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Tectonics of the Laptev Sea Region in North-Eastern Siberia

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THEME 3: Plate Boundary Problems in the Laptev Sea Area

Summary: Seismic reconnaissance lines were surveyed on the wide, virtually unexplored shelf of the Laptev Sea between the New Siberian Islands and the Taimyr Peninsula. The most prominent rift basin is the Ust' Lena rift with a minimum width of 300 km E–W at latitude 75 °N. It is bounded to the Laptev horst in the east by a westerly dipping major listric fault, the MV Lazarev fault. The 100 to 150 km wide Laptev horst is subdivided into three parts by minor rift basins. Another rift graben, the Anisin basin, is separated from the Kotel'nyi horst by a deep fault, the IB Kapitan Dranitsin fault. The onset of the rift is inferred to have been in the Late Cretaceous and the main extension took place from the Paleocene to the Oligocene.

INTRODUCTION

The eastern Arctic Ocean is unique among the world's oceans due to its wide continental shelves, and especially to its plate tectonic setting. Today, the total opening rate at the boundary between the North American and Eurasia plates varies between 1.3 cm/a and 0.7 cm/a over a distance of 300 km from seafloor spreading in the Eurasia Basin to extension of continental lithosphere on the shallow Laptev Shelf. The plate boundary is marked by earthquake epicenters which show a small scattering around the Arctic mid-oceanic ridge and continue on the shelf as an about 500 km wide zone. In 1997 the Federal Institute for Geosciences and Natural Resources (BGR), Hanover, in cooperation with Sevmorneftegeofizika (SMNG), Murmansk, carried out their third geophysical research expedition on the shelves of the Laptev and East Siberian Seas to better understand the variations within the lithosphere during the rifting process and the tectonic and structural evolution of the crust undergoing extension. Most multi-channel seismic (MCS) data from the Laptev Sea area of the 1997 BGR expedition and additional lines from the 1994 BGR expedition were the data base for this study and the revised structural map shown in Figure 1.

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SEISMIC DATA ACQUISITION

The energy for the about 4400 km of 120-channel high quality MCS data was generated by an airgun array consisting of four linear sub-arrays with 32 airguns and a total volume of 4258 in^3 (69.8 L). A digital Syntrac 480/16 streamer 3880 m long was used with 240 channels and 16 model T-4 hydrophones per channel. The recording interval was 12 s with a sampling rate of 2 ms. The shots were triggered in time intervals of 17.7 s for the MCS lines and 30 s for several combined reflection/refraction lines (BGR97-01, -05, -07, -21), resulting in a shot spacing of 50 m and 75 m, respectively. The data were depth migrated down to 25 km with adopted interval velocities.

MAIN SEDIMENT SEQUENCES

Three major regional unconformities, labeled LS1 (Laptev Sea 1), LS2 and LS3, were identified in the seismic data and mapped.

Unconformity LS1 (Fig. 7), the most prominent and extensive horizon, was well defined on all the profiles (except in the western part of the Ust' Lena rift). The low-frequency pattern and the absence of regular reflectivity directly beneath the horizon led to its interpretation as the acoustic basement. The horizon is a distinct erosional unconformity, forming a peneplain of several structural highs in the Laptev Sea.

LS2 is recognizable as a distinct unconformity in the basin fill of the major rift basins of the Laptev Sea. It is absent on the highest horsts. The seismic units between LS1 and LS2 consist of a moderate to low-reflectivity sequence overlain by a highly reflective unit. The combined thickness of these units increases from about 100 m at the edges of the structural highs to about 10 km in the main rift basins.

Unconformity LS3 is a distinct depositional unconformity in both the western and eastern parts of the Laptev Sea. It forms the top of a pronounced sequence characterized by sub-parallel reflectors. The thickness of the unit between LS2 and LS3 is less variable, ranging between 1 and 4 km. According to the seismic data, unconformity LS3 marks a drastic change in the depositional regime. On the few lines on the outermost shelf and continental slope, unconformity LS3 forms the base of a series of prograding and aggrading sequences.

