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Submarine permafrost in the nearshore zone of the southwestern Kara Sea

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Abstract The results of seismic studies in the shallow waters of the southwestern Kara Sea show the presence of a seismic unit that can be interpreted as relict submarine permafrost. The permafrost table has a strongly dissected upper surface and is located at a water depth of 5–10 m. A 3D modeling of the permafrost table suggests the presence of relict buried thermodenudational depressions (up to 2 km across) at a water depth of 5–10 m. The depressions may be considered to be paragenetic to thermocirques found at the Shpindler site. Relict thermocirques are completely filled with sediment and not exposed at the sediment surface.

Introduction

Permafrost is a remarkable feature of the coastal plains in the Russian Arctic and adjacent shallow water areas. Degradation and aggradation of permafrost are ongoing processes within both the coastal (onshore) and probably the nearshore (offshore) zones. It is to these processes that the most characteristic topographic features owed their development during the last several 1,000 years.

Many publications have been devoted to distribution and evolution of the permafrost in the Eastern and Western Russian Arctic (Antipina et al. 1981; Are 1976, 1987; Bondarev et al. 2002; Gataulin et al. 2001; Ginsburg and Soloviev 1994; Grigoriev 1993; Hubberten and Romanovskii 2001, 2003; Kassens et al. 2000; Leibman et al. 2000; Vasiliev et al. 2002; Zhigarev 1997; Zhigarev et al. 1982; and others).

The Laptev Sea represents one of few Arctic marine areas where submarine permafrost has been found (Hinz et al. 1998; Kassens et al. 2000; Rachor 1997; Soloviev et al. 1987). A mathematical simulation, made by Zhigarev et al. (1982), for the nearshore zones of the Laptev and East Siberian seas, shows that relict permafrost of limited thickness (8–20 m) could well occur in the nearshore shallow-water zone at depths of up to 18–20 m below the seafloor.

Echosounding evidence, which was interpreted to be caused by the top of sub-surface permafrost and/or accumulation of sedimentary gas, has already been reported from the Polarstern expedition ARK-XI/1 (Rachor 1997). As recorded in Parasound profiles, well-stratified sediments are commonly cut by strong post-sedimentary reflectors at sediment depths of about 10–20 m (Rachor 1997). Other seismic evidence for the extent of permafrost was observed during investigations of the BGR (Hannover, Germany) in cooperation with SMNG (Murmansk, Russia) in 1993 and 1994 in the Laptev Sea (Hinz et al. 1998). This seismic data reveal a 300–800 m thick seismic sequence beneath the sea floor, characterized by a distinct, highly reflective and mostly sub-parallel pattern. This distinct sequence crosscuts and masks real structural features such as top-lapping depositional units and anticlinal features at several localities. For these reasons, these authors inferred that the distinct superficial sequence images the permafrost layer. The upper surface of this sequence is located very close to sea floor, and was not identified on seismic data.

Direct observation of submarine permafrost was made during shallow drilling expeditions in the Laptev Sea (Kassens et al. 2000) and in the Pechora Sea. Ice-bearing sediments on the shallow Pechora shelf were covered by number of holes in water depths of 10–30 m (Bondarev et al. 2002). The permafrost table at this key site was located at a depth of 0.5–30 m in the sediment. In some places the thickness of the permafrost increased to 100 m or more. The boundary between the frozen and

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the unfrozen sediment sequences has a very hummocky relief and does not correspond to any stratigraphic boundary.

This paper is devoted to an investigation of the subsea permafrost features using geophysical methods in combination with onshore observations.

The onshore and offshore surveys serve the following aims:

– Identification of an ancient (buried) topographic elements associated with ancient relief-forming processes of the permafrost similar to on-going processes in the coastal zone.
– Assessment of the intensity of relief-forming processes accompanied by degradation of the submarine permafrost by correlation of the modern and buried topography.

