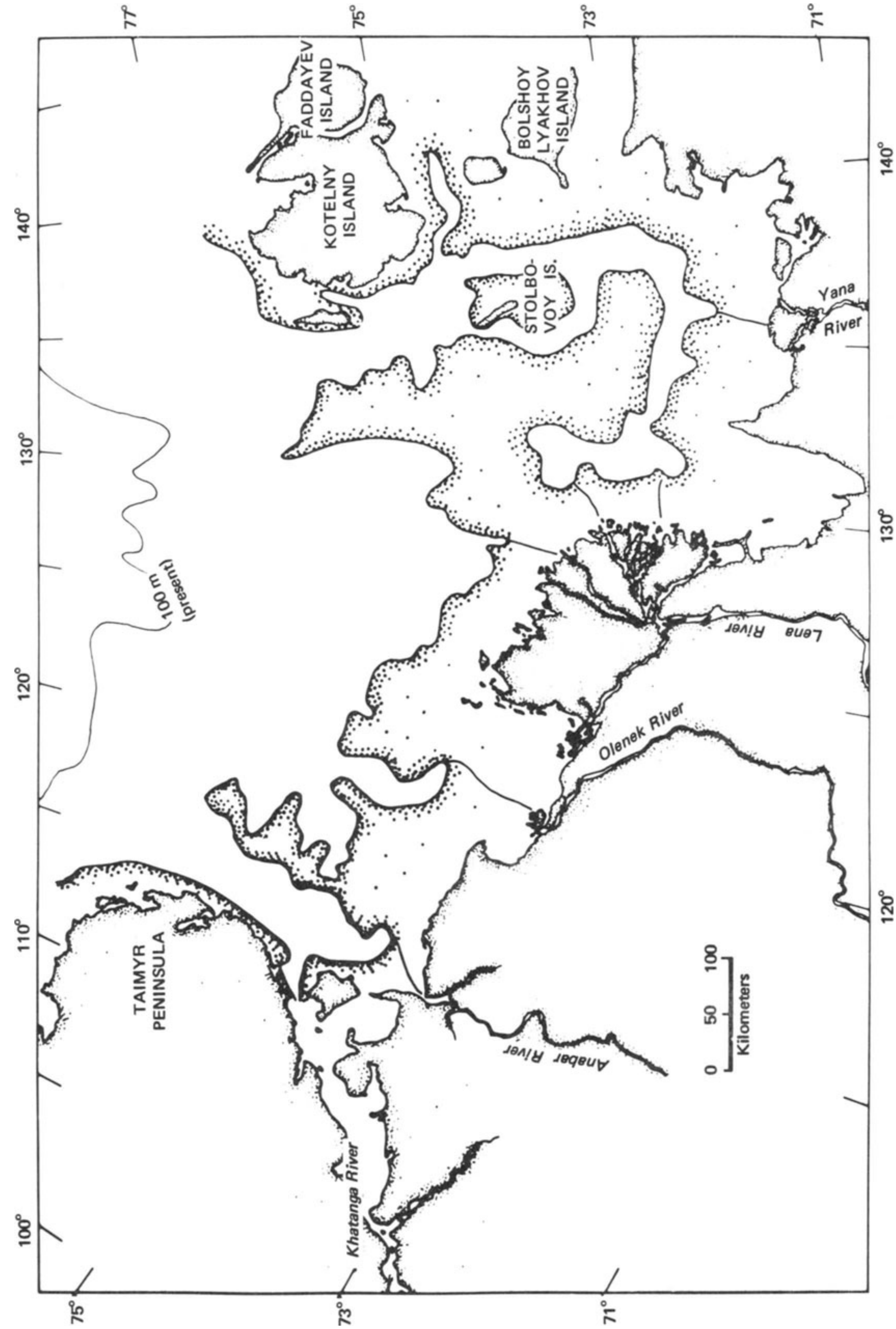

Fig. 6. Paleogeography of the Laptev Sea at about 9600 and 8100 years B.P.