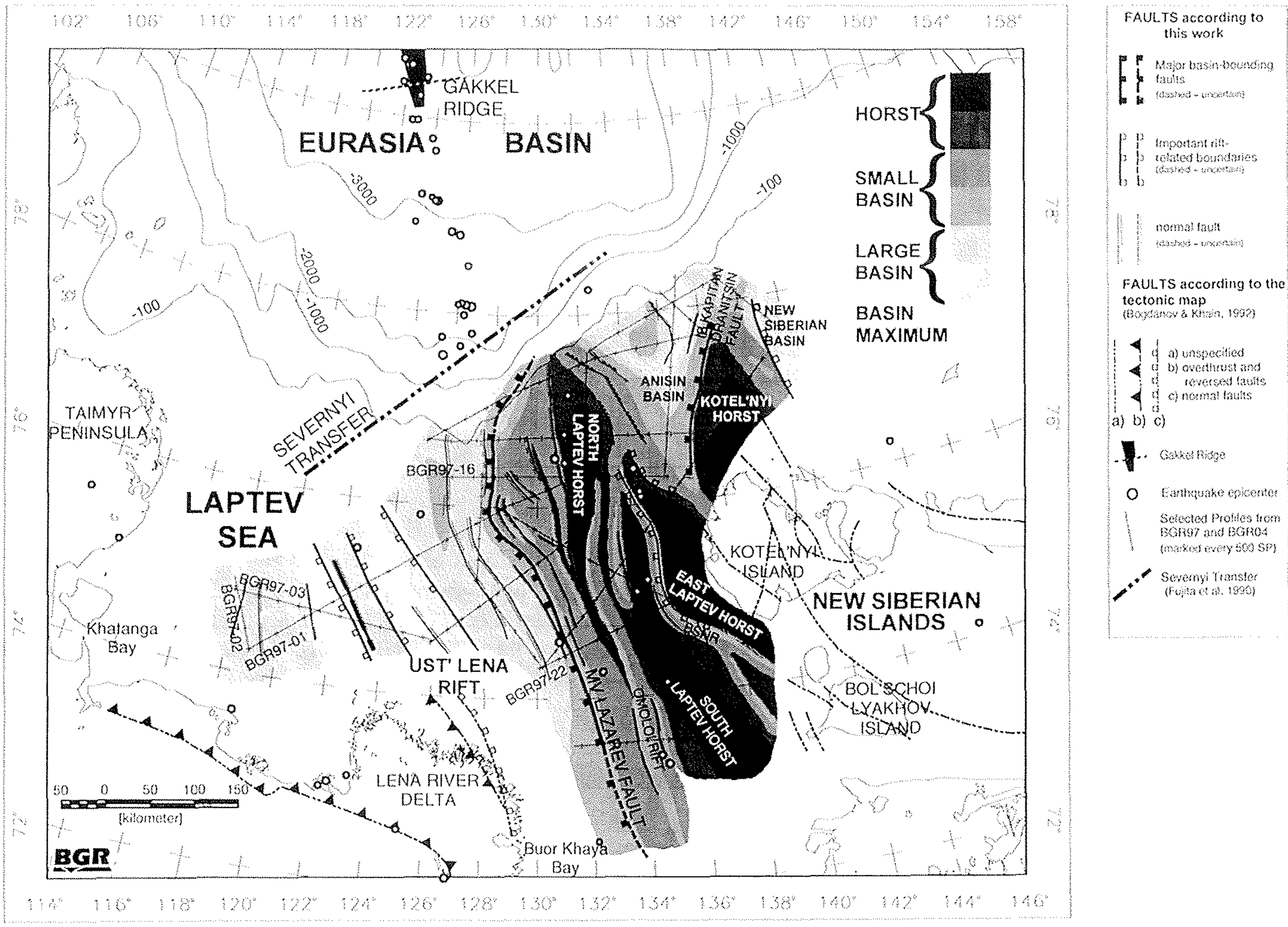


Fig. 1: Map showing the major structural elements of the Laptev Shelf. The seismic lines are indicated. Crosses mark every 500th shotpoint

An assumed permafrost zone, about 300 to 400 m thick (0.4-0.6 s twt) and locally even more, often masks an additional unconformity of inferred Pleistocene age, which is locally present in our seismic records.

THE MAIN STRUCTURAL ELEMENTS

The 343-km-long profile BGR97-01 (for location see Fig. 1) traverses from the western part of the Laptev horst through the Ust' Lena rift (Fig. 2). The major west-dipping MV Lazarev fault (shotpoint 220) offsets horizon LS1 vertically about 2 km. In the western part of the profile this horizon was not distinct and uncertainties were caused by highly reflective crust beneath LS1. Therefore, we assume an error of 1-2 s twt (2-5 km) for the position of marker horizon LS1 on this profile. In contrast, horizon LS1 is more distinct on profile BGR97-03 and correlation in the intersection of the profiles leads to an acceptable position of LS1 for profile BGR97-01. In the eastern part of profile BGR97-01, a seismically transparent zone is present beneath horizon LS1, which indicates a strongly deformed and disrupted basement of Mesozoic and/or Paleozoic sediments or igneous bedrock. In the depth range from 10-15 km, a high reflectivity band is visible which thins with decreasing distance from the rift basin (BGR97-01, shotpoints 1-1300). This is in contrast with the situation between shotpoints 1700 and 2900 on line BGR97-01, where a strong low-frequency reflection pattern is present directly beneath horizon LS1.

From the MV Lazarev fault to the west, the sedimentary fill increases continuously, associated with a series of synthetic and antithetic faults up to shotpoint 2270 (Fig. 2). To the west of shotpoint 2270, there is a graben with an maximum fill of 13 km (Figs. 2 and 5b). In satellite gravity data (LAXON & MCADOO 1994), which are as a first approximation inversely proportional to the depth to the basement, a NNW-SSE-trending gravity low is present. The deep graben is bounded on the west by a 4-km-wide block; the west end of this graben shows a complex pattern of listric faults, mostly dipping east. We suggest that this represents a hanging wall collapse above a listric fault (e.g., NAYLOR et al. 1994, ELLIS & MCCLAY 1988) either in connection with sediment transport by the Lena River or to a rift-related basement fault. The assumption of some sort of wrench faulting is less likely because on profile BGR97-03, about 30 km away, a similar block at shotpoint 3300 is separated from the graben by a clearly identified listric fault. The sedimentary cover is thinner there, about 9 km.

