The depositional environment of the Laptev Sea continental margin: Preliminary results from the R/V POLARSTERN ARK IX-4 cruise

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Marine geological investigations were performed across the Laptev Sea continental shelf and slope. Thirty sampling sites were selected covering a depth range of ca 3500 m. Maximum core recovery was 9 m. PARASOUND sub-bottom profiling was used for site surveying and provided important information on the depositional environment of the continental margin together with sedimentological and stratigraphical investigations.

Undisturbed horizontal layering of the sea-floor sediments is a common feature for the Laptev Sea shelf. There is no indication for glaciation of the broad shelf region during the Last Glacial, since moraine deposits are missing. However, a high number of plough marks in places points to recent to sub-recent ice-erosion which has led to an intensive sediment reworking on the shelf. Several broadly incised river channels recorded near the shelf edge are related to Pleistocene drainage systems of large Siberian rivers which cut into the dry shelves during the Last Glacial Maximum and were subsequently filled during the Holocene. During the Last Glacial we therefore suspect a significant freshwater contribution from the Eurasian continent to the Arctic Ocean.

The composition of the normally consolidated core sediments indicates a strong flux of terrigenous material, which is mainly provided by the Siberian rivers. Currents distributing the suspension load and sea ice are supposedly major agents transporting sediments across the shelf to the central arctic deep sea basin.

Sediment cores from the upper and middle continental slope exhibit only minor lithological changes. Bioturbated, fine-grained sediments with high organic carbon contents dominate. The presence of free hydrogen sulphide gas within the sediment column indicates that an intense decay of organic matter under reducing conditions is taking place. Sedimentation rates are estimated to be ca. 50 cm/1000 years at the upper slope of the western Laptev Sea, being approximately 10 times higher than at the continental rise. The suboxic to anoxic environment diminishes at deep sea sites of the western Laptev Sea, where sedimentation rates and influx of organic matter are reduced.

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Introduction

Approximately one third of the Arctic Ocean area is occupied by shallow epicontinental seas (Gierloff-Emden 1982; Carmack 1986), the global importance of which is related to sea ice production (Colony & Thorndike 1985) and brine formation (Middtun 1985; Aagaard 1988, 1989). The Laptev Sea is supposed to be one of the main sea-ice producing areas in the Arctic where huge amounts of sediments may be incorporated and subsequently transported into the Transpolar drift. The shelf edge lies between 50 and 60 m water depths (Holmes & Creager 1974), and as far as 500 km from the continent. Five large submarine valleys, which are interpreted as submerged extensions of the major rivers in that region (the Lena and Kotuy: Holmes & Creager 1974), cut into the gently dipping shelf plain. An irregular pattern of major shoals, which sometimes reach or break the sea surface, characterises the sea-floor topography.

In the framework of the joint German-Russian expedition ARCTIC '93 during summer/autumn

1993, multidisciplinary research was undertaken for the first time in the Laptev Sea from the coast across the outer shelf and continental slope to the deep sea. The R/V POLARSTERN worked mainly on the outer shelf, the slope and in the deep sea (Fütterer 1994). The R/V KIREYEV from the Arctic and Antarctic Research Institute (AARI, St. Petersburg, Russia) investigated the inner shelf of the Laptev Sea (Kassens & Karpiy 1994). The marine geology programme aboard R/V POLARSTERN focused on the reconstruction of the depositional environment and its change through time. Specific aspects addressed include (1) the spatial and temporal development of the arctic sea-ice cover during glacial/interglacial changes, (2) the varying impact of North Atlantic water masses intruding into the Arctic Ocean via Fram Strait and the Barents Sea, and (3) the influence of the large Siberian river systems for the terrigenous sediment supply onto the broad shelf and changes in marine productivity through time which are assumed to be reflected in the sea-floor deposits.

Four transects covering the entire continental slope area down to approximately 3500 m were chosen for sedimentological investigations. The easternmost Laptev Sea (Transects G and H, Fig. 1) was ice-free during September, allowing the survey to extend far into the deep sea basin. The western Laptev Sea (Transects E and F) suffered from heavy ice conditions. Transect E was restricted to less than 1200 m water depth. In this study we present preliminary results from shipboard investigations. Detailed stratigraphical, sedimentological, geochemical and mineralogical investigations are currently in progress.

Methods

High resolution subbottom profiling (PARASOUND)

Bottom and sub-bottom reflection patterns of the uppermost sea-floor sediments received by the PARASOUND sediment echosounder system (Atlas Electronics, Bremen, Germany) document sedimentary features, which can be used to characterise sedimentary environments and their changes in space and time. The aims of the PARASOUND profiling were (1) to select locations for coring, (2) to identify and interpret lateral differences in sedimentary facies along shelf-slope transects and between the Barents and Laptev seas, and (3) to evaluate major stratigraphic features indicative of past environmental changes, in particular glacial-interglacial transitions.

