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The Laptev Sea system since the last glacial

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ABSTRACT

There is growing concern about the rapidity and extent of climate change in recent decades in the Arctic. The changes already evident in the Arctic, such as the cyclonic shift in the distribution of Atlantic and Pacific water masses, atmospheric pressure and winds, as well as the thinning and retreat of the sea ice, will be felt first and most dramatically around the circum-Arctic shelves, which comprise nearly 50% of the area of the Arctic Ocean. In this context, the Laptev Sea and its Siberian hinterland are of particular interest because of their distance both from the Atlantic and Pacific Oceans. River discharge into the Laptev Sea constitutes a key source for the Arctic freshwater input, and it generates a shallow brackish layer on top of the halocline. The shallow Laptev Sea shelf is a major area of sea-ice production that links the Siberian shelves of the Arctic Ocean with the Nordic seas. During the Last Glacial Maximum, most of these shelves were above sea level and developed thick permafrost sequences; today they are submarine, after having experienced the postglacial late Pleistocene and Holocene transgression. The history of the submarine permafrost and its modern state of decay are largely unknown.

Keywords: Arctic shelf sea, River Lena, flaw polynya, permafrost.

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INTRODUCTION

During the past decade, a large-scale change in the Arctic atmospheric circulation took place as part of a pole-centered pattern termed the Arctic Oscillation (e.g., Thompson and Wallace, 1998; Monahan et al., 2000; Mysak, 2001; ACIA, 2004). There is a complex of related atmospheric, oceanic, and terrestrial changes, including an increased discharge of fresh water from the six largest Eurasian rivers to the Arctic Ocean (Peterson et al., 2002), reduced sea-ice extent and volume (e.g., Serreze et al., 2000; Johannessen et al., 2004), and increased air temperature over most of the Arctic (Proshutinsky and Johnson, 1997; Jones and Moberg, 2003). Freshening of the Arctic Ocean is expected to reduce North Atlantic Deep Water formation and Atlantic thermohaline circulation (e.g., Broecker, 1997; Rahmstorf and Ganopolski, 1999; Delworth and Dickson, 2000), but the precise nature of any future changes is unknown, and because of their impact on the livelihood of high Northern Hemisphere populations, they are subject of intense scientific and political debate.

The positive temperature trend in the Russian Arctic favors decay and thawing of terrestrial permafrost (Pavlov, 1994; Goldman, 2002; Nelson, 2003; ACIA, 2004). The submarine permafrost regime is largely determined by heat and mass transport processes that control the response rate to the new warm and salty boundary conditions (e.g., Osterkamp et al., 1989; Gosink and Baker, 1990). A considerable amount of organic carbon is stored in the upper layer of permafrost, and gas hydrates are expected within and beneath the submarine permafrost (Romanovsky et al., 2004; Romanovsky et al., 2005). Large increases of CO_2 and CH_4 emissions are expected to be associated with degradation of the permafrost (Nelson, 2003). Thawing of the permafrost could release large quantities of greenhouse gases into the atmosphere, thus further increasing global warming. Taking into account these concerns, extensive studies of the water column and seafloor of the Laptev Sea shelf and of the environment of its hinterland have been carried out during all seasons of the year in the scope of the research program "Laptev Sea System" (Kassens et al., 1999; Larsen et al., 1999; Thiede, 2004; Bauch and Kassens, 2005) (Fig. 1). The primary scientific goal was to decipher the mechanisms that controlled past climate variations as well as those controlling ongoing environmental changes.