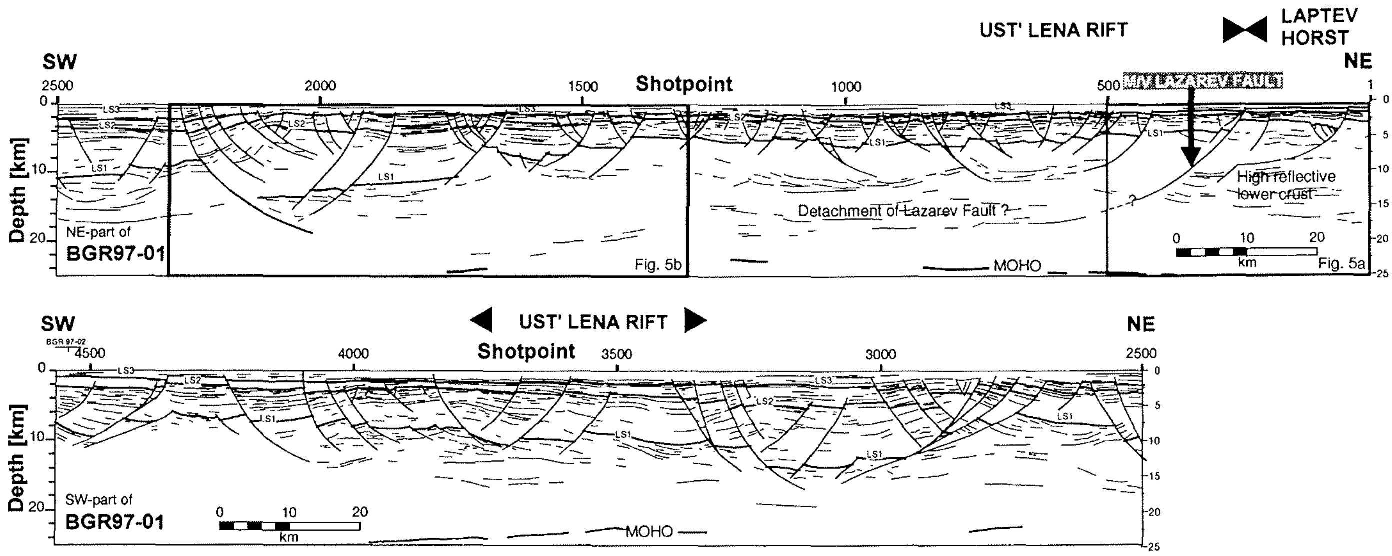


Fig. 2: Interpretation of profile BGR97-01

Farther west on profile BGR97-01, LS1 is found at around 7 to 10 km depth. The Trofimov uplift postulated by Bogdanov & Khain (1989), Alekseev et al. (1992), Drachev et al. (1995), among others, is indistinct or does not exist. At shotpoint 2700 on line BGR97-01 (Fig. 2), another westerly dipping listric fault forms the eastern boundary of another depression in the Ust' Lena rift, also containing fill up to 13 km thick. Along mainly antithetic listric faults the depth of horizon LS1 decreases in steps up to shotpoint 4300, where the horizon is at a depth of 6 km. At the western end of the profile, the sedimentary cover increases again along several westerly dipping listric faults. The 86-km-long profile BGR97-02, connecting the western ends of BGR97-01 and BGR97-03, shows an average sedimentary thickness of 8 km.