Geological sampling and processing

Geological sampling and coring recovered undisturbed surface and near-surface samples (large box corer) and undisturbed, long sediment sequences (kastenlot and gravity core) for stratigraphic, paleoenvironmental and sedimento-

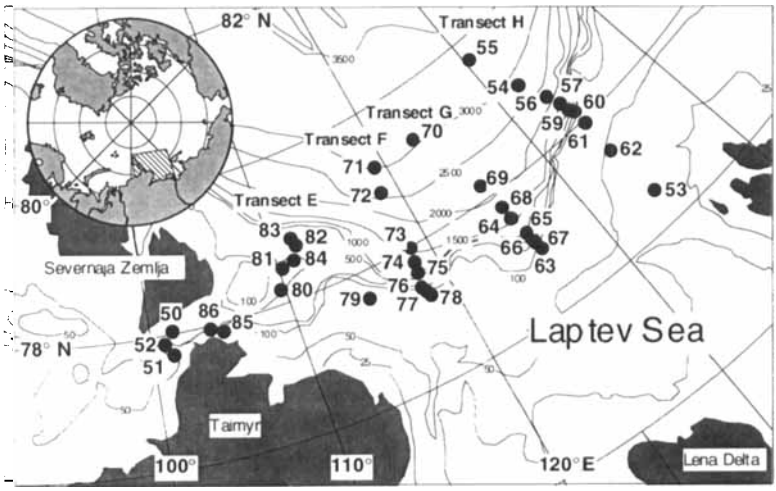

Fig. 1. Bathymetric chart of the Laptev Sea indicating coring sites of R/V POLARSTERN expedition ARK IX-4. Numbers indicate the AWI number code (71 = PS2471). Inset shows the location of the study area.

logical investigations. Fig. 1 shows the sampling locations. Sediment cores were obtained along four transects from the shelf to the lower continental slope. Transects F, G and H covered the depth range from approximately 50 m to 3500 m. Coring operations along Transect E were terminated at a water depth of approximately 1200 m.

The large box corer (GKG) recovered 25 undisturbed sediment surfaces and subsurface sediments (maximum depth 50 cm). The gravity corer (SL) was applied at 16 stations and penetrated sediment sequences with an average length of 430 cm. Maximum recovery was 908 cm. Five kastenlots (KAL) recovered sediment sequences with an average sediment thickness of ca. 620 cm. Maximum recovery was 800 cm.

The sediment cores obtained were routinely photographed, described in detail and graphically displayed. Sediment colours were identified according to the "Munsell Soil Colour Chart" (Kollmorgen Instruments Corp., Newburgh, USA). Samples were coded by an AWI-code (e.g. PS2460-3 SL).

For the analysis of the coarse grain fraction, the bulk sediment of selected sediment samples was washed through a 63 μm mesh, dried, and analysed under a binocular. For X-ray imaging, sediment slabs of ca. 0.5 cm thickness were taken continuously downcore in order to elucidate sedimentary and biogenic structures.

Grain size distribution and distribution patterns of major sediment components were estimated from smear slide examinations. Abundances of coccoliths could easily be determined under the microscope with crossed nicols, and could be applied as preliminary time constraints. Whole core measurements of magnetic susceptibility in 2 cm intervals were applied for core correlation. The records mainly reflect the content of magnetite in the sediments investigated as the ferrimagnetic magnetite exhibits high susceptibilities in contrast to all other rock-forming minerals with weak diamagnetic or paramagnetic characteristics. A detailed description is given in Nowaczyk (1991) and Fütterer (1992). Measurements were performed with a Bartington susceptibility control unit M.S. 2 in conjunction with two different sensors, one for measurements of entire core segments, the other for paleomagnetic standard samples with volumes up to 10 cm^3. During the analyses, the sample within the sensor was subjected to a weak magnetic field (0.5 mT, f = 565 Hz or f = 460 Hz).

Results and discussion

Sediment echo-sounding

PARASOUND profiles reveal that the Laptev Shelf is characterised by a flat bottom topography (Fig. 2). Moraines, which would give an indication for the glacial history of this area, were not

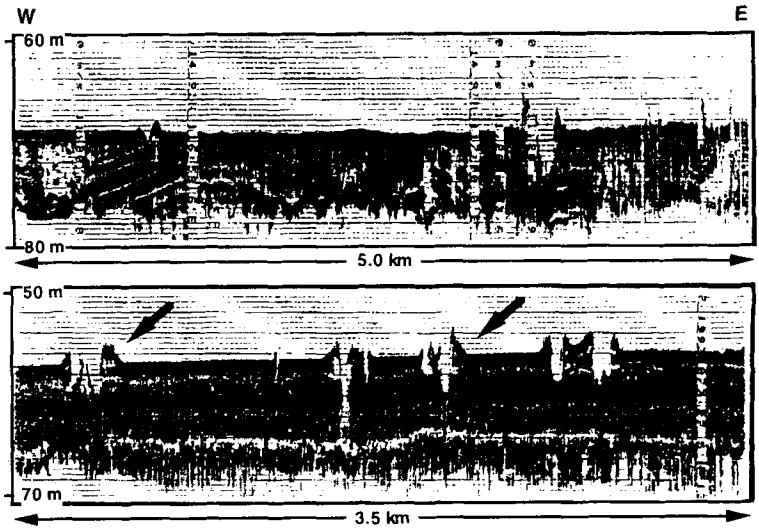

Fig. 2. PARASOUND profiles from the central and eastern part of the Laptev Sea shelf. Top: between 77°15'N, 116°58'E and 77°14'N, 116°54'E. Bottom: between 77°30'N, 133°37'E and 77°27'N, 133°37'E. Horizontal and sub-horizontal layering and ice gouges (arrows) are clearly visible.