MODERN AND PAST ENVIRONMENT OF THE LAPTEV SEA SHELF

Environmental forcing factors, i.e., atmospheric circulation, sea-ice cover, and river runoff, mainly affect the shallow-water environment of the Laptev Sea (Eicken et al., 2005). In particular, the predominance of cyclonic or anticyclonic atmospheric circulation over the Arctic influences the current system and the distribution of river runoff on the shelf (Proshutinsky et al., 2001). The wind-forced Laptev Sea flaw polynya, open water between pack and fast ice, is one of the key elements of the environmental system of the Laptev Sea (Bareiss and Görgen, 2005) (Fig. 2). Continuous southerly winds that blow during the whole winter season are able to maintain open-water areas, up to one hundred kilometers wide, between the fast and drift ice, despite the low temperatures of air and sea-surface waters. Year-round measurements with acoustic doppler current profilers and oceanographic data have shown that the water column in the polynya region of the SE Laptev Sea is stratified during all seasons (Dmitrenko et al., 2002, 2005). Low air and seawater temperatures result in sea-ice formation and local increases of salinity in the water column. For instance, in the eastern Laptev Sea flaw polynya, the mean salinity increase of the surface layer can reach up to 4 units, corresponding to an ice production of 3 to 4 m (Dmitrenko et al., 2001a). Therefore, the flaw polynya is an important ice source for the Transpolar Drift system (Alexandrov et al., 2000). Regardless of the strong ice formation, the low initial salinity of the surface layer and the strong density stratification in the polynya prevent a convective mixing down to the seafloor. Thus, this stratified system limits the transport of energy as well as of particulate and dissolved matter (Pivovarov et al., 2004) (Fig. 3).

Like the wind-forced dynamics of the ice regime, sediment transport is also strongly affected by different regimes of atmospheric circulation and ice cover. New data show that this effect starts as soon as the Laptev Sea flaw polynya opens up during winter (Dmitrenko et al., 2001b, 2005). Long-term measurements with bottom-moored instruments provide strong evidence that modern shelf sediment transport is mainly wind-forced and connected to the N-S–running submarine valleys on the shelf of the eastern Laptev Sea (Wegner et al., 2003, 2005). In these valleys, suspended sediments are transported in a distinct bottom nepheloid layer, a layer of increased suspended matter concentration up to 12 m thick, which is strongly influenced by the prevailing atmospheric circulation and the ice cover (Burenkov et al., 1997; Dmitrenko et al., 2001b; Wegner et al., 2003). Calculations of the net horizontal sediment flux during the ice-free period have revealed that the main transport within the bottom nepheloid layer in the submarine valleys is directed toward the inner shelf (Wegner et al., 2003). With respect to the sediment export from the eastern Laptev Sea shelf into the deep Arctic Ocean, Wegner et al. (2005) inferred that during the ice-free period, most of the material derived from riverine input is trapped within a quasi-estuarine circulation system on the inner and mid-shelf regions. This pattern of sediment transport might also explain the low sediment accumulation rates on the outer shelf and the slope of the Laptev Sea since the end of the Holocene transgression (Bauch et al., 2001; Stein et al., 2001). If the net sediment transport in the bottom nepheloid layer is directed toward the central and inner shelf, and if we further take into account that large areas of the Laptev Sea are covered by relict sediments and lag deposits (Viscosi-Shirley et al., 2003) with no present-day sediment deposition, we can draw the conclusion that the sediment input into the Laptev Sea is not balanced by sediment deposition on the shelf and long-range export through the water column to the Arctic basins. This discrepancy in sediment budgets may be explained by an eastward sediment transport to the East Siberian Sea that follows the Siberian Coastal

