PERMAFROST - Seventh International Conference (Proceedings),
Yellowknife (Canada), Collection Nordicana No 55, 1998

SEISMIC EVIDENCE FOR THE DEPTH EXTENT OF PERMAFROST IN SHELF SEDIMENTS OF THE LAPTEV SEA, RUSSIAN ARCTIC?

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Abstract

Some 7000 km of deep seismic reflection data have been acquired by the BGR, Hannover, in cooperation with SMNG, Murmansk, on the eastern Laptev Sea shelf and on the East Siberian Sea shelf in 1993 and 1994. The new seismic data from the Laptev Sea shelf reveal a 300 m to 800 m thick seismic sequence beneath the sea floor, characterized by a distinct high-reflective and mostly sub-parallel pattern. This distinct sequence cross-cuts and masks real structural features, e.g., toplapping depositional units and anticlinal features at several localities. For this reason we infer that the distinct superficial seismic sequence images the permafrost layer.

Introduction

A large number of seismic reconnaissance data have been aquired by Russian institutions mainly in the western and southeastern Laptev Sea from 1986 through 1991 (Ivanova et al., 1990; Sekretov, 1993; Drachev et al., 1994; Drachev et al., 1995). These data and the results of our subsequent seismic cruises have demonstrated the presence of a complex system of horst and graben structures beneath the Laptev Sea shelf (Figure 1), comprising major Cenozoic rift basins. The sedimentary infill of the rift basins is variable and in excess of 6,000 to 7,000 m (e.g., Roeser et al., 1995).

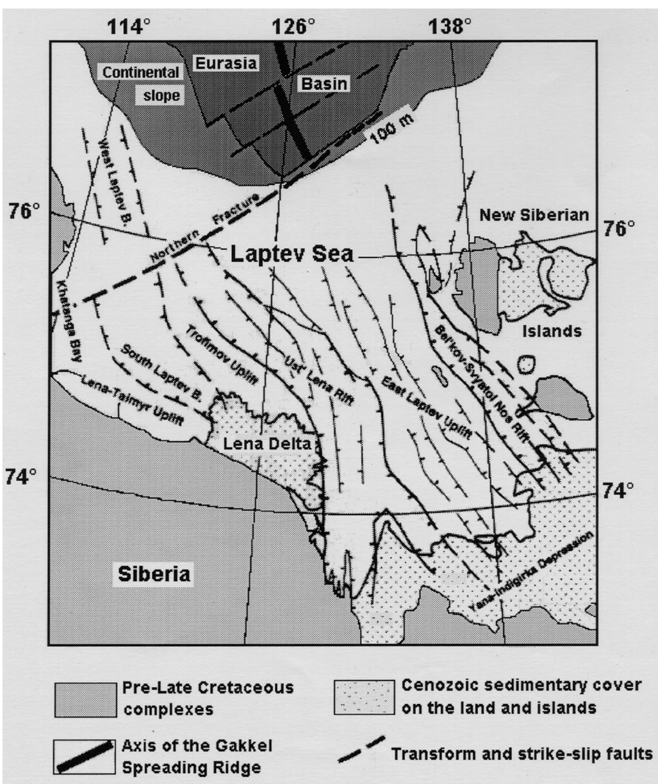

Figure 1. The tectonic structure of the crustal extension zone of the Laptev Sea (modified from Drachev et al., 1995). The continuation of the rift zone of the Eurasian Basin in the Arctic Ocean, towards the Siberian land mass has formed a series of horsts and grabens (shaded areas), which were seismically mapped by two Russian surveys in 1987 and 1989 and during two BGR-cruises in 1993 and 1994.

The Laptev Sea represents one of the few marine areas where extensive submarine permafrost has been found (Soloviev et al., 1987; Kassens et al., 1994). Similar conditions are known to exist in the Canadian Beaufort Sea (Morack et al., 1983; Taylor et al., 1993). The submarine permafrost zone of the Laptev Sea is believed to be largely isothermal today (see Delisle, 1998). By coincidence, our seismic surveys have revealed distinct seismic images of the near-surface section along most of our lines from the eastern and central Laptev Sea shelf. We infer that a permafrost zone causes the distinct seismic images discussed in this paper.

Seismic data acquisition and processing

The 2-D seismic surveys were carried out in cooperation with Sevmorneftegeofizika, Murmansk, using the Russian research vessels AKADEMIK LAZAREV and M/V AKADEMIK NEMCHINOV. For a majority of the lines, two tuned linear arrays were used, consisting of twenty airguns with a total volume of 27.8 liters and a operating pressure of 13 MPa at a operating depth of 6 m to 8 m.