observed. PARASOUND penetration was mostly limited to a few metres locally increasing up to 20 m. Subsurface reflectors have mostly subparallel geometries. In places, they appear slightly deformed or "folded" (Fig. 2). These subsurface reflectors often toplap against an unconformity and are overlain by a horizontal bed, mostly only a few metres thick. The latter is interpreted as late glacial and Holocene deposits. With exposure of the shelf area, the unconformity may relate to the Last Glacial Maximum. The fact that PARASOUND was able to penetrate pre-Holocene Laptev shelf deposits is taken as indication of the lack of an ice load during the Last Glacial. The top of subglacial deposits would be characterised by a strong contrast in acoustic impedance. Therefore, the top of ice-consolidated sediments is indicated by sound reflection rather than penetration. For example, during ARK-IX/4, PARASOUND penetration into Pleistocene deposits was not observed on the Barents Shelf, where sediment consolidation due to a late Pleistocene ice cap is proposed by Vorren et al. (1983). Even without consolidation of sediments by an ice sheet, Laptev Shelf sound penetration into deeper strata is a surprising observation because relict permafrost from a periglacial tundra environment is expected to be present underneath Holocene deposits. In such a case, permafrost would cause acoustic impedance near the sediment surface probably high enough to prevent further sound penetration. It is too early, however, to speculate on the reasons of the above observation before a detailed survey for permafrost features in seismic profiles is carried out.

Several incised river channels were recorded on profiles near the shelf edge (Fig. 3). The widths of the channels are on the order of a few kilometres, the depths are about 10–15 m. All channels are filled with well-stratified sediments. These channels are presumably related to Pleistocene drainage of the large Siberian rivers, such as the Lena and Kotuy, and were cut into the shelf (e.g. Holmes & Creager 1974). Most likely, this occurred during the Last Glacial when the sea level was proposed to be 120 m below that of today (Chappell & Shackleton 1986), and the coastline was located north of the shelf region near the present shelf/slope boundary. Consequently, considerable freshwater drainage most likely occurred during glacial times from the Eurasian continent into the Arctic Ocean. These findings together with the lack of moraine deposits imply that the area of investigation was not covered by an extended ice sheet during the Last Glacial as proposed by Grosswald (1988). Our investigations rather support the predominance of periglacial environmental conditions in the Laptev Sea area as suggested by Dunayev & Pavlidis (1988).

East of Severnaja Zemlja and west of the New Siberian Islands, a large number of ice gouges have been observed at the sediment surface (order of magnitude 10^3 numbers in total) (Fig. 2). Incisions of 1–10 m depth are generally flanked by berms on just one or both sides. The total widths are on the order of a few tens of metres. In most cases, it appears that the sediment accumulated in the berms would fill the scars. The relatively small total width of the features compared to their total relief make them clearly distinguishable from drainage channels flanked by levee deposits. Furthermore, the occurrence of ice gouges is strictly limited to a range of water depth between 30 and 90 m water, whereas erosional channels were observed at all water depths on the shelf.

Most ice gouges appear to be "fresh" and unfilled (Fig. 2 bottom). Some incisions show alteration as indicated by their smoothed topography (e.g. Fig. 2 top left). In places, the well-stratified character of subsurface sediments seems to be locally ploughed despite the presence of a presently flat and undisturbed sediment surface.

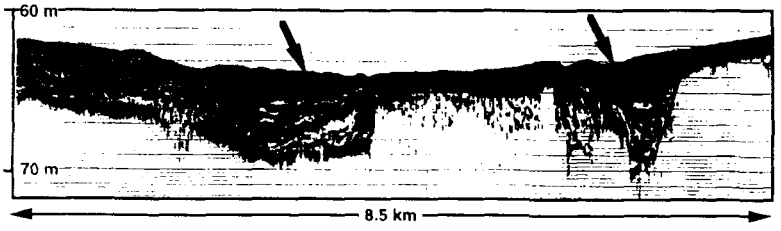

Fig. 3. PARASOUND profile showing incised river channels (arrows) from the centre of the Laptev Sea near the continental slope between 77°03'N, 131°06'E and 77°02'N, 130°48'E.