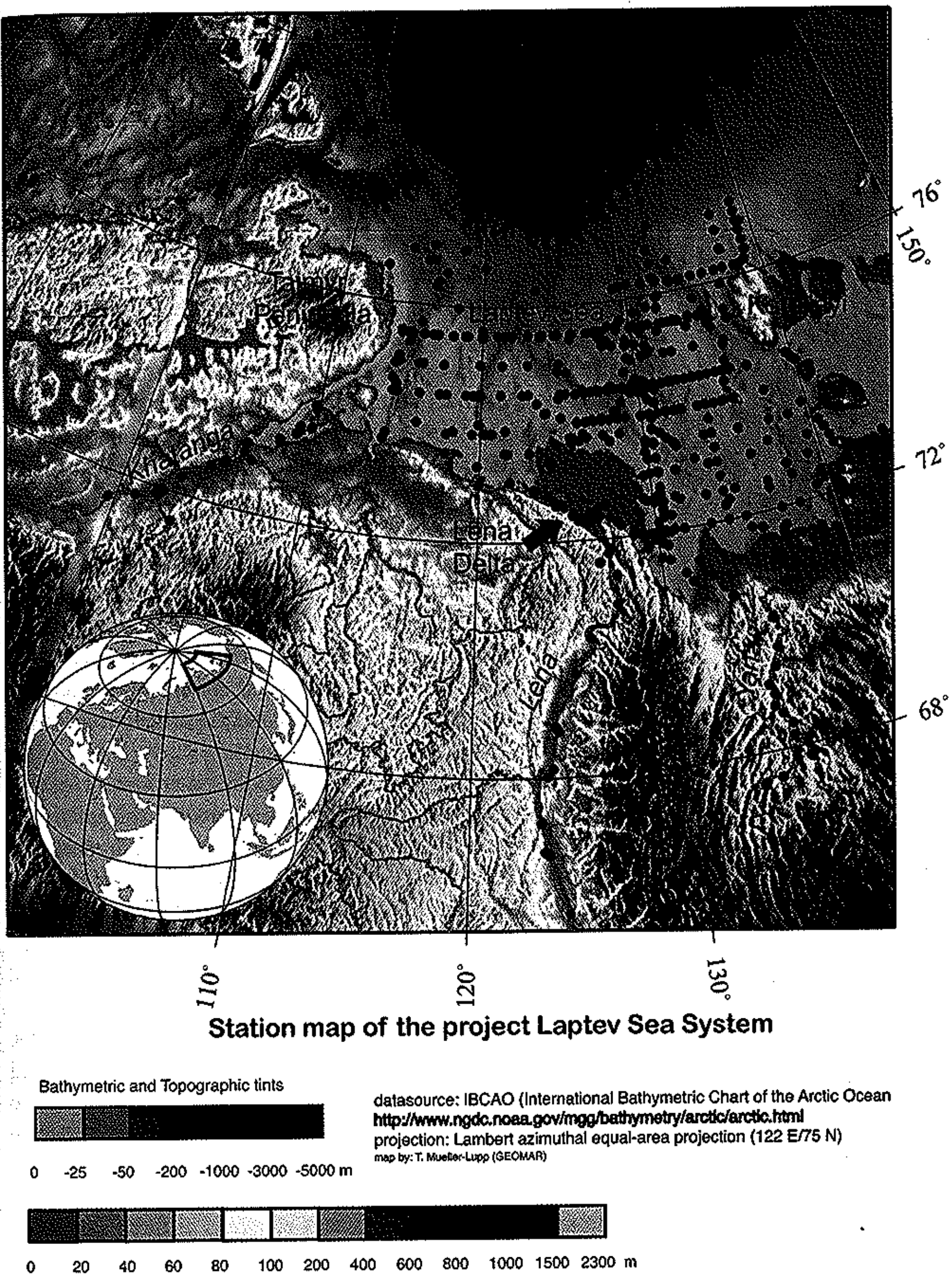

Figure 1. Station map of the Laptev Sea System project in the Siberian Arctic.

Current (Viscosi-Shirley et al., 2003) and a long-range transport of sediments by sea ice (Wegner et al., 2005).

Evidence has accumulated over the past two decades that demonstrates that the entrainment of sediments into sea ice is a common phenomenon on the shallow Siberian shelves (Reimnitz et al., 1993; Eicken et al., 1997). It has been shown that even under calm weather conditions, the freezeup during October seems to be an important time period for sediment transport by sea ice from the shallow shelf areas of the Laptev Sea toward the Arctic basin (Lindemann et al., 1999). By combining field measurements, remote sensing, and numerical modeling, Eicken et al. (2000) were able to identify the shallow shelf near the New Siberian Islands as a key site for ice entrainment and a basinwide dispersal of sediments by sea ice. They documented a total ice-bound sediment export of 18.5 million tons for one entrainment event in 1994–1995. Another possible mechanism for the formation of sediment-laden sea ice is the resuspension of fine-grained bottom sediments in the polynya area and the subsequent entrainment of these sediments into newly formed ice (Pfirman et al., 1990; Nürnberg et al., 1994; Rigor and Colony, 1997; Eidsvik, 2000). Recent studies have shown that the Laptev Sea is one of the major source areas for sea ice in the Transpolar Drift System (Rigor and Colony, 1997; Alexandrov et al., 2000) and a center of sediment entrainment by ice (Pfirman et al., 1990; Darby, 2003). However,