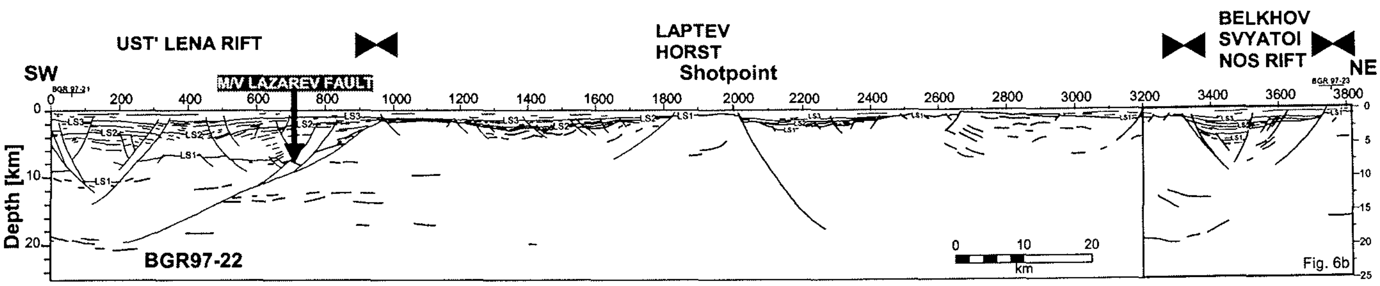


Fig. 3: Interpretation of profile BGR97-22

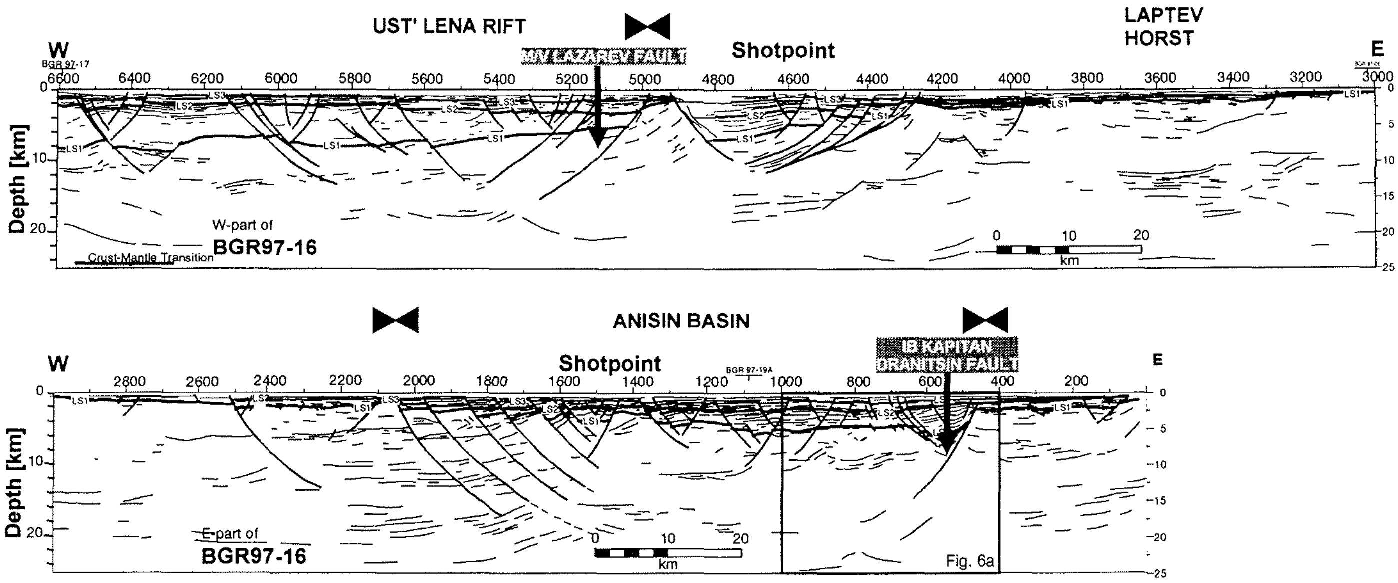
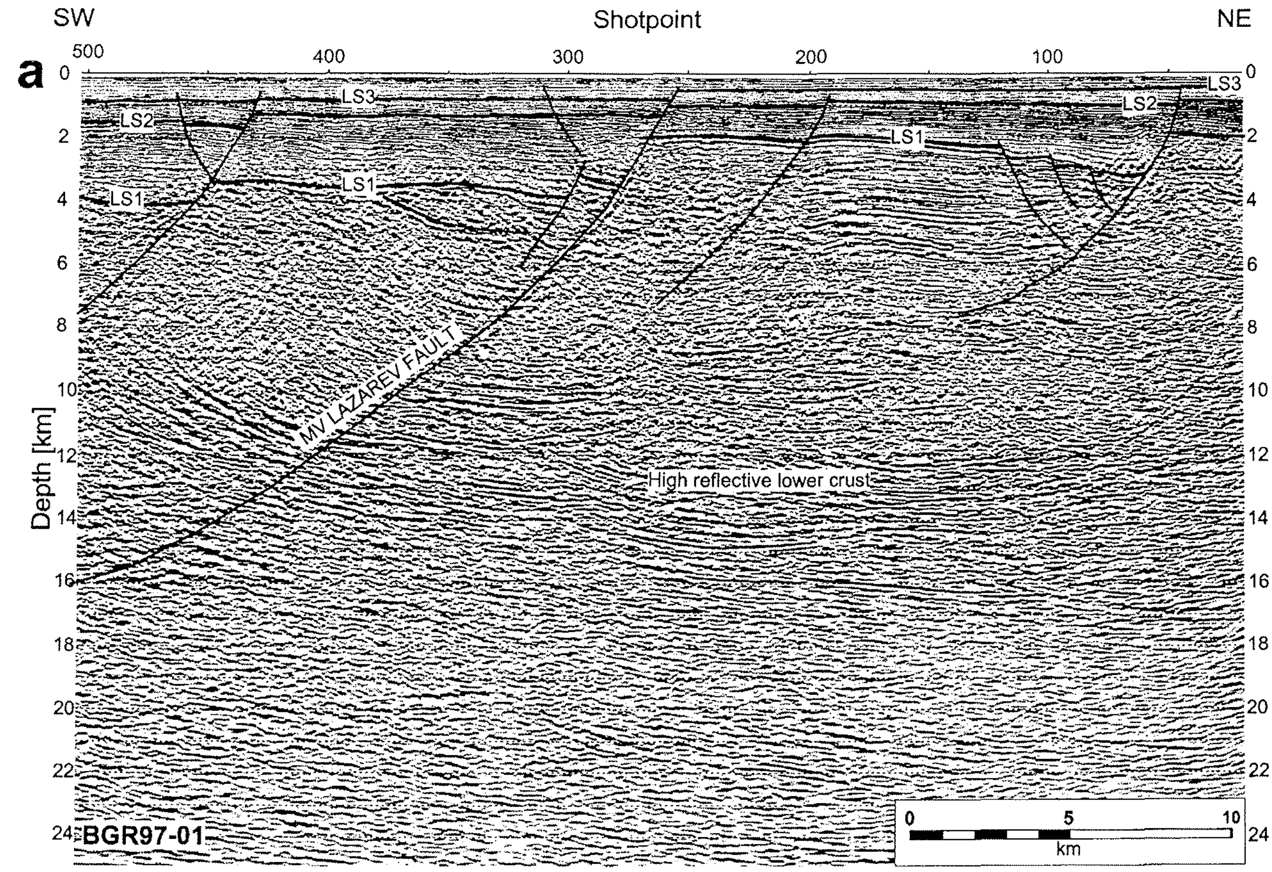