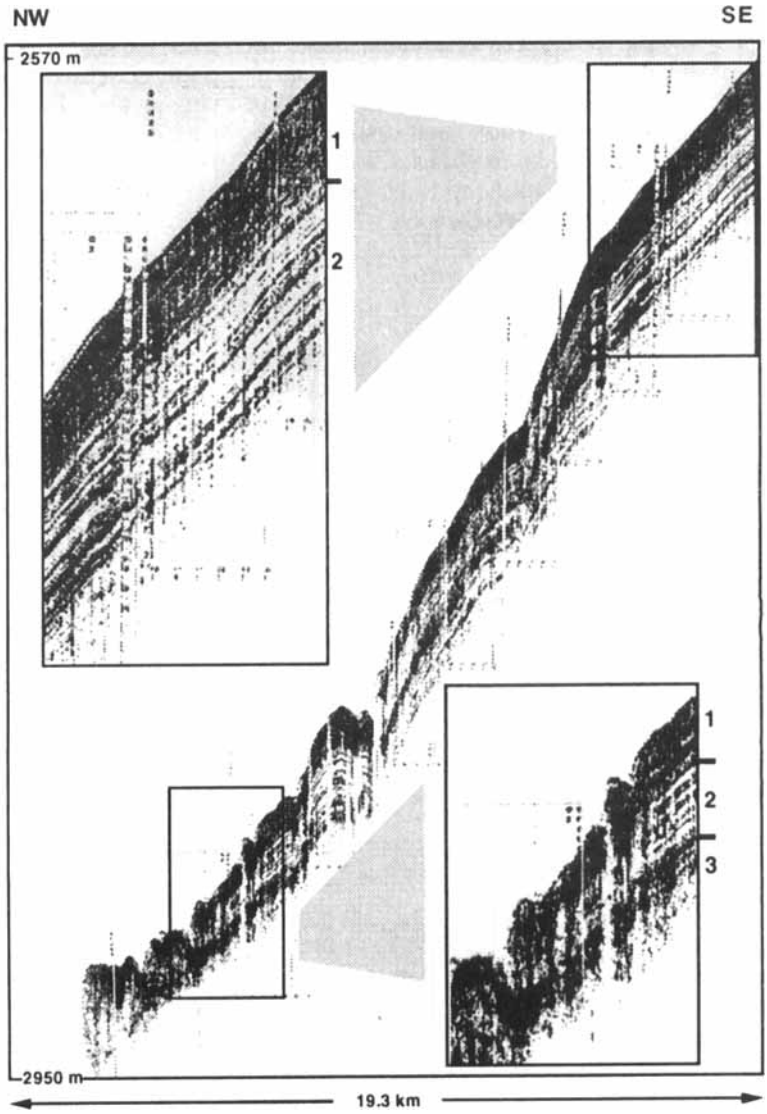

Fig. 4. PARASOUND profile from the lower part of the continental slope along Transect H between 78°41′N, 132°41′E and 78°31′N, 132°51′E. The uppermost and lowermost sections are magnified in order to elucidate the thinning out of sediment layers.

From observations and simulations of formation and filling of ice gouges from the Alaskan Beaufort Sea, Barnes et al. (1990) concluded that ice gouges are short-lived and filled within a few years. This interpretation is consistent with our observations in the Laptev Sea. It implies that ice erosion is presently an important shelf process on the Laptev Sea shelf, potentially inducing resuspension and lateral sediment transport over the shelf. Indeed, PARASOUND profiles indicate that, in places, subsurface reflectors underwent strong deformation (Fig. 2, top). This is interpreted as a result of strong sediment reworking by ice gouging during the Holocene. Whether ice gouging is related to grounding icebergs, or pressure ridges, or both, is still unclear.

The continental slope deposits belong to different facies. The central part of the Laptev Sea slope (Transect G, from 77°01,9′N 126°25,4′E to 79°13,7′N 122°51,7′′E) is characterised by reflection patterns of slumps down to water depths of ca 2000 m, followed by channel and levee deposits to the deepest point at 3200 m. Channels have distinct or prolonged reflection character. Some

channels show truncation of older beds. In places, thick undisturbed sections were found. They comprise subparallel reflectors which drape underlying topographies. Penetration was down to 50 m sediment thickness. These well-stratified sediments are interpreted as levee facies, which are, in conjunction with channels, typical for submarine fans. Since incised river channels of the Lena drainage system were found on the continental shelf, the fan facies observed below 2000 m water depth may have formed mainly during the Last Glacial, when the riverine transport of continental debris reached to the edge of the present slope/shelf boundary.

Thick, mostly undisturbed, slope deposits were recorded along sections H and F (Fig. 4). Reflec-