Figure 2. The Laptev Sea flaw polynya (roughly 1 km wide) north of the Lena Delta in April 1999.

the general idea that suspension freezing during sea-ice formation in the winter polynya is the dominant sediment entrainment process in the Laptev Sea is in conflict with the field observations of Dmitrenko et al. (2001a), who have shown that even during winter, the strong density stratification of the water column, especially in the eastern Laptev Sea, prevents convection from penetrating down to the seafloor. Thus, resuspension of fine-grained bottom sediments accompanied by suspension freezing beneath the polynya is unlikely to occur in the eastern Laptev Sea. This supports the hypothesis that the fall freezeup (October) might also be an important and as yet underestimated period for the formation and export of sediment-laden sea ice. The incorporation of sediments into newly formed ice is not only important for the transport of sediments, Arctic sea ice also plays a crucial role for the large-scale transport and cycling of trace elements (Rigor and Colony, 1997) and radionuclides (Meese et al., 1997). Within the framework of an interdisciplinary field study of freezeup processes in the Laptev Sea, Hölemann et al. (1999) observed that the concentrations of dissolved Mn, Fe, Zn, Cd, and Pb in newly formed sediment-laden ice were up to 40 times higher than the dissolved concentrations that were measured in seawater and fresh water in the region of ice formation. The elevated concentrations of dissolved trace metals in the newly formed ice were probably caused by a remobilization of trace elements from the ice-rafted sediment particles. This mechanism can play an important role for the dispersal of trace elements through the Arctic environment. As an example, Winter et al. (1997) have shown that the primary source of rare earth elements and Pb for the dissolved reservoir in Arctic seawater is not river water, but ice-rafted debris, which through dissolution or exchange processes is an important source of trace elements for seawater in ice-covered oceans. This is supported by Measures (1999), who observed that Arctic Ocean surface waters with the highest reactive Al and reactive Fe values appear to coincide in many cases with the presence of high concentrations of ice-rafted sediments. The author presumed that the seasonal melting of ice containing rafted sediments added particulate and dissolved trace metals to Arctic surface waters.

Another key element of the modern environment of the Laptev Sea and the transport processes between this marginal sea and the Arctic basin is the spring freshet of the Lena River (Pivovarov et al., 1999; Hölemann et al., 2005). During the high discharge period in May and June, ~30% of the annual runoff and 60% of suspended sediments are discharged onto the still-ice-covered shelf. In the course of the freshet, riverine dissolved and particulate substances are transported in a freshwater layer beneath the fast ice of the Laptev Sea (Pivovarov et al., 1999). These river-to-sea transport processes show strong interannual variations because the dynamics of the spring flood and the extension of the fast ice in spring are controlled by short-term atmospheric processes.