Fig. 4: Interpretation of profile BGR97-16



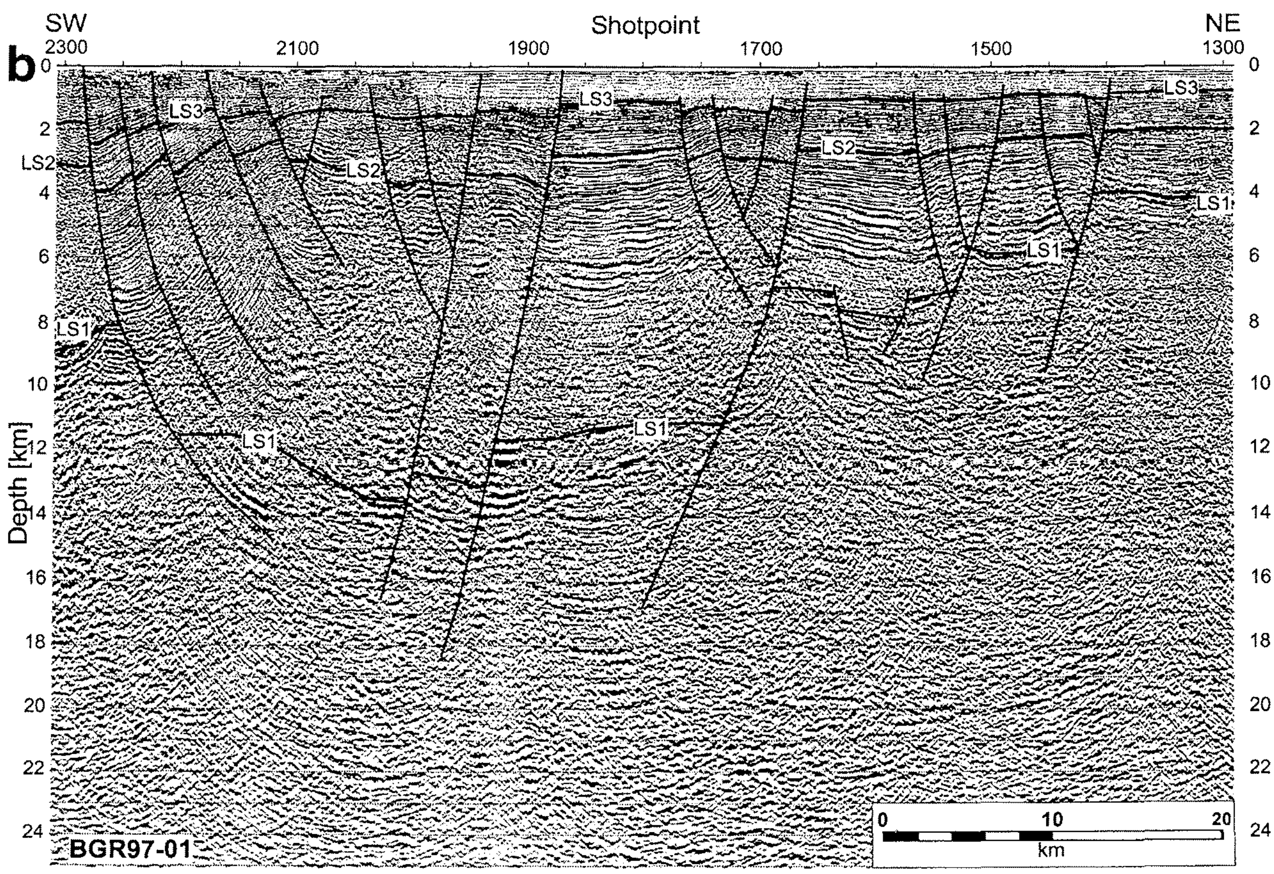


Fig. 5: Interpreted seismic sections showing (a) the MV Lazarev fault and (b) the increase of the sedimentary fill. The line segments illustrated are for profile BGR97-01 shown in Fig. 2.