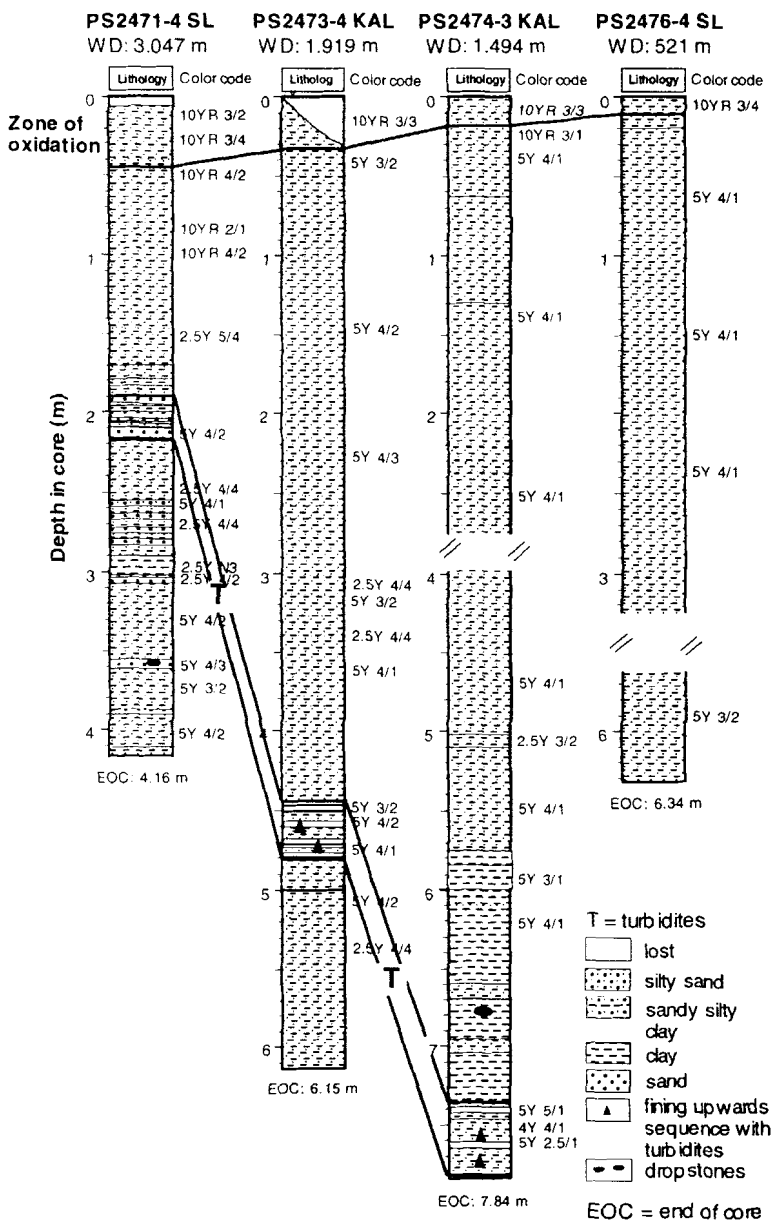

Fig. 5. Lithological core description of sediment cores from the Laptev Sea continental slope along Transect F.

tions are predominantly numerous down to about 100 m sediment depth. The deposits drape underlying topographies. Distinct reflectors correlate over long distances and show a pronounced wedging out downslope. Only in the lowest part of section H (deeper than 3000 m) was a major slump identified.

Sedimentological and geophysical investigations

All box core tops consist of soft brown mud. The surface deposits from the shelf and upper slope (50–1000 m) contain approximately 10–20% sand-sized material. Terrigenous grains (quartz, feldspar, rock fragments) predominate. Ostracods, small bivalves, and calcareous and agglutinated benthic foraminifers are common, whereas planktonic foraminifers are absent or rare. The sand content decreases significantly downslope and is less than 1% in water depths greater than 3000 m, there consisting almost entirely of planktonic foraminifers. The density of benthonic populations is high on the shelf and uppermost slope, but decreases significantly downslope.

The uppermost, brown lithological unit of the sediment cores is thickest on the lower slope (ca. 60 cm) and decreases to 3–10 cm on the upper slope and shelf (Fig. 5). This strongly bioturbated unit resembles the sediment surface in the box cores and apparently reflects the depth of oxygenation. On the shelf and upper slope, the underlying dark grey to black sediments mainly consist of sandy, silty clays. Occasionally, thin sandy layers (turbidites) are intercalated, predominantly in the lower parts of the sediment cores (Fig. 5). The amount of coarse material (>63 μm) slightly decreases with increasing water depth. When exposed to the atmosphere for a sufficient time (12–48 hours), the dark sediment changes to brownish and olive greenish colours. The sediments contain high amounts of organic matter (max. 2%), the main component of which is terrigenous in origin (e.g. plant fibres) (Stein & Nürnberg 1995). Formation of free hydrogen sulphide gas is typical in these sediments, pointing to the decay of organic matter by the activity of sulphate-reducing bacteria under reducing conditions. Early diagenetic precipitations of calcium carbonate hexahydrate (ikaite) were found in ca. 235 cm depth of core PS2460-4 from shallow waters (200 m).

In the eastern Laptev Sea (transects G, H), the dark subsurface-sediments from the upper slope and outer shelf occur down to ca. 3500 m water depth. Sediments from the western Laptev Sea (transects E, F), however, are partly different. The subsurface sediments from water depths greater than 3000 m contain mostly silty clays of brownish to olive greenish colours, being significantly lighter than sediments from shallower depths. Free hydrogen sulphide gas is no longer present.