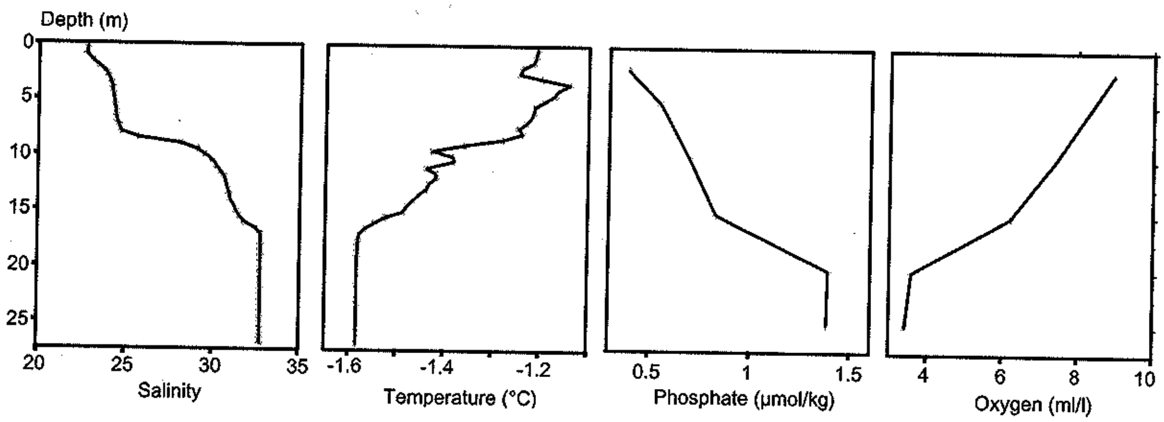

Figure 3. The two-layer system of the water column in the polynya north of the Lena Delta in spring 1999. The strong stratification limits the exchange of oxygen and phosphate between the bottom and surface waters. Remineralization of organic matter near/at the seafloor results in a depletion of oxygen and an enrichment in phosphate.

River runoff has a pronounced influence on the distribution, activity, and community structure of the phytoplankton and zooplankton in the whole shelf region (Abramova, 2000; Tuschling, 2000; Bauch and Polyakova, 2003; Pivovarov et al., 2004). Triggered by the Lena River discharge, this influence varies during the seasons and shows the highest impact on the ecosystem in spring and early summer, when outflow rates are high. The strong seasonal and interannual variability not only affects the phytoplankton distribution (Abramova and Tuschling, 2005) but also leaves a mark on the spatial distribution of benthic communities (Stepanova et al., 2003) as well as their geochemical signature (Müller-Lupp et al., 2003; Müller-Lupp and Bauch, 2005).

Radiocarbon-dated gravity cores up to 9 m in length have been recovered from the Laptev Sea shelf. Their chronologies provide a detailed reconstruction of the Laptev Sea inundation history since early Holocene times (Bauch et al., 2001). Paleosalinity reconstructions based on diatoms and benthic foraminiferal $\delta^{18}O$ from these cores indicate that Holocene river input into the eastern Laptev Sea has been governed by dominantly cyclical behavior. While the diatom record primarily reflects the southward retreat of the coastline during the postglacial transgression between 9000 and 7000 yr ago, as well as variable sea-ice conditions during the later Holocene, the foraminiferal data indicate changes in bottom-water salinity with a recurrence interval of 1000 yr over the past 8500 yr (Bauch and Polyakova, 2003). Although global transgression in the Laptev Sea came to an end ~5000 yr ago, modern environment conditions were established only during the later phase of the Holocene transgression, which reached the southern region of the Laptev Sea between 7000 and 5000 yr ago.

In order to study Arctic climate change on time scales beyond the Holocene, a drilling campaign was conducted on the outer Laptev Sea shelf in 2000 (Kassens et al., 2001). Radiocarbon ages and micropaleontological data show a Holocene sediment package that is ~10 m thick. The cores recovered during the drilling campaign from below this depth level reveal various types of ice-bearing sediments (Fig. 4) that contain a rich terrestrial plant flora as well as remains of beetle faunas, implying a late glacial age in accordance with radiocarbon data (Kassens et al., 2001). However, there is evidence that the stability of the permafrost is presently threatened due to global warming. Such a change would be of major climatic significance, considering the potential release of gas hydrates now trapped in the frozen ground.