The streamers used had an active length of 2,400 m and 3,000 m, consisting of 48 and 118 channels, respectively. The recording time was 12 seconds at a sampling rate of 4 ms with a LC filter set at 5 Hz and a HC filter set at 64 Hz.

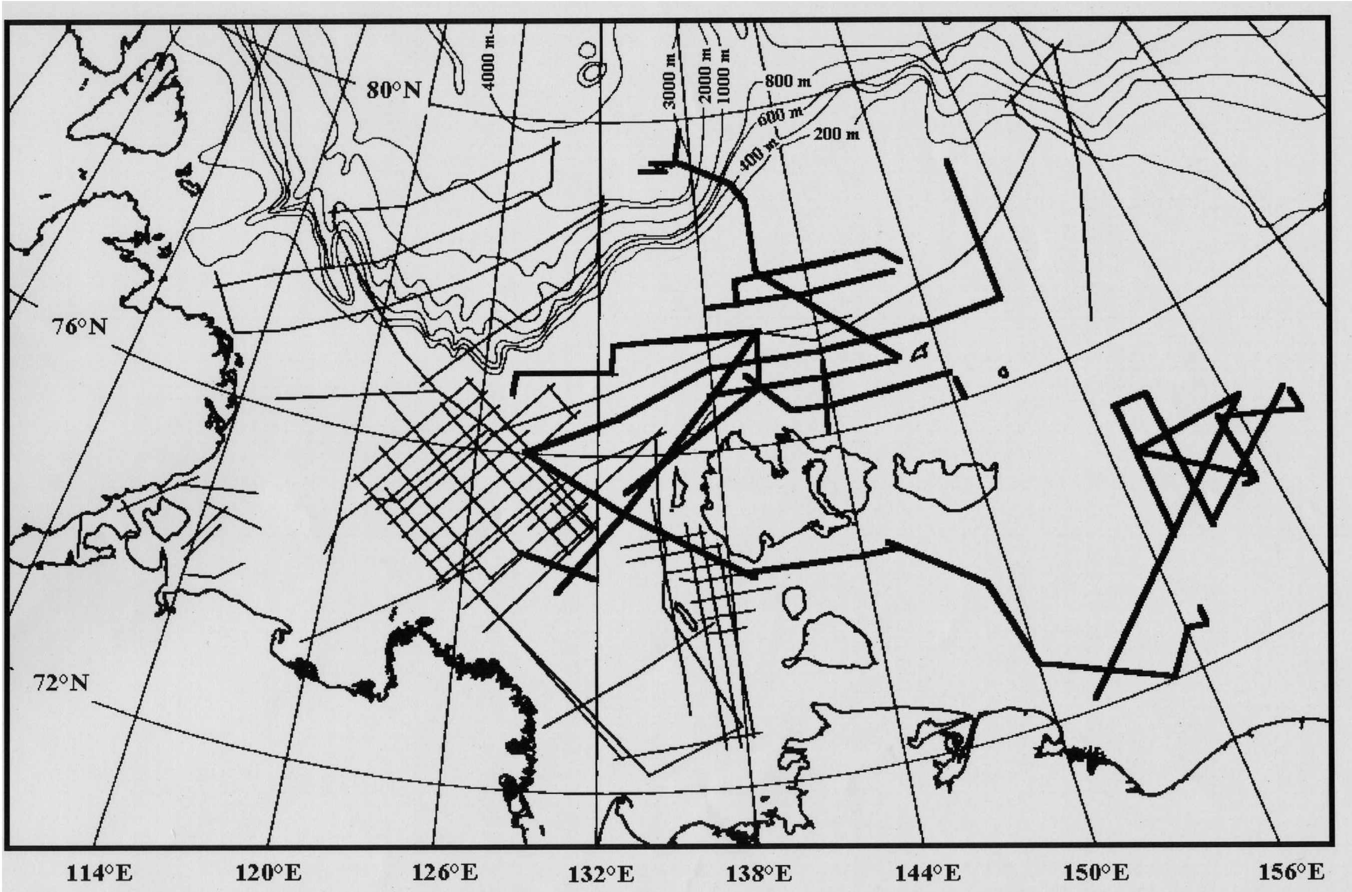

Figure 2. Available seismic lines in the Laptev Sea and adjacent areas. Thin lines: Russian lines; thick lines : BGR-lines.