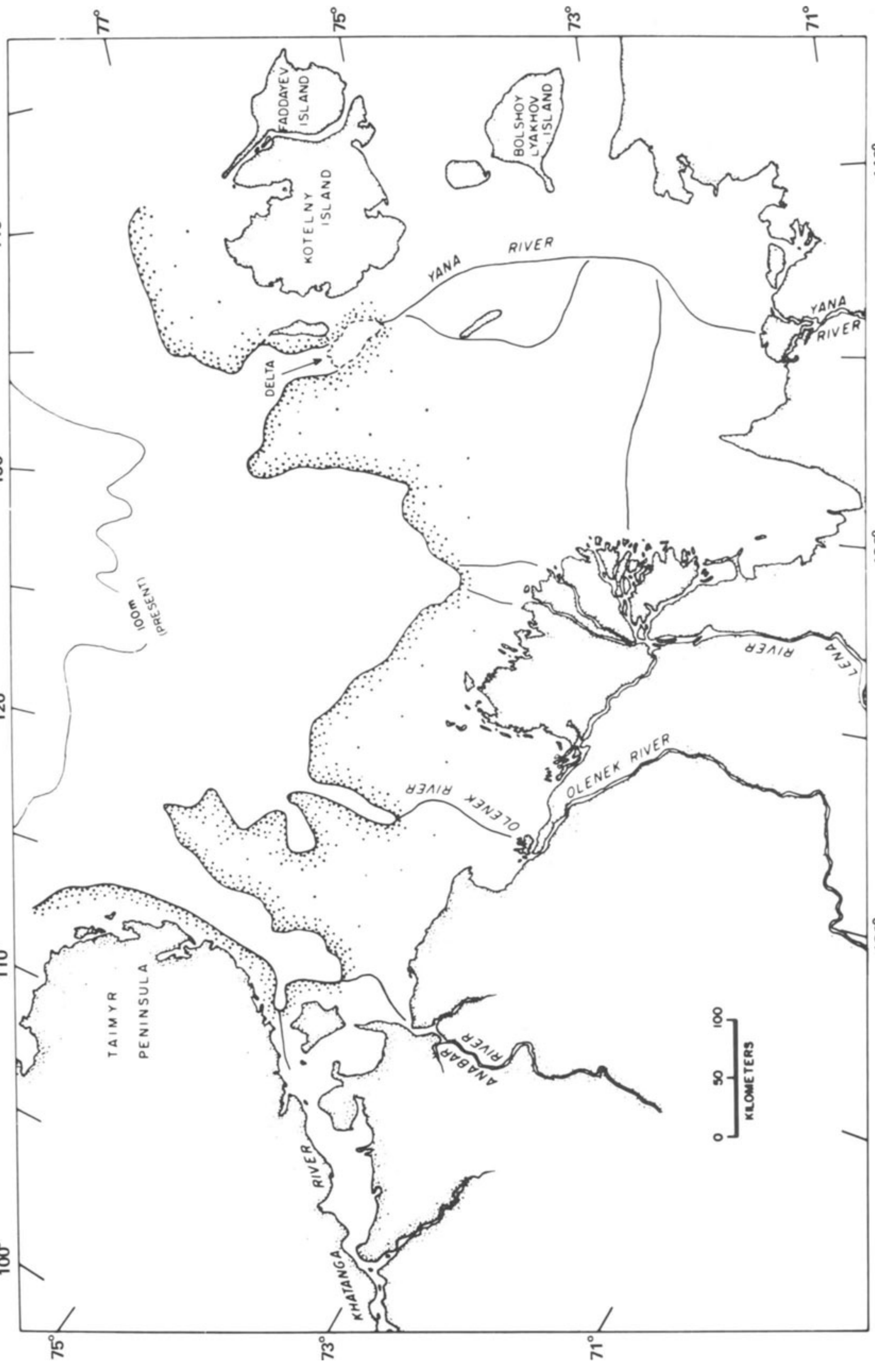

Fig. 7. Paleogeography of the Laptev Sea at about 8700 years B.P.