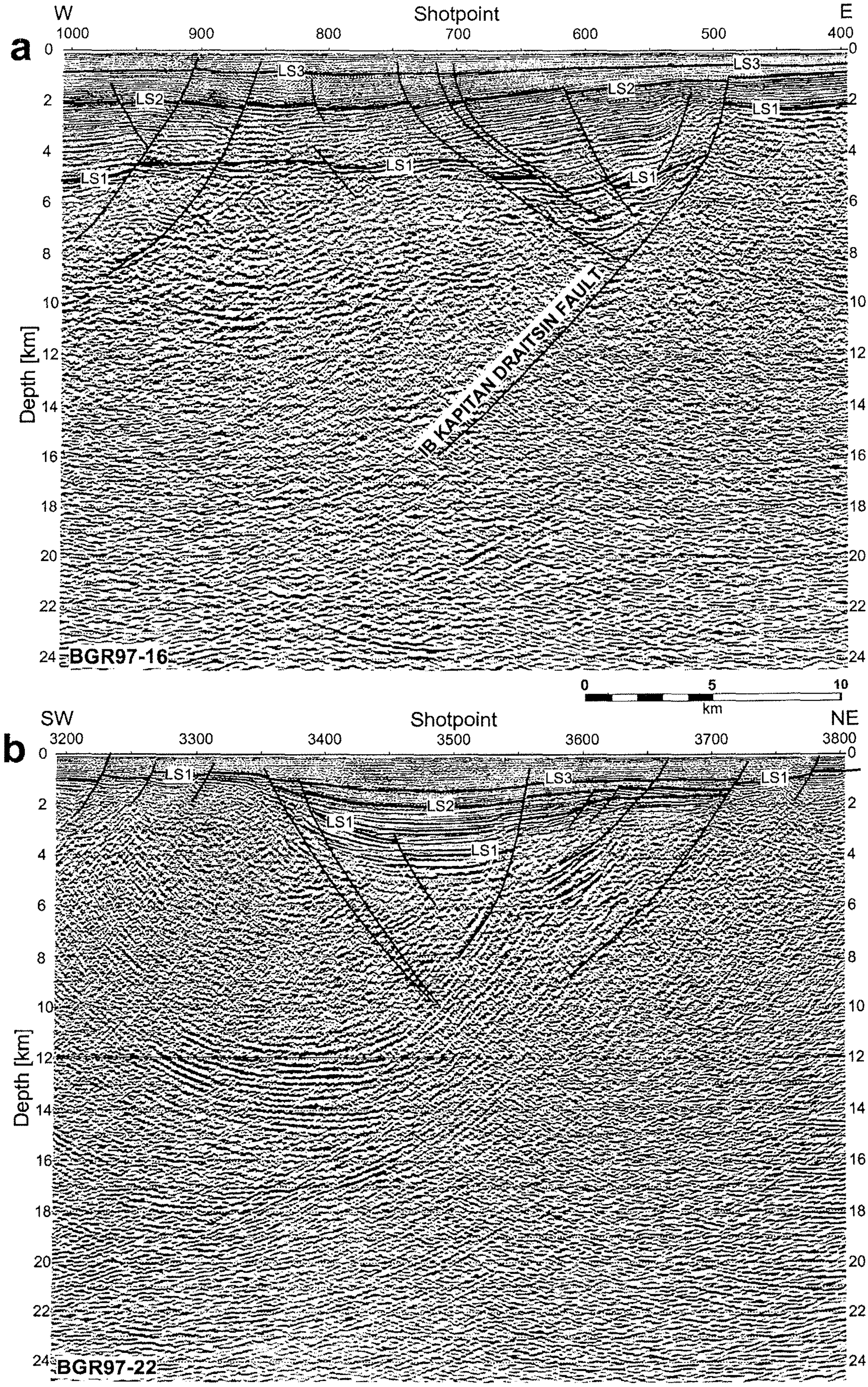


Fig. 6: Interpreted seismic sections showing (a) the IB Kapitan Dranitsin fault and (b) the Belkov Svyatoi Nos rift. The line segments illustrated are from profiles BGR97-16 and BGR97-22 shown in Figures 4 and 3.