The Laptev Sea shelf represents the southern rim of the Eurasian Arctic Ocean basin in northern Russian (Fig. 5), where there is a currently active spreading axis, the Gakkel Ridge, which is the divergent boundary between the North American and the Eurasian plates in the Arctic. Gakkel Ridge, the world's slowest spreading mid-ocean ridge (Jokat et al., 2003; Michael et al., 2003), approaches the Laptev Sea shelf at a right angle and terminates against a steep continental slope with a complex tectonic structure. Multichannel seismic-reflection studies, carried out over the Laptev Sea shelf during the past two decades, have revealed a vast rift system with a very slow spreading rate of 0.3 cm/yr (Ivanova et al., 1990; Drachev et al., 1999; Drachev, 2000; Roeser et al., 1995; Hinz et al., 1998; Franke et al., 2000). Its origin is related to the opening of the Eurasian Basin and the evolution of the Gakkel spreading center. This process started ~58 million yr ago and has remained active through the whole Cenozoic (Karasik, 1974; Vogt et al., 1979; Savostin et al., 1984). The Laptev Sea shelf is one of a few places worldwide where a currently active mid-ocean-ridge system approaches a continental margin. The high tectonic activity of this region is resulting in fault formation and earthquakes along the major structural elements. Considering that ice-bonded and ice-bearing sediments with thicknesses of several hundred meters have been verified by seismic records, the Laptev Sea shelf is a very sensitive area in terms of stability and global climate changes. Pockmark features, which have diameters that vary between 100 and 600 m and are presumably caused by expulsion of fluids and gases as discussed by Hinz et al. (1998), as well as open taliks as proposed by Romanovsky et al. (2004), are suggested to be the first indicators of ongoing changes.

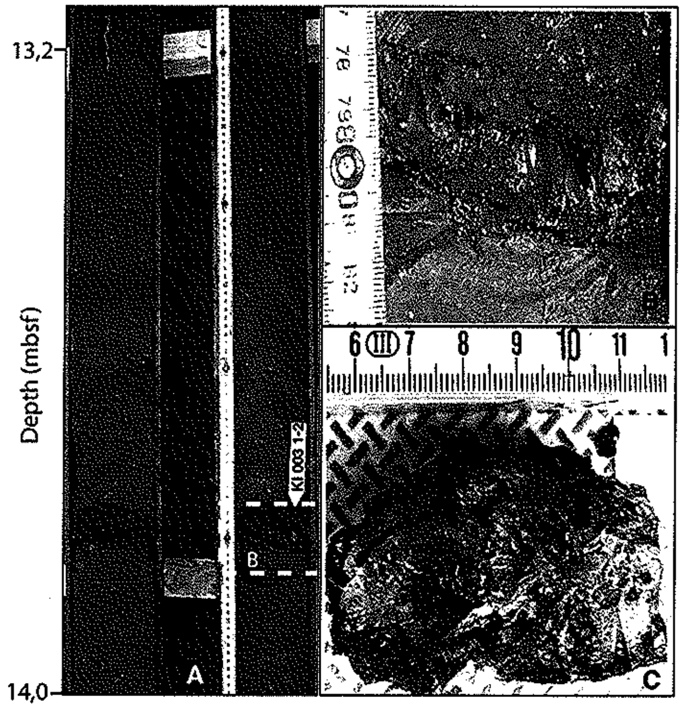

Figure 4. (A) Ice-bearing submarine permafrost in the eastern Laptev Sea at 33 m water depth (KI003–1-2; cored interval 13.13–14.00 m below seafloor [mbsf]). (B) Lens of segregated ice in fine-grained near-surface sediments, enlargement of Figure 4A. (C) Surface view of the ice lens.

CONCLUSIONS

The changing environment of the Arctic may also alter the aquatic biogeochemical cycles and thus the fluxes of materials like climate-relevant trace gases through the marine Arctic environment. Especially over the broad Siberian continental shelves, the balance between terrestrial and benthic inputs and marine production of organic carbon is strongly dependent on