During the cooperative BGR/SMNG expeditions in 1993 and 1994, seismic data were obtained along 7,150 km with a coverage of 2,400% and 3,000%, respectively (Figure 2). The data were processed using conventional processing routines with velocity analysis every 3 km. After true amplitude recovery, bandpass and F-K filtering and dynamic correction the CDP gathers were stacked. Predictive deconvolution before and after stack was applied.

Seismic image of the superficial section

A sequence characterized by a high-amplitude pattern of sub-parallel reflection elements underlies the sea bottom along most of our lines from the Laptev Sea shelf (Figure 3). This distinct sequence with thicknesses in excess of >0.7 s (TWT), i.e., about 800 m, crosscuts and even masks structural elements such as toplapping depositional units, anticlinal features (Figure 4) and faults at several localities. Analyses of refraction seismic arrivals of several individual shot gathers show seismic velocities in the range between 1,800 ms^{-1} and 2,000 ms^{-1} for the uppermost part of the reflective unit, and velocities in the range between 2,200 ms^{-1} and 4,000 ms^{-1} for its deeper levels. The results of our wide-angle reflection/refraction seismic studies using ocean bottom hydrophone systems confirm the presence of an approximately 300 m to 400 m thick high-velocity (2,500 - 3,000 ms^{-1}) near-seafloor layer above a depositional unit with velocities in the range of 2,100 - 2,300 m s^{-1}.

The distinct superficial seismic sequence comprises different colluvial and alluvial deposits of predomi-

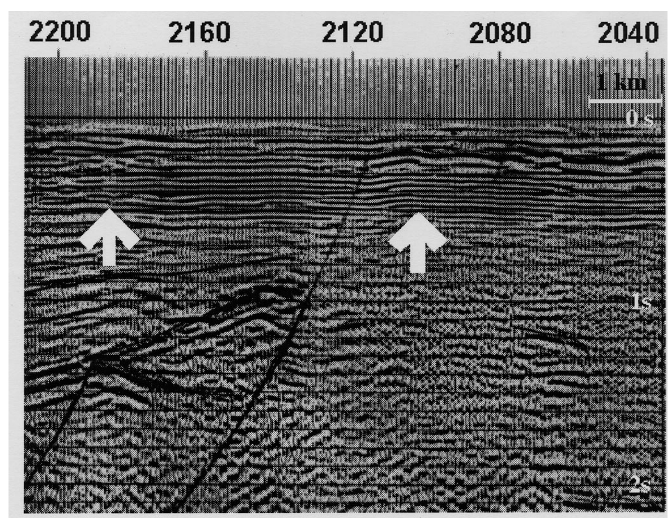

Figure 3. Example of the seismic image of the highly reflective sequence (0.0 - 0.6 s, twt) suspected to image the permafrost zone. White arrows point to the lower boundary of the sequence.

nantly Late Cenozoic age primarily derived from the discharge of the Lena River (e.g., Kim, 1994; Dehn and Kassens, 1995).

Figure 5 shows a reflection time contour map of the lower boundary of the reflective sequence interpreted by us to represent the permafrost. The greatest subsealevel depth of the sequence is about 0.7 s (twt) and it was observed to the northeast of Kotel´nyi Island and to the north of Novaya Sibir' Island. Two stripes with thicknesses of less than 0.4 s (twt) of the inferred permafrost zone intersect the area in NW-SE direction. Neither the one to the west nor the stripe to the east can be correlated with the Cenozoic structural regime observed so far. The thickness of the distinct superficial seismic unit decreases towards the outer shelf and apparently disappears when approaching the shelf edge. A superficial seismic unit having similar seismic characteristics as described above is not recognizable in our multichannel seismic data from the East Siberian Sea. This observation could have important implications regarding the reconstruction of water/ice coverage in the surveyed area during the last glacial cycle.