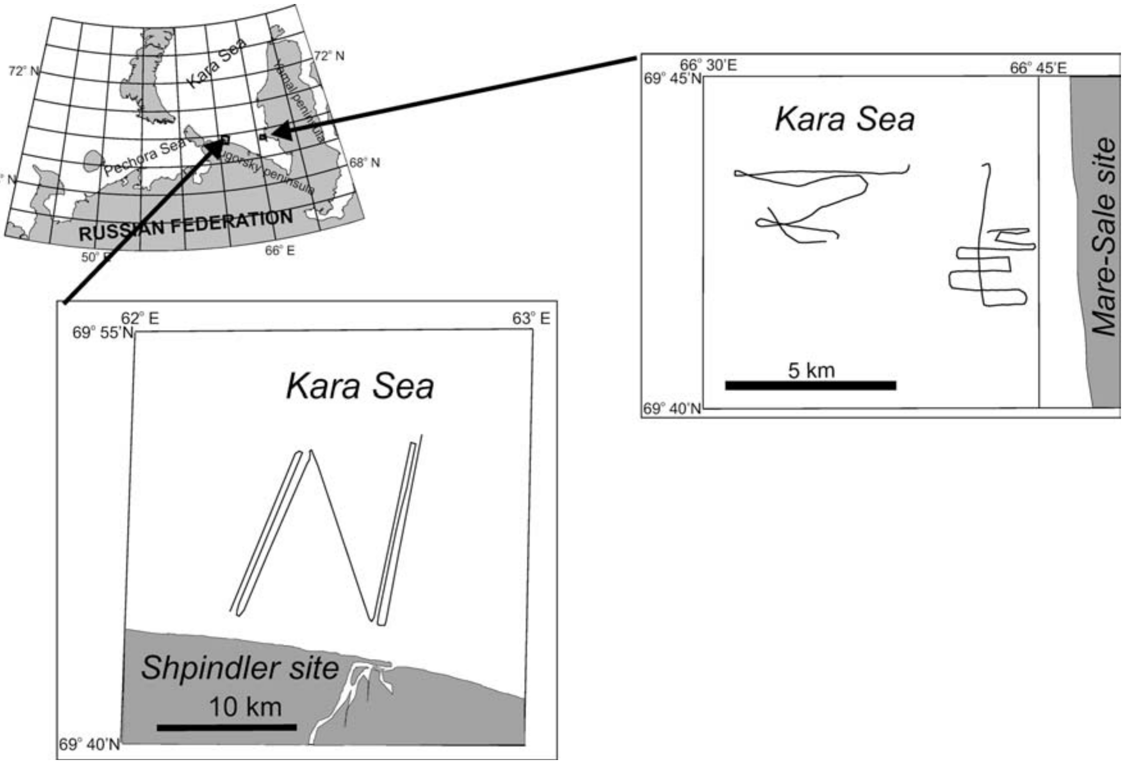
Study area

The survey was carried out on shore and in the shallow water zone at the Shpindler site (Yugorsky Peninsula) and the Mare-Sale site (western coast of the Yamal Peninsula) in the southwestern Kara Sea (Fig. 1). Both the Shpindler and Mare-Sale are key sites in the international Arctic coastal dynamics (ACD) project. The southwestern part of the Kara Sea and its coast is known for the wide distribution of tabular ground ice. The thawing ice bodies determine the specific activities of coastal processes with formation of thermocirques (Fig. 2). The onshore studies included high precision topographic surveys of nearshore exposures as well as interpretation of aerial photographs taken in the nearshore zone in different years (Vasiliev et al. 2004).

The *Shpindler site* is located 80 km east of the settlement Amderma (Fig. 2). The cliffs and other coastal structures were studied over an area of 3 km^2 . Widely distributed ground ice in the sand-clay unit is an integral part of the regional landscape at this site. The presence of huge ice masses in the Pleistocene section gives rise to such processes as thermoabrasion, thermodenudation and thermoerosion (Zhigarev 1997) which in turn become a powerful if not the most important modern relief-forming factor in the area. Such peculiar landforms as thermocirques owe their development to the thawing of ground ice. The largest thermocirque developed in a 20–30 m high mound with an approximately width of 500 m. Sediments overlying the ice are Holocene in age and of fluvial, lacustrine or slope origin. Sediments lie unconformably on the melted surface of the upper ice body. The lower surfaces of both ice bodies have conformable contacts with the enclosing rocks. Unlike the strongly dissected topography of the coastal part of the region, the sea bottom of the adjacent shoal has a smooth, gently dipping surface with depths of up to 30–40 m.