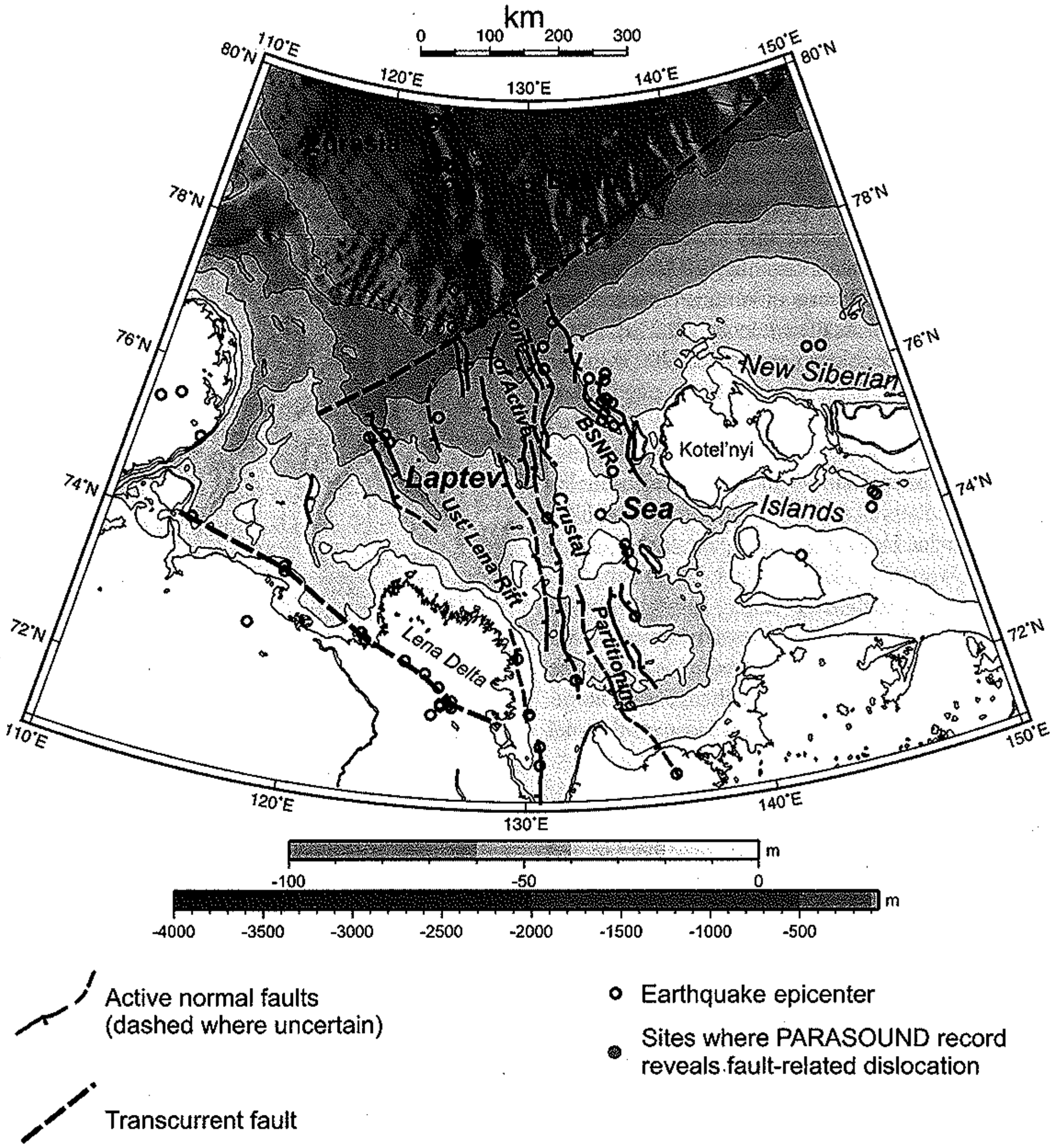

Figure 5. Main structural elements of the Laptev Sea shelf (after Drachev, 2000). BSNR—Bel'kov–Svyatoi Nos Rift.

seasonal changes in light levels, ice cover, and freshwater input. As a consequence, marine biogeochemical cycles may respond strongly to the ongoing climatic changes and amplified variations of abiotic factors.

Only a research strategy that combines satellite-based information with data from ocean observatories and the ability to conduct year-round measurements of key hydrographic, biological, and chemical parameters under extremely harsh environmental conditions can provide new insights into the recent changes of the Arctic environment and how they may alter the transfer of materials and energy through the Arctic geo-ecosystem. Key areas for these new and essential studies are the broad Eurasian Arctic shelf seas, like the Laptev Sea, which have a blanket of highly variable and dynamic sea-ice cover and seafloors underlain by submarine permafrost, with its unique specialized microbial communities that control the turnover and benthic fluxes of carbon and other climate-relevant elements.

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