A few well-preserved shallow marine bivalves (*Yoldia amygdalea*) were observed in cores PS2458-4 and PS2460-4 (Transect H) at 400–700 cm core depth. Smear slide investigations of core PS2471-4 revealed the coccolith species *Emiliania huxleyi* and *Gephyrocapsa* sp. to be present down to 400 cm core depth. Maxima in abundance occur in near-surface sediments (ca. 20 cm), between ca 200 cm and 300 cm, and around ca 380 cm (Fig. 6).

Mixing of sediment by bioturbation is extremely strong on the shelf and upper slope. Vertical chitinous worm tubes with a length up to 30 cm indicate a very thick upper mixed sediment layer. Although the degree of benthonic coverage decreases downslope, bioturbation is still an important environmental process, which prevents any stratification.

Fig. 6 shows magnetic susceptibility records of sediment cores from Transect F (see Figs. 1 and 5). Continental slope and shelf sediments are typically characterised by magnetic susceptibilities of approximately 40–250 $\times 10^{-5}$ SI. These values are significantly higher than values previously published for central Arctic Ocean sediments. Cores recovered during the ARCTIC '91 expedition of R/V POLARSTERN have magnetic susceptibilities of approximately 25–50 $\times 10^{-5}$ SI (Amundsen and Nansen Basin) and 15–30 $\times 10^{-5}$ SI (Gakkel and Lomonosov ridges) (Fütterer 1992).

The magnetic susceptibilities generally decrease downslope. Shelf and upper slope sediments (<500 m water depth) are commonly characterised by magnetic susceptibilities larger than 60 $\times 10^{-5}$ SI, mainly ranging around 100 $\times 10^{-5}$ SI with extremes up to 250 $\times 10^{-5}$ SI. Below ca 500 m water depth, mean magnetic susceptibility values decrease to 20–60 $\times 10^{-5}$ SI. The decrease of magnetic susceptibilities from shelf to continental slope and into the central Arctic deep-sea and mid-ocean ridge sediments presumably reflects a constant, density-dependant loss of heavy, ferrimagnetic minerals of