The cryogenic structure of the Quaternary deposits and dynamics of coastal processes at *the Mare-Sale site* were studied on a 4.3 km long stretch of coast and related to the second and third marine terraces. The base of the geological section is composed mainly of marine

Fig. 1 Location of the key sites in the southern Kara Sea



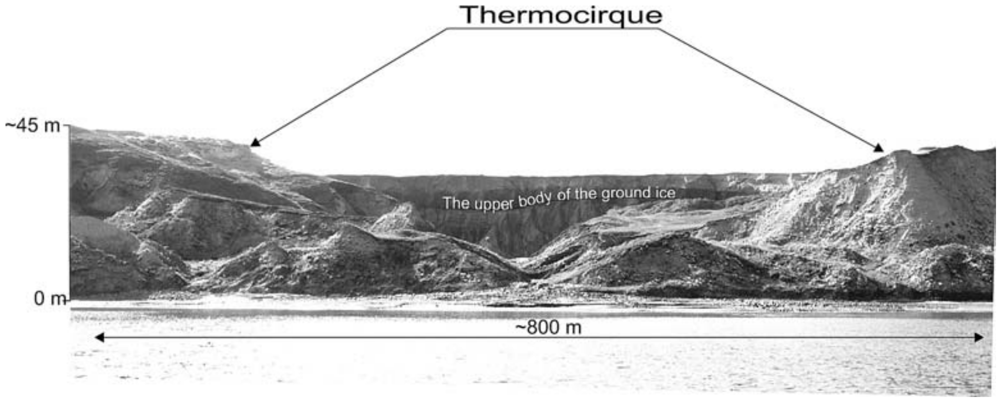


Fig. 2 Photograph from the Shpindler site showing a northward view of one of the thermocirques (photo by D. Perednya)

clay interbedded with often-folded sands. The upper part of the section consists mainly of continental sands, often characterized by peat formation at the surface and by the presence of sand-and-clay loams, enclosed in the alluvial, lacustrine-palustrine facies. The cryogenic structure of the cliff deposits is rather complex. Syncryogenic and epicryogenic sediments of both marine and continental origin were recognized in the section.

Onshore study shows significant differences in the dynamics of coastal erosion at the Mare-Sale and Shpindler sites. The retreat rate of the shoreline at the Mare-Sale site is 1.9 m/year and is linear in nature (Vasiliev et al. 2002). At the Shpindler site the retreat of the shoreline exhibits a ''volumetric'' pattern and has an average rate of 5 m/year caused by the formation of thermocirques (Leibman et al. 2000). It may be presumed that previously formed thermocirques can be found on the sea floor where they were flooded by the advancing sea (Zinchenko et al. 2004).

Offshore geophysical surveys were carried out mainly in the shallow water zone (15–35 m) and focused on the proposed direction of a zone of thermodenudation topographic features exposed at the shore (Fig.1).

Methods

The geophysical survey was carried out by means of the towed ''Sonic-3'' system (VNIIOkeangeologia) consisting of a high-and-low frequency side scan sonar (30 and 100 kHz respectively), and a 4–8 kHz seismic chirp-type profiler with impulse power of up to 2.5 kW. This system acquired seismic images with a resolution of 35 cm and a penetration up to 20 m of the sediment depth.

At present, the southern Kara Sea shoal has a smooth, gently dipping surface with water depths of up to 30–40 m. Most of the negative submarine cryogenic relict relief elements are buried and filled with sediments, and are not reflected in the bottom topography. Side scan data was, therefore, not efficient for studying the submarine permafrost zone. Instead, we used only high-resolution seismic (HRS) data for our investigation.

The original format of the seismic image file obtained by the Sonic-3 system includes both the seismic (SEG-Y) and navigational data. For visualization, HRS data generalization and digitizing of seismic features (i.e. horizon), we used the original software viewer for Seismic data v1.2.1. Preliminary interpretation of the HRS data shows two easily discernible seismic units (SU-1 and SU-2) with the seismic reflector A (SR-A) (Fig. 3) separating them. The considerable difference of the seismic image of the SU-1 and SU-2 leads to reliable correlation of the SR-A boundary separating the lines. Finally, three parameters were digitized: (1) the depth of SR-A (Fig. 3a), (2) the thickness of upper seismic unit SU-1 (Fig. 3b), and (3) the contrast range of the relief of SR-A (Fig. 3c).