The Laptev horst (East Laptev uplift of ALEKSEEV et al. 1992) occupies the entire eastern part of the Laptev Sea. Several small rift basins subdivide the horst into three units: North Laptev horst, South Laptev horst (Stolbovoi horst according to DRACHEV et al. 1998) and the East Laptev horst (Fig. 1). The East Laptev horst is possibly part of the Kotel'nyi horst, which is located north of Kotel'nyi Island. The rift basins in the southern and central horst areas, the Omoloi rift (FUJITA et al. 1990, ALEKSEEV et al. 1992) and the Belkhov Svyatoi Nos rift (BSNR) (Fig. 6b) (FUJITA et al. 1990, ALEKSEEV 1992, DRACHEV et al. 1998) are up to 3 and 5 km deep, respectively, and about 25 km wide. These depressions are clearly identified as half grabens. A prominent rift graben, the Anisin basin, is located between the Kotel'nyi horst and the North Laptev horst (Fig. 1). The main axis of the Anisin basin trends N-S and a less pronounced axis NW-SE. The southernmost part of the basin is found between shotpoint 480 and 2080 on profile BGR97-16 (Fig. 4, lower panel). Here, the rift basin boundaries are very distinct. Going further north along the western side of the graben, the acoustic basement dips gently towards the graben axis, whereas the eastern flank is formed by a prominent westerly dipping listric fault (IB Kapitan Dranitsin fault) (Fig. 4, lower panel and Fig. 6a) separating the basin from the Kotel'nyi horst. The New Siberian basin is in the easternmost part of the investigated area (Fig. 1). It extends over a length of at least 300 km NW–SE with a width of 70 km (ROESER et al. 1995, ROESER & HOFFMANN 1997). On profile BGR97-07, the north-western boundary of the New Siberian basin is formed by an easterly dipping normal fault at shotpoint 820.

The Belkov Svyatoi Nos rift (BSNR) (Figs. 3 and 6b) is a N-S-trending graben up to 5 km deep and about 25 km wide along the Eastern Laptev horst. On profile BGR97-22, the BSNR extends between shotpoints 3320 and 3720 with the maximum depth in the west (Fig. 3). There are several minor grabens in the Laptev horst area, but the sediment thickness never exceeds 3 km and so it was difficult to correlate the grabens from one seismic line to the next. In the western part of the Laptev horst, horizon LS1 is displaced downwards with decreasing distance from the MV Lazarev fault by a series of minor faults and tilted blocks.

SEISMIC STRATIGRAPHY

Since offshore drill holes are absent in the Laptev Sea and adjacent areas, there is much uncertainty about the age and nature of seismic unconformities in the MCS data. However, we combined the seismic marker horizons LS1, LS2 and LS3 with results of geological studies and mapping on the New Siberian Islands (Fig. 7, e.g., KOS'KO et al. 1990) and in the onshore region of Buor Khaya Bay (e.g., DRACHEV et al. 1998). These unconformities were also correlated with major plate tectonic events, as well as with major paleoenvironmental changes observed in the northern oceans.

A specific time for the onset of rifting is difficult to define. For other continental margins in the North Atlantic, rifting prior to the breakup and initiation of seafloor spreading has been suggested (e.g., ELDHOLM et al. 1990, HINZ et al. 1993). In fact, the magmatic and volcanic events of Late Cretaceous age, known from Kotel'nyi Island and the De Long Islands (KOS'KO et al. 1990), were presumably initiated simultaneously with the opening of the Eurasia Basin. This resulted in uplift and subsequent erosion and weathering of the area.

The early rift-phase unconformity LS1 probably developed prior to the major Cenozoic crustal stretching episode. We assume a maximum age of 65 Ma and a minimum age of 56 Ma (see time scale in KENT & GRADSTEIN 1986). In this period of time, the separation of Greenland from Eurasia was completed (Paleocene, chron 27, CHALMERS et al. 1993), the opening of the Norwegian–Greenland Sea commenced during chron 24R (e.g., ELDHOLM et al. 1987), and transient volcanic activity initiated the