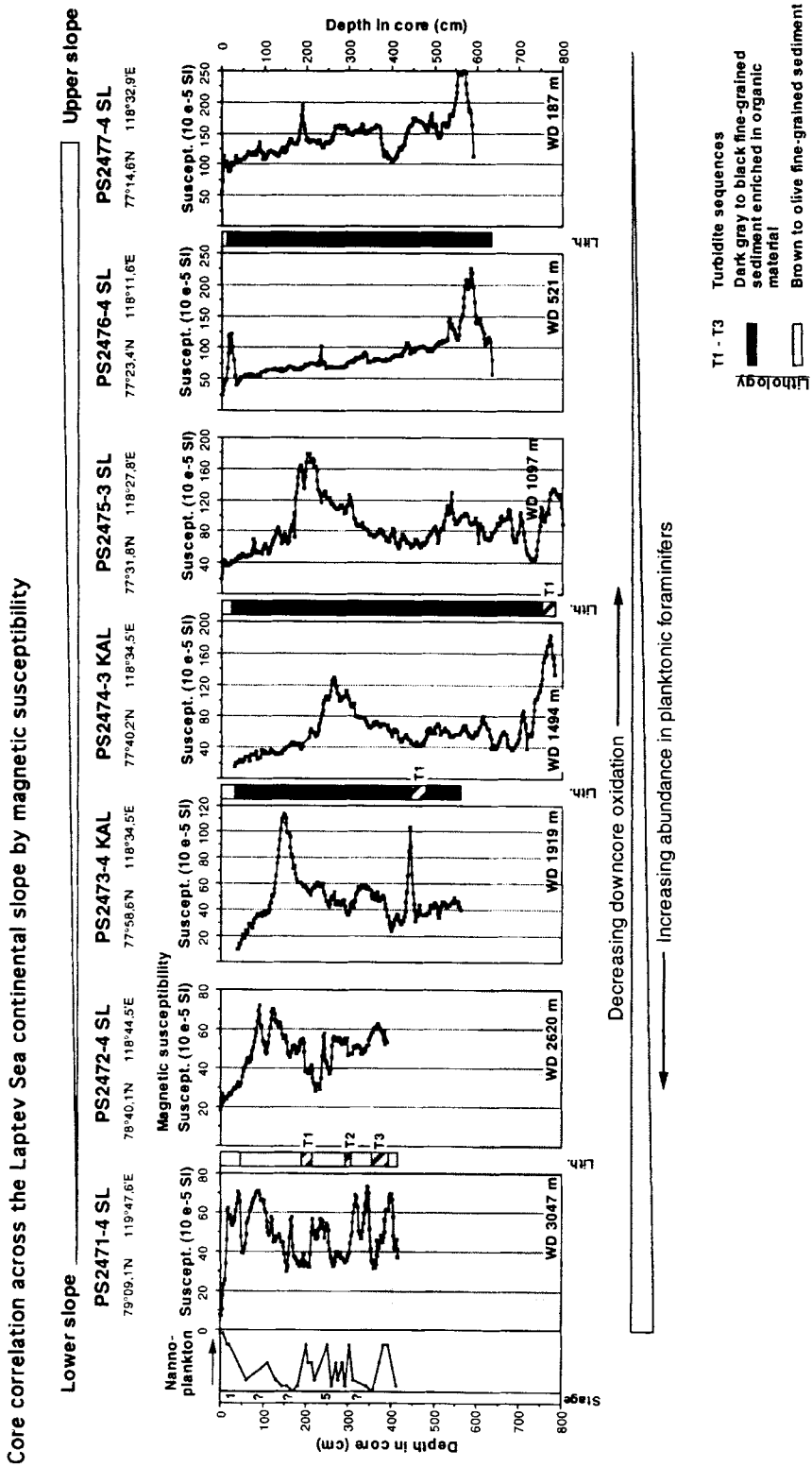

Fig. 6. Geophysical, sedimentological and stratigraphic results from Transect F covering a depth range of ca. 4000 m. Schematic lithology logs, the abundance of planktonic foraminifers and coccoliths and the depths of the oxidation zone are indicated. Core correlation (shaded areas) is based on magnetic susceptibility records. WD = water depth.

terrigenous origin (e.g. magnetite) during long-range sediment transport.

Depositional environment

The geophysical and geological investigations allow a preliminary characterisation of the outer Laptev Sea depositional environment. In general, the sediment composition indicates a strong supply of terrigenous material from the continent to the Laptev Sea shelf edge. The relatively high content of plant fragments and the occurrence of freshwater and shallow marine bivalves in cores from the middle and lower continental slope underline the importance of a large-scale downslope transport of sediments.

Most of the fine-grained material is probably transported in suspension by currents. The Lena River, with an outflow of approximately 520 km^3/year (Aagaard & Carmack 1989), is one of the largest river systems flowing into the Arctic Ocean. The Kotuy River adds another 105 km^3/year (Aagaard & Carmack 1989). The Lena suspension load is calculated to amount to 17.6 million tons/year (Gordeev & Sidorov 1993), which is relatively low compared to the 100 million tons/year of the McKenzie River (Milliman & Meade 1983). Significant amounts of sediment may also be contributed by sea ice. Dethleff et al. (1993) and Nürnberg et al. (1994) already demonstrated the importance of the Laptev Sea for Arctic sea-ice formation and resuspended sediment entrainment by sea ice. Dethleff (1995) estimates the amount of sea-ice sediments exported from the Laptev Sea shelf to approximately 10 million tons/year. Whether the entrained portion of shallow marine sediments in sea ice is subsequently released and adds to the slope sedimentation will remain unclear as long as the lack of stratigraphical information prevents accurate estimates of sediment mass balances in this area. It is, however, probable that major portions of these sediments leave the Laptev Sea area within the transpolar ice drift (Nürnberg et al. 1994). Sediment-rafting by glacier ice seems to be of minor importance in the Laptev Sea. Core-top sediments and sediment cores from the continental slope contain only minor portions of coarse sand and gravel, which may be indicative of iceberg transport.

The typical black spots colouring the subsurface sediments dark grey to black are related to iron and manganese precipitations, which must be attributed to the decay of marine organic matter by the activity of sulphate-reducing bacteria (e.g. Emelyanov et al. 1982). This process is active only under reducing conditions. The strong anaerobic bacterial activity (in Fütterer 1994) indicates a rapid burial of high amounts of marine organic matter before a sufficient oxidation from sea-water could take place. This process apparently is less important for the western Laptev Sea deep sites, where brownish and olive greenish colours indicate a "normal" deep-sea oxidation and/or a lower supply of marine organic matter to this area. Here, the sediment colour is presumably determined by iron and manganese oxides, clay minerals, etc.

Though most Laptev Sea continental slope cores only exhibit insignificant lithological changes, thus preventing visual core correlation, the magnetic susceptibility provides an excellent tool for core correlation and for determination of relative sedimentation rates across the continental slope. Transect F (Fig. 6) comprising 7 magnetic susceptibility logs elucidates the depositional pattern along the continental slope. The susceptibility record from core PS2471-4 (3047 m water depth) unambiguously correlates with all cores located on shallower slope positions. A distinct susceptibility peak at ca. 50 cm core depth in core PS2471-4 is present in all other cores from Transect F, but becomes increasingly pronounced when reaching the upper slope at 187 m water depth (indicated by light shading in Fig. 6). Here, this peak appears at approximately 560 cm core depth in core PS2477-4, indicating that sedimentation rates apparently are approximately 10 times higher near the shelf break than in the deep sea. The continuous downslope wedging-out of the approximately 6 m thick homogenous sediment package from the shelf break is supported by the PARASOUND echo-sounding profile along Transect H (Fig. 4).

The strongly decreasing sediment accumulation with greater water depths is also suggested from the increasing amount of planktonic foraminifers in the coarse fraction of the surface sediments (Fig. 6). Although conditions for planktonic life become unfavourable to the north due to perennial sea ice and colder waters, the downslope decreasing dilution of terrigeneous material makes planktonic foraminifers become the dominant coarse fraction component in surface sediments from the lower slope, whereas they are rare in upper slope deposits.