There are two typical zones, characterized by different types of relief of SR-A. The first is a zone of the relative smooth and distinct reflector SR-A (smoothed

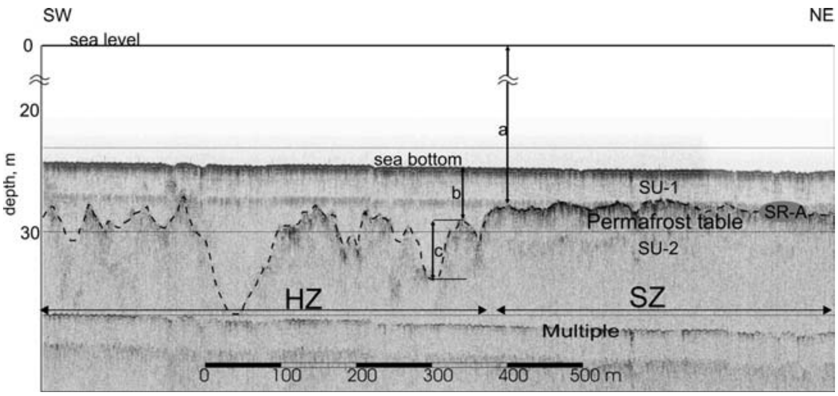


Fig. 3 Fragment of the HRS image at the Shpindler site showing the topography of the permafrost table. The picture shows: **a** the absolute depth of the SR-A (permafrost table); **b** the thickness of the SU-1; **c** the contrast range of the relief of SR-A. *HZ* Hummocky zone of SR-A, *SZ* smoothed zone of SR-A

zone “SZ”, Fig.3). The second is a zone where SR-A shows a hummocky pattern or different scale spikes into the overlying unit (hummocky zone “HZ”, Fig. 3). Hummocky zones alternate laterally with smoothed ones. The contrast range of the relief of SR-A, therefore, was separated into HZ and SZ (Fig. 3) distributed over the study area.

Digitized data were collected and gridded using Golden Software Surfer v.8.0 with the following specific parameters:

– Gridding method: Kriging
– Node spacing: 500 m
– Search radius parameter: 3.0 km.

Detailed derivation and discussion of the kriging gridding method is described by Cressie (1991) and Journel and Huijbregts (1978). The above parameters allowed us to confine the gridding space areas of interest and to avoid artifacts between the lines (Fig. 4).

Results

As was mentioned above, on the HRS profiles at both the Shpindler and Mare-Sale sites, the sedimentary sequence is subdivided into two acoustically non-stratified seismic units SU-1 and SU-2, separated by a strong reflector SR-A (Fig. 3).

SU-1 is characterized by a flat sediment surface and an acoustically transparent seismic pattern. This unit overlays the SR-A and is interpreted as a layer of unfrozen sediment. The original layering of the sediments was eliminated or strongly altered due to aggradation and degradation of the permafrost unit during the last transgressive-regressive cycle. The thickness of this seismic unit varies from 1–2 to 15–18 m.

SU-2 shows an acoustically non-transparent and non-stratified pattern. This seismic unit characterized by a hummocky sediment surface, which does not permit the seismic signal to penetrate into the sequence and leads to appearance of acoustic voids within SU-2. The sediment surface exhibits a distinct “tooth” pattern, V-shaped depressions, or small-scale spikes into the overlying SU-1. There are also many internal zones where the amplitude of the seismic signal drastically increases. A most significant seismic feature at both key sites is, therefore, SR-A, subdividing the entire sediment sequence into two parts: the permanently frozen and unfrozen sediments.

The results of 3D modeling of the permafrost table topography showed no evidence of a distinct seaward increasing of the thickness of the positive temperature sediments strata (Figs. 5, 6). The most prevalent depth of the permafrost table is 4–6 m below the seafloor at the Shpindler site and 3–10 m at the Mare-Sale site (in Figs. 5b, 6b).