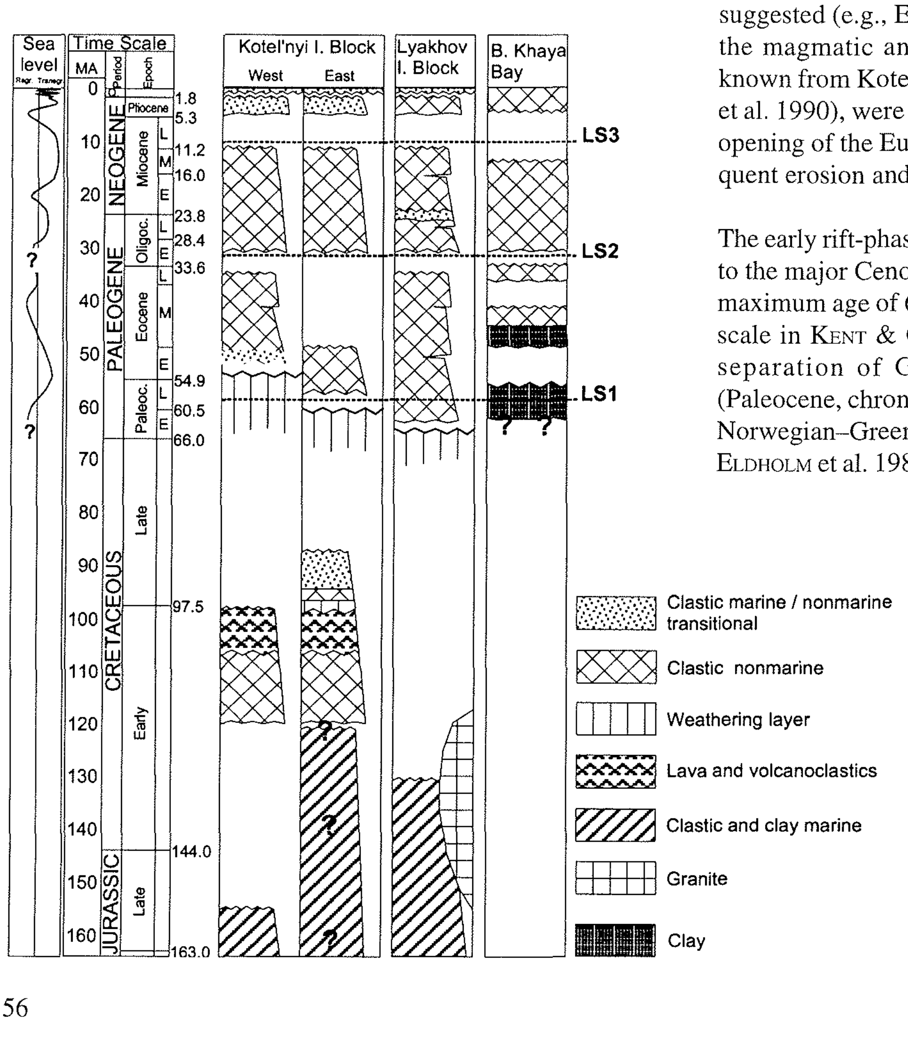


Fig. 7: Stratigraphic and lithologic events known from the Kotel'nyi Island and onshore around Buor Khaya Bay. The diagram was slightly modified from M. KOS'KO in HINZ et al. (1997), DRACHEV et al. (1998) and ALEKSEEV et al. (1992). The unconformities LS1, LS2 and LS3 are shown.

huge North Atlantic volcanic province (e.g., TALWANI & ELDHOLM 1977, LARSEN et al. 1988, HINZ et al. 1993).

For unconformity LS2, we infer an age of about 33 Ma because a significant reorientation of the relative plate motions occurred in the oceans when seafloor spreading ceased in the Labrador Sea and the separation of NE Greenland from Svalbard was initiated along a regional transform linking the Atlantic with the Eurasia Basin in the early Oligocene (e.g., CHALMERS et al. 1993, HINZ et al. 1993). This unconformity is well expressed in all the onshore sections (Fig. 7). The overlying Oligocene to Early Miocene sediments reflect the Oligocene regression (DRACHEV et al. 1998).

We infer an early Late Miocene age (9-10 Ma) for unconformity LS3. The Late Miocene and Pliocene tectonic deformation associated with the Indo-Asian collision modified the drainage pattern across the Siberian craton, causing large amounts of fresh water to flow into the Arctic. The relationship between fluvial discharge and sediment load suggests that there has been a large input of terrigenous sediment since the early Late Miocene (e.g., DRISCOLL 1995). This is attested by the Lena Delta, which covers an area of approximately 32,000 km^3 and the development of prograding and aggrading depositional sequences, including channel-levee complexes, along the margin and outer shelf. Moreover, volcanism has affected the area of the De Long Islands since the Late Miocene. Unconformity LS3 is well expressed in the onshore sections, at least in the Kotel'nyi block and the Lyakhov block (Fig. 7) as well as in the onshore area around Buor Khaya Bay, where it may be slightly older (DRACHEV et al. 1998).

CONCLUSIONS

Tectonic extension on the Laptev Shelf since the Late Cretaceous has resulted in a complex horst and graben system. The main structural elements include the Ust' Lena rift, the Laptev horst, the Anisin basin and the New Siberian basin (Fig. 1). The most prominent rift basin is the Ust' Lena rift, which is at least 300 km wide at latitude 75 °N. The Cenozoic sedimentary cover exceeds 3 km everywhere, increasing up to 13 km in the grabens. In the northern part of the shelf, the complex N-S-trending Anisin basin has a basin fill of up to 10 km thickness. A second basin with a thinner sedimentary fill trends NW-SE. In the northwestern part of the New Siberian basin, the graben fill is up to 9 km thick. The Laptev horst is locally subdivided by deep-reaching faults into several tilted blocks and there are several half grabens of smaller extent and thinner sediment fill than the main rift grabens described above. These narrow half grabens divide the Laptev horst into three parts: the North, the South and the East Laptev horst. A major, westerly dipping listric fault (MV Lazarev fault) bounds the Laptev horst from the Ust' Lena rift. Another prominent fault (IB Kapitan Dranitsin fault), also westerly dipping and listric, forms the boundary between the Anisin basin and the Kotel'nyi horst.

According to the seismostratigraphy, the main part of the Ust' Lena rift developed from Paleocene to Oligocene times. Horizons LS1 and LS2 show the main offsets with values of up to 5 km, whereas horizon LS3 was less affected by faulting. The thickness of the sedimentary sequence between LS1 and LS2 changes along the rift valley, while the deposits above LS2 show nearly constant values. Exceptions from this scenario are found in the two graben maximums in the central Ust' Lena rift, which also show an increase for the Miocene to Oligocene (LS1-LS2) sedimentary cover. These sediments were presumably deposited by the Lena River during the Oligocene regression, when the delta was probably located more seawards than today.

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