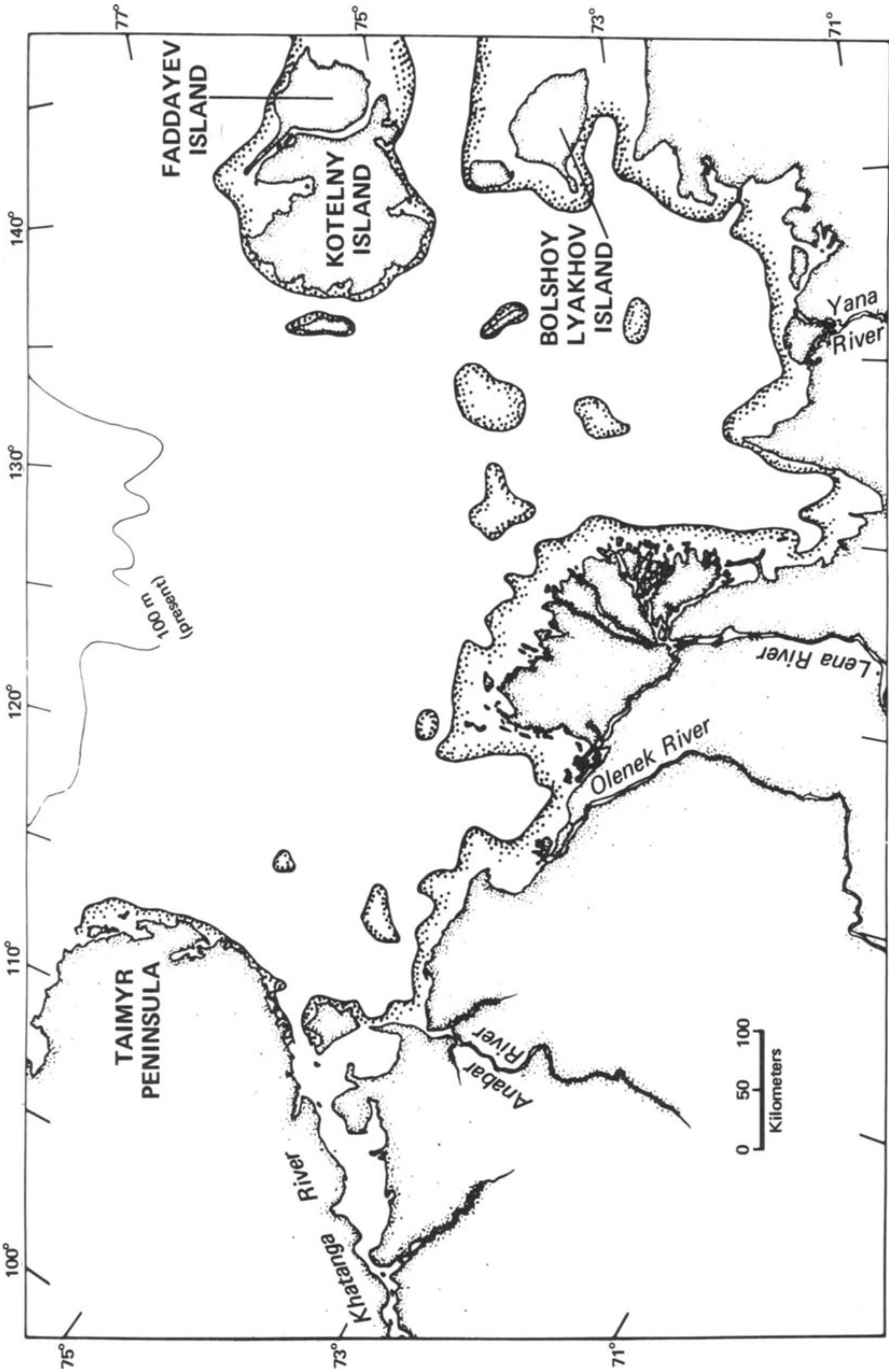

Fig. 8. Paleogeography of the Laptev Sea at about 7000 years B.P.