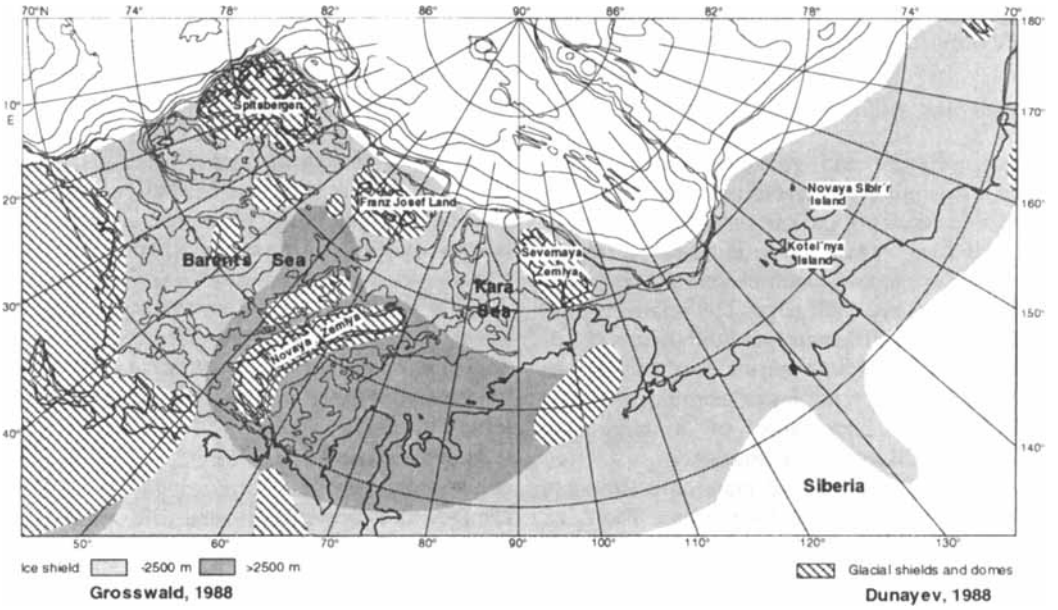

Fig. 7. Map of the Siberian Arctic showing glaciation models from Grosswald (1988) and Dunayev & Pavlidis (1988).

Assuming a Holocene age for the upper ca. 50 cm of core PS2471-4 based on the abundance maximum of *Gephyrocapsa* sp., which has proven to be a useful indicator for arctic interglacial sediments (Gard 1988), we speculate from the core correlation presented in Fig. 6 that the upper approximately 6 m of sediments in cores PS2476-4 and PS2477-4 were entirely deposited during Holocene times. Corresponding sedimentation rates of ca. 50 cm/1000 years are in accordance with rates of 40 cm/1000 years calculated from a radiometrically dated sediment core from the Laptev Sea shelf (Kassens, pers. com. 1994). The homogeneity of the sediments suggest that environmental conditions did not change significantly during this time interval.

The cores from the lower slope, which often contain sandy layers, presumably span over a longer time interval, possibly several glacial-interglacial cycles. The occurrence of the coccolith *Gephyrocapsa* sp. at 200–300 cm in the lower slope core 2471-4 (Fig. 6) might be related to the Last Interglacial (oxygen isotope stage 5).

Conclusions

The sedimentary environment of the Laptev Sea continental margin is characterised by comparatively high bulk sedimentation rates. The deposition of relatively high amounts of terrigenous and marine organic matter and, in many areas, bacterial activity and insufficient oxidation lead to the presence of hydrogen sulphide gas within the dark grey to black sediments.

Since there is no major change either in lithology or in reflection geometry, it is speculated that these deposits are of Holocene age. A preliminary coccolith stratigraphy, in combination with the magnetic susceptibility records allowing the correlation of cores across the entire slope, support this assumption. High sedimentation rates near the shelf edge, which are presumably caused by a strong lateral transport of debris on the shelf in an off-shore direction, decrease with increasing water depth. Downslope wedging-out of undisturbed sediment layers, slumps, and fan deposits on the lower slope are typical for prograding slopes. Whether progradation is still active today is questionable since (1) the large Lena Delta shoreline is generally retreating (Zenkovitch 1985) and (2) the present suspension load of the Lena River is relatively low (Gordeev & Sidorov 1993). Important changes affecting the relationship between continental supply and destructive marine forces may have occurred during postglacial time.

The lack of moraines and diamictons and of

considerable amounts of dropstones on the outer shelf do not support the assumption of a glaciated Laptev Sea shelf during the Last Glacial. An unglaciated Laptev Sea shelf is also supported by the incised river channels observed on the outer shelf, which were cut into the exposed shelf in late Pleistocene times. A continuous freshwater supply into the Arctic Ocean during the Last Glacial under presumably periglacial conditions as suggested by Dunayev & Pavlidis (1988) (Fig. 7) is more in agreement with our observations. The post-glacial environment is generally characterised by ice-erosion and sediment reworking as indicated by significant numbers of ice-gouges.

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