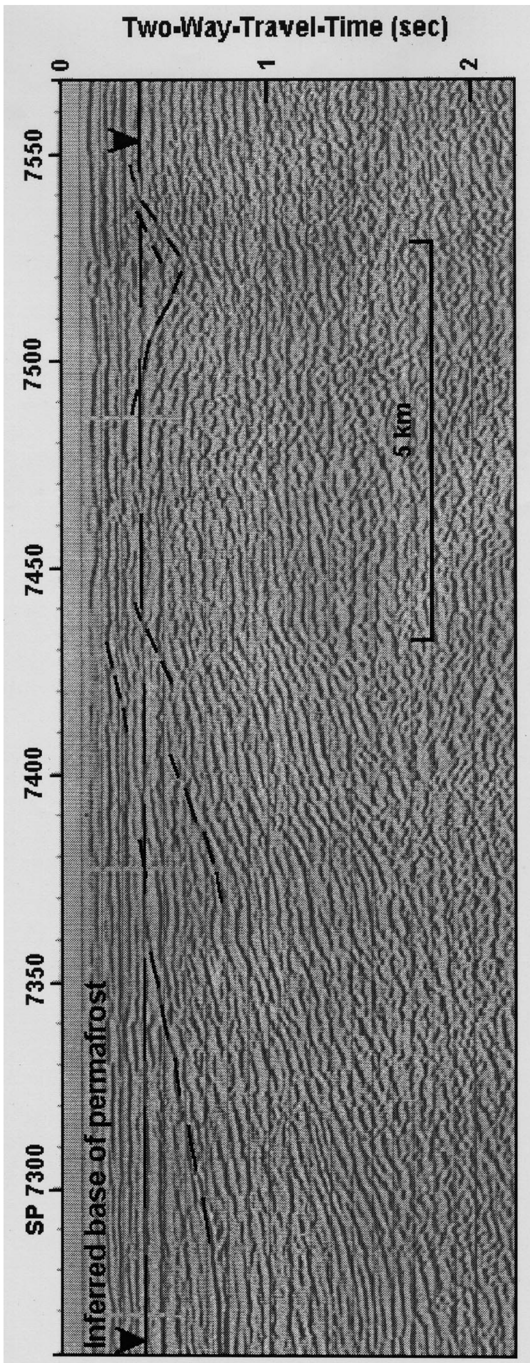

Figure 4. Example of the seismic image of the inferred permafrost zone masking updomed and folded Cenozoic sediments. Black arrows indicate the lower boundary of the inferred permafrost zone.

Discussion

Using a seismic velocity of 2.4 km s^{-1} (Zykov et al., 1988), the thickness of the strong reflective sequence ranges between about 300 m and 850 m based on the twt -values as shown in Figure 5. It appears that the greatest thickness of this sequence clusters around the West Siberian Islands, where the shallowest water depths occur. These areas should have been exposed to subaerial conditions over the longest time period in the past, offering the comparatively longest time period for the permafrost growth in the area.

The thickness of a permafrost layer depends on a number of factors, of which heat flow is only one. Equally important is the distribution of the thermal conductivities of the rock formations in the subsurface. Modelling indicates that high conductivity (i.e., 3.2 W m^{-1} K^{-1}) of crystalline rocks in combination with a low heat flow of continental type (i.e., 40 mW m^{-2}) results in a permafrost thickness of 1,120 m in an area with a mean annual temperature of -14°C (typical for the West Siberian Islands). Conversely, high heat flow (i.e., 60 mW m^{-2} in actively rifting realm) in combination with a low thermal conductivity of clayey sediments (i.e., 1.7 W m^{-1} K^{-1}) results in a permafrost thickness of only 400 m under the same climatic conditions. These examples show that a correlation of permafrost depth with tectonic structures cannot readily be expected in a tectonically complex area such as the Laptev Sea rift system.

In the case of the Laptev Sea an additional controlling factor of permafrost thickness is the periodicity of marine incursions over the shelf area during interglacial stages (see Delisle, 1998). The water depth of the Laptev Sea today is on the order of 10 m to 50 m. This region must have experienced subaerial conditions during the last cold stages, when the sea level was lower worldwide on the order of 115 m (Peltier and Tushingham, 1991). This episode provided a long time span for build-up of deep permafrost. The timing of the flooding of formerly subaerial land by sea water is a controlling