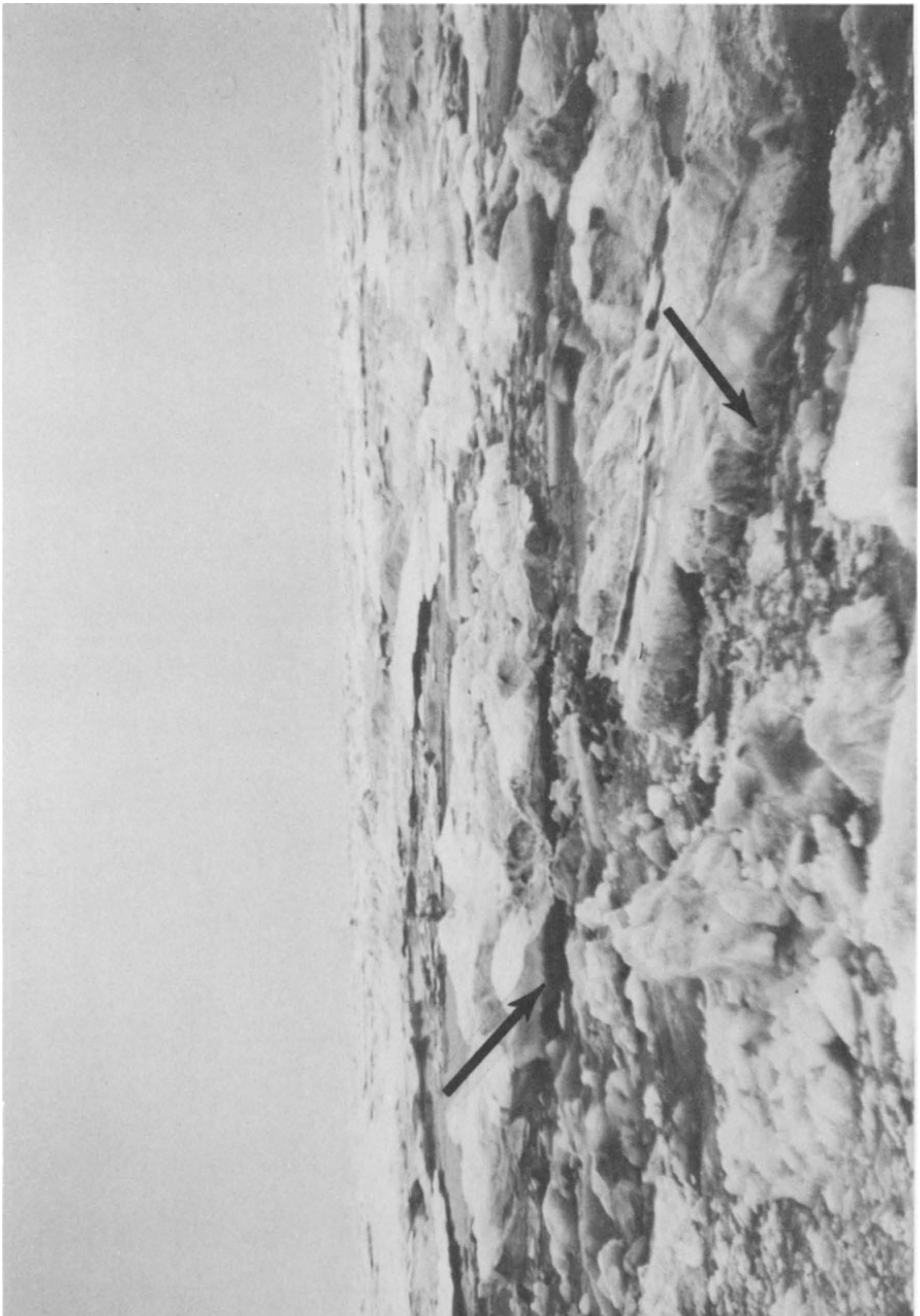

Fig. 9. Large pieces of floe ice containing a single dark stratum of sediment just above the water line (arrows).

Fig. 10. A large pile of rubble containing boulder-size material resting on an ice floe about 50 km from shore.

would thus carry large loads of sediment out onto the pack ice, and when the ice near shore breaks up it would transport this sediment load with it until the floes melted or were overturned. Spring and summer warming also results in very active slumping of the high banks containing large amounts of buried ground ice (Suslov, 1961, p. 172). Any fast ice still attached to the shore below these cliffs could acquire a large surface load of material as a result of this mass movement, as may be illustrated in Fig. 10.

The only evidence for ice rafting in the sediments of the cores comes from those in the outer parts of the Eastern Lena valley. The nuclear material of the manganese nodules and crusts was undoubtedly brought into the area by ice because of their very large size (-2 to $-4ø$) compared to the fine-grained (7.5 to 8.5ø) sediments. The original source of these small rock fragments would be very difficult to identify, but the general current and ice drift patterns (Suslov, 1961, p. 162) would indicate that they were probably carried to sea from the Lena Delta area or the southwestern shores of the Laptev Sea. Cores 144 through 146 also contain small layers of silty-sand which are coarser than the other sediments in the cores. If these do represent ice-borne detritus, it is odd that no similar layers were observed in any of the other cores. A possible explanation is provided by the extent of ice cover during mid-summer. The area from which the cores were taken is located at the northern edge of the ice-free region caused by the plume of the Lena River. The offshore surface currents may carry masses of pack ice, some with appreciable concentrations of sediment acquired in the near-shore areas, northward to the edge of the open water zone where they would melt and discharge their sediment load.