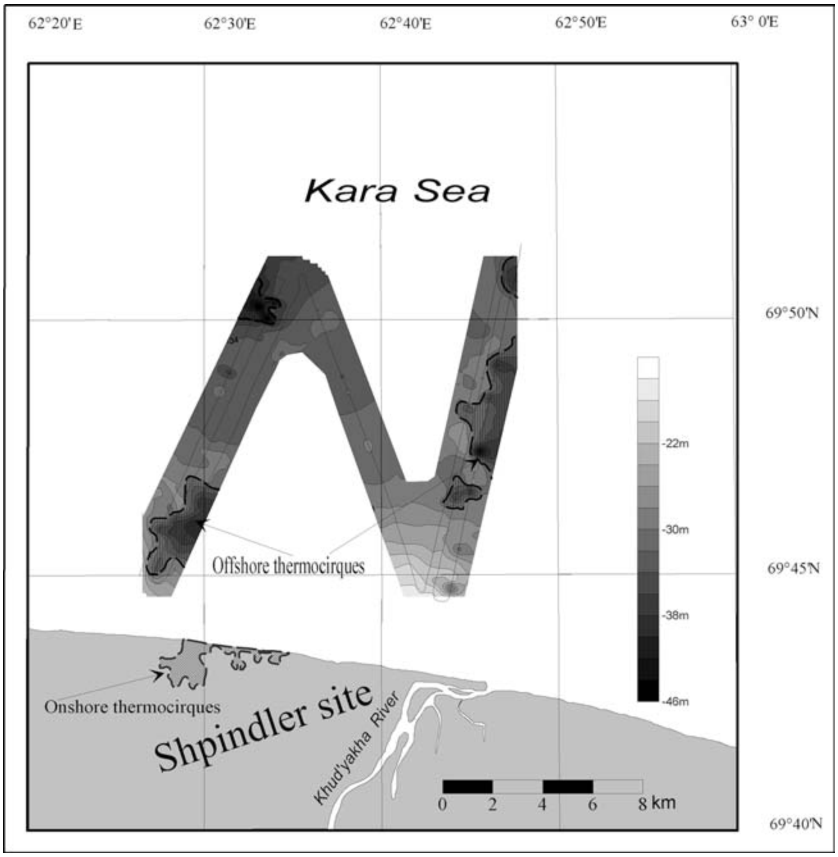


Fig. 4 Depth of the permafrost table at the Shpindler site. The *dashed areas* show the distribution of the onshore and offshore buried thermodenudational depressions

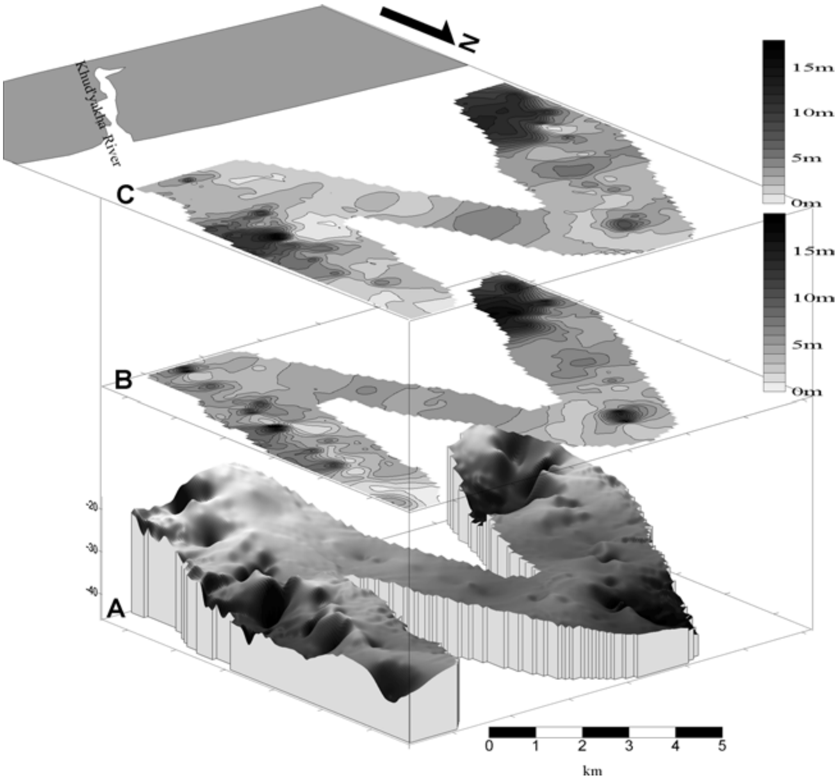


Fig. 5 A model of the permafrost table relief at the Shpindler site: **a** the absolute depth of the SR-A (permafrost table); **b** the thickness of the SU-1; **c** the contrast range of the relief of SR-A

The reflector separating the upper (SU-1) and lower (SU-2) seismic units is the most distinctive and often the only one on the seismic section. SU-2 has distinct acoustic voids beneath the reflector SR-A. Very often SR-A shows a strongly dissected topography and very strong amplitude. This distinct reflector crosscuts and masks real structural features, e.g., the weak original sedimentary reflectors within SU-1 (Fig. 3). For these reasons we suggest a post-depositional origin of the SR-A, and infer that the distinct reflector represents the permafrost table. In general, the seismic boundary may be interpreted as the upper part of a permanently frozen sediment sequence (i.e. permafrost table), overlain by strata of unfrozen sediments. A rather similar specific seismic pattern has been found at several key sites on the Eastern Laptev Sea (Rachor 1997) and at Nikolay Lake at the West Lena Delta (Schwamborn et al. 1999).