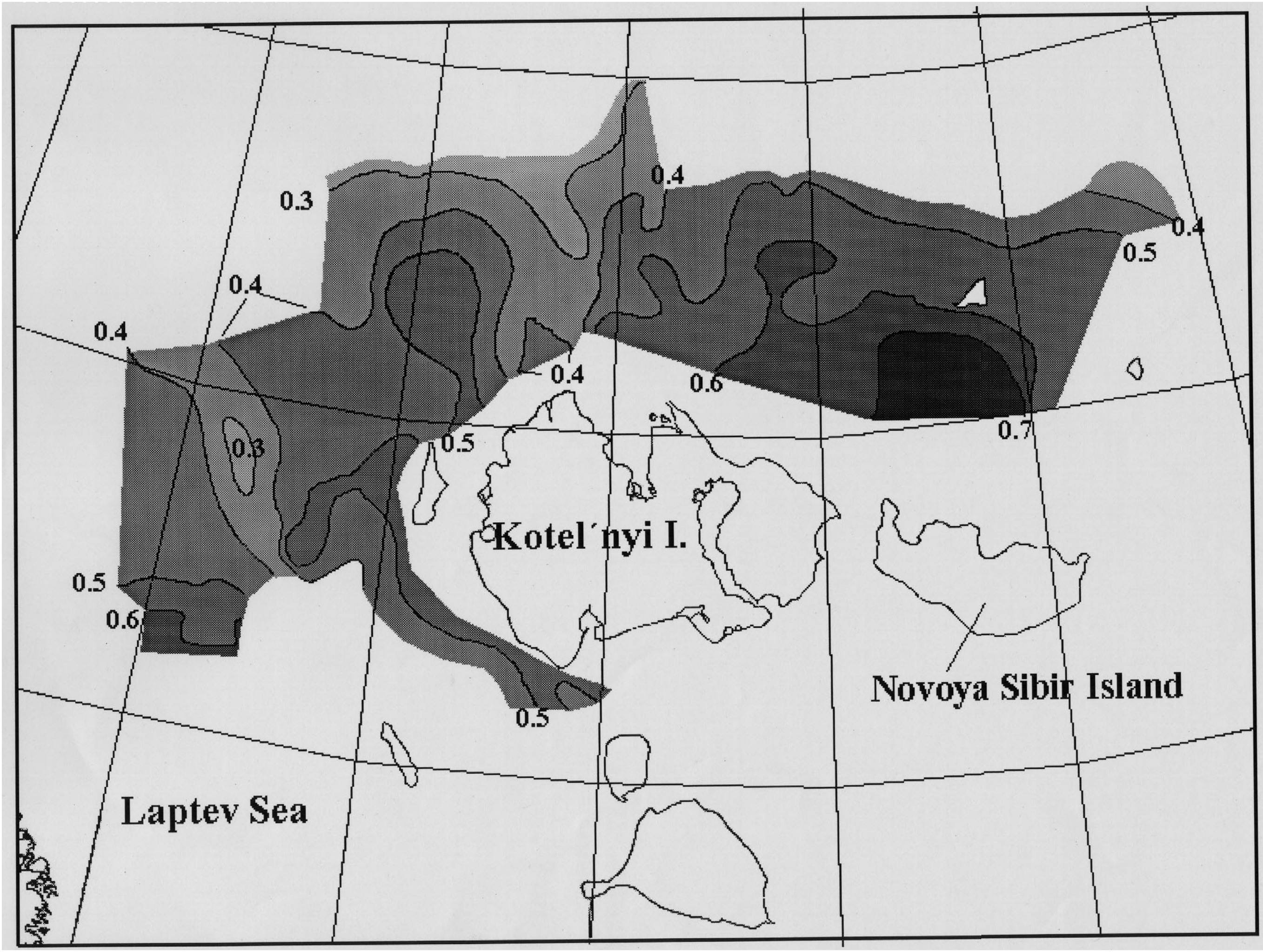

Figure 5. Mapped base of the strongly reflective sequence in s (twt) assumed to represent the base of the submarine permafrost.

factor for the reduction in permafrost thickness. The sea water acts as a substantial heat source on top of the permafrost zone, causing, with time, the permafrost layer to reach isothermal conditions near 0°C and melting to occur at its base under the influence of terrestrial heat flow from below. Some correlation of permafrost thickness with current water depth should therefore be expected. In a similar fashion, the thermal effect of rivers crossing the shelf during cold stages should have left some imprint on the permafrost thickness to be observed today (see Delisle, 1998).

With the above factors in mind, we present the following arguments, which in our opinion favours attributing the strongly reflective sequence with the current permafrost layer:

• There is no plausible correlation between the thickness of this sequence with likely depositional scenarios of the Late Cenozoic.

• A general trend of thinning of this sequence away from islands implies some correlation with water depth.

• The thickness of this sequence appears to be of the right order for modern submarine permafrost (see also Delisle, 1998).

• The sequence disappears at water depths of more than 100 m, where the permanent presence of sea water throughout the last glacial cycles prevented the formation of submarine permafrost.

Conclusions

1. A strong reflective sequence has been identified in the Laptev Sea south of 77°N, extending from the sea floor to a maximum depth of about 850 m, wherever water depths of less than 100 m prevail. This sequence is tentatively interpreted to image the vertical extent of submarine permafrost.

2. This sequence does not correlate well with the regional tectonic structure. If our interpretation is correct, it follows that the thickness of submarine permafrost not only depends on the magnitude of regional

heat flow, but also on such factors as the distribution of thermal conductivities in various rock types of the area and on the detailed history of the Holocene marine incursion.

3. The interpretation of this sequence would be greatly assisted, should detailed bathymetric maps of the Laptev Sea become available.

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