Ice rafting of material for short distances probably occurs quite regularly in the areas near the coast and the mouths of the rivers. Offshore, however, this process is only locally important, and ice rafting does not appear to be a prominent factor in the distribution of sediments in the Laptev Sea.

Summary and Conclusions

From the data presented and the interpretations made, the following summarizing statements may be set forth:

1. The sediments in 14 cores from the eastern Laptev Sea are fine-grained and poorly to very poorly sorted. This is the result of: (a) fine-grained soils produced by the permafrost weathering processes; (b) low river gradients; (c) trapping of sandy sediments by the river deltas; and (d) the very low energy environment of the Laptev Sea.

2. Manganese nodules and crusts were recovered from the surface at two of the coring stations and represent the shallowest known occurrence of these materials. The manganese encrustations were probably formed after the nuclear material (rock fragments) had been rafted into place by ice.

3. Average sedimentation intensities were calculated from four cores using radiocarbon dates. Values ranged from 2 to 15 mg/cm^2/year. An approximate sedimentation intensity based on the annual silt discharge of the Yana and Lena Rivers (7 mg/cm^2/yr) agrees well with these values, although the presence of the manganese crusts indicates that the present rate of deposition in the outer shelf area may be considerably slower.

4. Data from the bathymetric features, certain sediment characteristics and subsurface carbon-14 dates suggest that at least five stillstands of sea level may have occurred since about 17,000 yr B.P. The depths below present sea level and dates for these stillstands agree quite well with those which have been documented from other parts of the world.

5. Ice rafting is probably not as important a geological agent as the severity of ice conditions in the Laptev Sea would indicate. The nuclear material of the manganese nodules and possibly some silty-sand zones in some of the cores indicate that floe ice is capable of transporting material into the outer shelf regions, but these seem to represent only local occurrences.

Acknowledgments

The work was supported by grants from the National Science Foundation (GA808, 11126, 28002).

References

Bates, C. C. 1953. Rational theory of delta formation. *Bull. Am. Assoc. Petroleum Geol.*, 37(9):2119–2162.

Codispoti, L. A. 1965. *Physical and chemical features of the East Siberian and Laptev Seas in the summer.* Unpublished Thesis, University of Washington. 51 pp.

Creager, J. S., and D. A. McManus. 1965. Pleistocene drainage patterns on the floor of the Chukchi Sea. *Marine Geol.*, 3:279–290.

———, and D. A. McManus. 1966. Geology of the Southeastern Chukchi Sea. In: N. J. Wilimovsky and J. M. Wolfe, eds. *Environment of the Cape Thompson Region, Alaska.* Oak Ridge, Tennessee: U.S. Atomic Energy Commission. pp. 755–786.

Curray, J. R. 1960. Sediments and history of Holocene transgressions, continental shelf, northwest Gulf of Mexico. In: F. P. Shepard, F. B. Phleger, and T. H. van Andel, eds. *Recent Sediments, Northwest Gulf of Mexico.* Tulsa, Oklahoma: American Association of Petroleum Geologists. pp. 221–266.

———. 1961. Late Quaternary sea level: a discussion. *Geol. Soc. Am. Bull.*, 72:1707–1712.

———. 1965. Late Quaternary history, continental shelves of the United States. In: H. E. Wright, Jr. and D. G. Frey, eds. *The Quaternary of the United States.* Princeton, N.J.: Princeton University Press. pp. 723–735.

Donn, W. L, W. R. Farrand, and M. Ewing. 1962. Pleistocene ice volumes and sea-level lowering. *J. Geol.*, 70(2):206–214.

Eardley, A. J. 1964. Polar rise and equatorial fall of sea level since the Cretaceous. *J. Geol. Educ.*, 12:1–11.

Fairbridge, R. W. 1961. Eustatic changes in sea level. *Phys. Chem. Earth*, 4:99–185.

Fleming, R. H., and D. Heggarty. 1966. Oceanography of the Southeastern Chukchi Sea. In: N. J. Wilimovsky and J. N. Wolfe, eds. *Environment of the Cape Thompson Region, Alaska.* Oak Ridge, Tennessee: U.S. Atomic Energy Commission. pp. 697–754.