The permafrost table has several depressions (up to 2 km across) with isometric or close to isometric morphology (Figs. 4, 5,6). The relief between the edges and bottoms of these structures reaches 10–12 m. The walls are steep and often stepwise without tectonic dislocations. The sediment fills all the depressions.

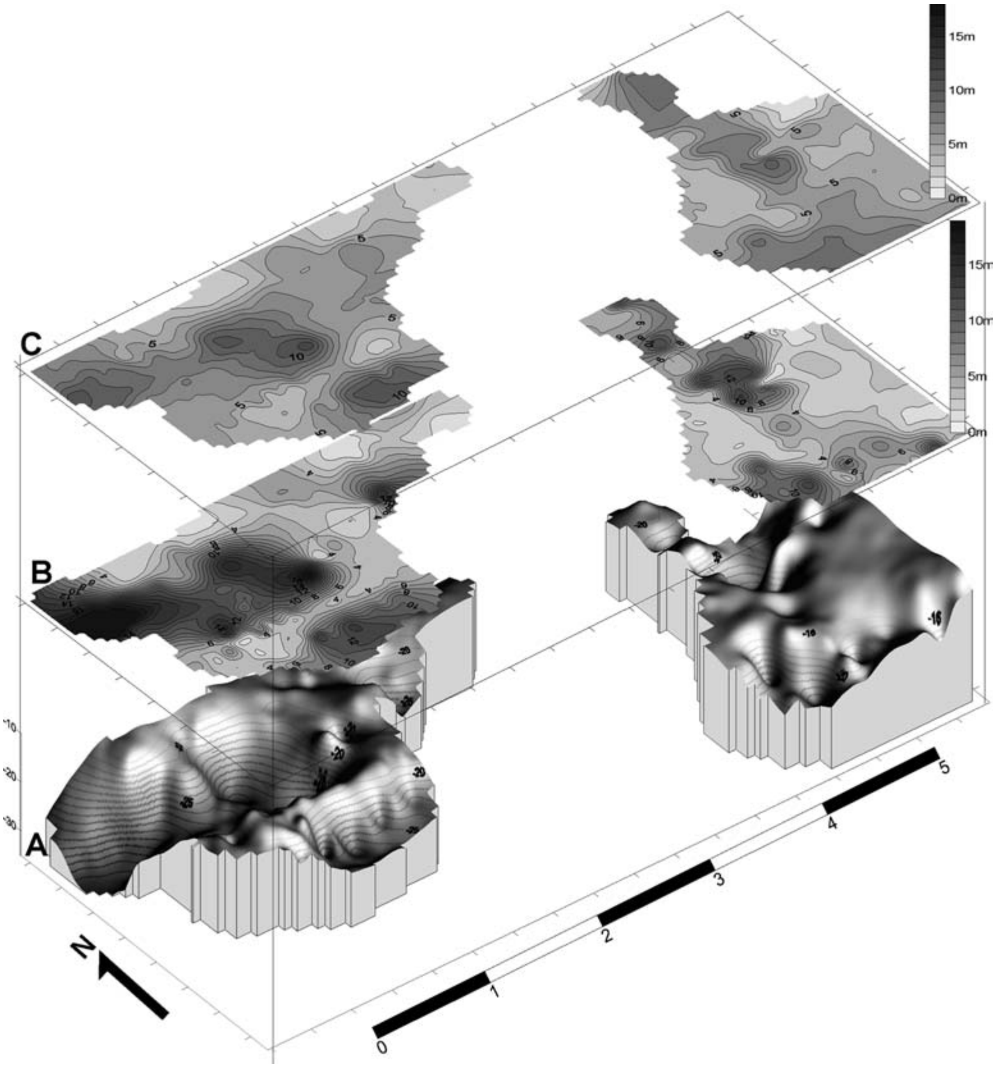
The permafrost table throughout most of the Shpindler site has a smooth surface outside the depression (Fig. 3c). The contrast range of relief generally does not exceed 3–5 m and increases sharply up to 10–15 m within the several depressions. The permafrost table at the Mare-Sale site has a much more dissected relief with a range of about 5–10 m. As a result, the pillar-like structures of the permafrost table alternate with crater-like depressions (Fig. 6).