Flint, R. F. 1971. *Glacial and Quaternary Geology.* New York, N.Y.: John Wiley and Sons. 892 pp.

———, and H. G. Dorsey, Jr. 1945. Glaciation of Siberia. *Geol. Soc. Am. Bull.*, 56:89–106.

Folk, R. L., and W. C. Ward. 1957. Brazos River bar: a study in the significance of grain size parameters. *J. Sedimentary Petrol.*, 27:3–26.

Gakkel', Ya. Ya. 1958. Signs of recent volcanic activity in the Lomonosov Range (transl.). *Priroda*, 4:87–90.

Grigorov, I. P. 1946. Ischezayuschie Ostrova. *Priroda*, 10:65–68.

Gusev, A. I. 1959. K. Istorii Razvitia Primorskoi Ravniny v Chetvertichnoe Vremya. In: F. G. Markova, ed. *Sbornik Statei Geologii Arktiki.* Nauchno-Issledovatel'skog Instituta Geologii Arktiki, Leningrad. Trudy, 102(10). pp. 160–165.

Holmes, M. L. 1967. *Late Pleistocene and Holocene History of the Laptev Sea.* Unpublished thesis, University of Washington. 176 pp.

———, J. S. Creager, and D. A. McManus, 1968. High frequency acoustic profiles on the Chukchi Sea continental shelf. *Trans. Am. Geophys. Union* (abstract), 49(1):207.

Hume, J. D., and Schalk, M. 1967. Shoreline processes near Barrow, Alaska—a comparison of the normal and the catastrophic. *Arctic*, 20(2):86–103.

Jackson, M. L. 1958. *Soil Chemical Analysis.* Englewood Cliffs, N.J.: Prentice-Hall. 498 pp.

Kindle, E. M. 1924. Observations in ice-borne sediments by the Canadian and other Arctic expeditions. *Am. J. Sci.*, 7(40):251–286.

Koczy, F. F. 1951. Factors determining element concentration in sediments. *Geochem. Cosmochim. Acta*, 1:73–85.

Larionova, A. N. 1959. Attempts to classify elevations and depressions of the ocean bottom. In: *Traveling on the Sea Bottom.* Leningrad: Hydrometeorological Publishers. pp. 20–70.

Lisitsyn, A. P. 1957. Types of marine sediments connected with the activity of ice. *Akademia Nauk S.S.S.R., Geological Science Section*, 118(1):45–47.

McManus, D. A., and J. S. Creager. 1963. Physical and sedimentary environment on a large spitlike shoal. *J. Geol.*, 71(4):498–512.

Mörner, N. A. 1971. Eustatic changes during the last 20,000 years and a method of separating the isostatic and eustatic factors in an uplifted area. *Paleogeography, Paleoclimatology, Paleoecology*, 9(3):153–181.

Olson, E. A., and W. S. Broecker. 1958. Sample contamination and reliability of radiocarbon dates. *Trans., New York Academy Sci.*, Ser. 2, 20(7):593–604.

Samoilov, I. V. 1952. *Ust'ya Rek.* Moskava: Gosudarstvennoe Izdatel'stvo Geograficheskoi Literatury. 526 pp.

Shepard, F. P. 1960. Mississippi delta: marginal environments, sediments, and growth. In: F. P. Shepard, F. B. Phlegar, and T. H. van Andel, eds. *Recent Sediments, Northwest Gulf of Mexico.* Tulsa, Oklahoma: American Association of Petroleum Geologists. pp. 56–81.

———. 1963. *Marine Geology.* New York: Harper and Row. 557 pp.

Suslov, S. P. 1961. *Physical Geography of Asiatic Russia.* San Francisco, California: W. H. Freeman and Co. 594 pp.

Sverdrup, H. U. 1927. *The Waters of the North Siberian Shelf.* Scientific Results Norwegian North Polar Expedition Maud (1918–1925), Vol. 4. 131 pp.

Tarr, R. S. 1897. The Arctic Sea ice as a geological agent. *Am. J. Sci.*, 3(15):223–229.

U.S. Navy Hydrographic Office. 1954. Sailing directions for the northern U.S.S.R. Vol. 3. *Hydrographic Office Publication 137c.* 346 pp.