Discussion

The relict depressions in the permafrost table offshore are much larger than recent thermocirques exposed at the Shpindler site. It is very probable that these large thermodenudation depressions incorporate a group of thermocirques destroyed in the submarine position. A thorough examination of the data presented here suggests that all of the large depressions combine several smaller ones, 200–400 m across. The process of submarine thermodenudation by the formation of large thermodenudation depressions could well originate there.

Three thermocirques at the coast of the Shpindler site (Eastern, Central and Western) were described by Zinchenko et al. (2004). Thermocirques are located on a prolongation of a tectonic fault that extends northwest. The main lineaments within the thermocirques inherit a main system of faults with a maximum in rose diagrams of 300–320° . Evidently, the system of hills containing ice domes and dissected by thermocirques had a larger extent seaward (Zinchenko et al. 2004). Moreover, these authors also point to the presence of buried thermodenudational depressions in the nearshore zone (0–10 m water depth), which are reflected in the seafloor topography. A possible ‘‘relict’’ thermocirque in the form of an elongated depression at a depth of 6.5–7.5 m is limited by a wall with a northwest strike (315–320°) and shows a clear morphological similarity with the Western thermocirque onshore. Thus, it is possible to propose a tectonic control on thermocirque formation and on the position of a retreating scarp (Zinchenko et al. 2004).

Fig. 6 A model of the permafrost table relief at the Marre-sale site: **a** the absolute depth of the SR-A (permafrost table); **b** the thickness of the SU-1; **c** the contrast range of the relief of SR-A



This offshore study, therefore, suggests the presence of similar recent buried negative relief elements which are considered paragenic with those described above and distribute seaward to a water depth of 15–40 m. Hence, there are good grounds to interpret the depressions mapped by HRS data as buried morphostructures that belong to the same system of thermocirques. The depressions probably represent ancient thermocirques submerged by the sea and covered by sediments. The fact that these thermodepressions developed in the submarine position after the thermocirques can indicate the position of the coastline during formation in the latest periods. The most easily discernible thermodepression is related to a terrace-like surface at water depth of 18 m.

Conclusions

1. A HRS survey in near-shore shallow waters in the southwestern Kara Sea has permitted detection of a reflector that could be interpreted as the permafrost table. In addition, the regional distribution of the submarine cryolithozone was mapped and the position and morphology of the permafrost table described.
2. The permafrost table typically lies 4–6 m below the sea floor at the Shpindler site and 3–10 m at the Mare-Sale site. Several depressions in the permafrost table (up to 2 km across) with isometric or close to isometric morphology were observed. The large thermodenudation depressions incorporate a group of thermocirques that were destroyed in the submarine position. Thawed sediments fill all depressions.
3. The depressions may be considered to be paragenetic to onshore thermocirques found in cliffs at the Shpindler site. These relict thermocirques were submerged by the sea and subsequently covered by sediments. Their present-day position at the sea bottom demarcates the coastline position during the period of their formation. A 3D representation of the topography of the permafrost table shows the absence of any trends in the thickness of the unfrozen strata with distance from the coastline.

The data obtained show that the discussed techniques may be considered promising for mapping the submarine permafrost in the shallow water. However, the phenomena described require further study in order to monitor the ongoing processes, both onshore and offshore.

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References

Antipina ZN, Are FE, Voychenko VV (1981) Cryolithozone of the Arctic shelf of Eurasia. In: Late Quarternary history and sedimentation of external and interior seas (in Russian). MSU press, Moscow, pp 47–60

Are FE (1976) About sub-sea cryolithozone of the Arctic Ocean: regional and thermal physics studies of the permafrost in Siberia (in Russian). Yakutsk Press, Russia, pp 3–26

Are FE (1987) Cryogenic processes of Arctic coastal zone dynamics. In: Fundamental investigations of the earth csssry-osphere (in Russian). Nauka Press, Novosibirsk, pp 123–129

Bondarev VN, Rokos SI, Kostin DA, Dlugach AG, Polyakova NA (2002) Underpermafrost accumulations of gas in the upper part of the sedimentary cover of the Pechora Sea (in Russian). Geol Geophys 43(7):587–598

Cressie NAC (1991) Statistics for spatial data. Wiley, New York, p 900

Gataulin V, Mangerud J, Svendsen JI (2001) The extent of the late Weichselian ice sheet in the southeastern Barents Sea. Glob Planet Change 31:453–474

Ginsburg GD, Soloviev VA (1994) Submarine gas hydrates. VNIIOkeangeologia (in Russian). St. Petersburg, p 199

Grigoriev MN (1993) Cryomorphogenesis of the Lena River mouth area (in Russian). Permafrost Institute Press SB RAS, Yakutsk, p 176

Hinz K, Delisle G, Block M (1998) Seismic evidence for the depth extent of permafrost in shelf sediments of the Laptev Sea, Russian Arctic? In: Lewkowicz AG, Allard M (eds) Proceedings of the 7th international conference on permafrost, June 23–27 1998, Yellowknife, pp 453–458

Hubberten H-W, Romanovskii NN (2001) Terrestrial and offshore permafrost evolution of the Laptev Sea region during last Pleistocene-Holocene glacial-eustatic cycle. In: Paepe R, Melnikov V (eds) Permafrost response on economic development, environmental security and natural resources. Proceedings of the NATO-ARW, Novosibirsk. Kluwer, Dordrecht, pp 43–60

Hubberten H-W, Romanovskii NN (2003) The main features of permafrost in the Laptev Sea region, Russia—a review. In: Proceeding of the 8th international conference on permafrost, Zurich, pp 431–436

Journel AG, Huijbregts C (1978) Mining geostatistics. Academic, p 600

Kassens H, Bauch H, Drachev S, Gierlichs A, Niessen F, Taldenkova E, Roudoy A, Thiede J, Wessels M (2000) Transdrift VIII expedition to the Laptev Sea: the shelf drilling campaign of "Laptev Sea System 2000". In: Sixth workshop on Russian–German cooperation: Laptev Sea system. Terra Nostra 2000, vol 8, pp 39–40

Leibman MO, Vasiliev AA, Rogov VV, Ingolfsson O (2000) Study of massive ground ice of Yugorsky peninsula with crystallographic methods (in Russian). Earth Cryosphere 4(2):31–40

Niessen F , Gierlichs A, Weigelt E, Jokat W (1999) High-resolution seismic and sediment echosounding investigation of submarine permafrost on the Laptev Sea shelf. In: Fifth workshop on Russian–German cooperation: Laptev-Sea System 2000, Abstracts. Terra Nostra 99/11

Rachor E (ed) (1997) Scientific cruise report of the Arctic expedition ARK-XI/1 of RV "Polarstern" in 1995. Rep Polar Res 226:157

Schwamborn G, Schneider W, Grigoriev M, Rachold V, Antonov M (1999) Sedimentation and environmental history of the Lena Delta. Rep polar Res 315:94–145

Soloviev VA, Ginsburg GD, Telepnev EV, Mikhalyuk Yu N (1987) Cryothermy and hydrates of the nature gas within North Polar Ocean (in Russian). Sevmorgeologiya, Leningrad, p 150

Vasiliev AA, Cherkashov GA, Vanstein BG, Firsov YG, Ivanov MV (2002) Coastal dynamics in Mare-Sale, Kara Sea: a new observation program. Rep Polar Mar Res 413:78–79

Vasiliev A, Kanevskiy M, Cherkashov G, Vanshtein B (2004) Coastal dynamics at the Barents and Kara Sea key sites. Geo Mar Lett (in press)

Zhigarev LA (1997) Oceanic cryolithozone (in Russian). MSU Publications, Moscow, p 320

Zhigarev LA, Suhodol'skaya LA, Chernyad'ev VP (1982) Cryolithozone of the Arctic seas in the Late Pleistocene and Holocene (in Russian). MSU Letters 93

Zinchenko AG, Leibman MO, Firsov Yu G, Vanstein BG (2004) Formation of thermodenudation relief in the coastal zone in connection with tectonics, Yugorsky peninsula, Kara Sea. Rep Polar Mar Res