

Manifestations of deep degassing into the water column and upper part of the Pechora sea sedimentary section

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Abstract. Studies of acoustic anomalies in the water column and seismoacoustic anomalies in the Quaternary sediments of Pechora sea and their relationship with deep hydrocarbon sources were conducted by the Institute of Oceanology of the Russian Academy of Sciences and the Geological Institute of the Russian Academy of Sciences in the 38th cruise of RV “Akademik Nikolaj Strakhov” in 2018. Mapping of free gas manifestations presents an additional indicator of tectonic activity and the fault network frame, which provides the flow of fluids from deep horizons. Comparison of high-resolution seismic survey data with deep seismic survey data shows that the fluid in the upper part of the section is first accumulated under the bottom of Jurassic-Cretaceous sedimentary sequences, which are fluid-resistant. Local dislocations of fluid trap lead to further rise and redistribution of free gas in Quaternary sequences. Natural or artificial break of their integrity results in the release of gas into the water column from near-surface accumulations that were found in the form of “bright spot” anomalies on seismic-acoustic records. Mapping of sound scattering objects in the water column shows the degassing areas, which are usually located above the deep faults. “Bright spots” of free gas in the Quaternary sequences have a variety of shapes – multi-tiered and inclined. Gas breaks into the water column occur near the edges of these anomalies. Systematic mapping of the considered phenomena is a necessary element in the preparation of the area for industrial operation.

Keywords: sound scattering objects, seismic acoustic, faults, degassing, bright spot

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Introduction

The Pechora sea has a good geological and geophysical study of deep seismic methods and drilling, the results of which are summarized in the State geological map of the 3rd generation (State geological map..., 2013) (Fig. 1). The hydrocarbon potential of this region is huge and the Prirazlomny field has already been put into operation from the platform in the sea. Drilling in the Pechora sea has experienced accidental gas emissions. When drilling with the “Bavenit”-AMIGE drilling ship in the Pechora sea in 1995, 60-70 km west of Vaygach Island, a gas deposit was discovered at a depth of 50 m below the bottom inside sandy sediments under a permafrost layer with ice presence. The resultant gas discharge into the water column created an emergency for the drilling vessel, and the aeration continued for several days with gradual attenuation (Bondarev et al., 2002;

Bogoyavlensky, 2015). The upper part of the section of the sedimentary sequence in this region, as in other parts of the Barents Sea (Solheim et al., 1998), is characterized by strong variability in the composition, thickness of the Quaternary sediments and diamicton (Krapivner, 2018; Dunaev et al., 1995), occurring in eroded Mesozoic complexes (Shipilov, Shkarubo, 2010), and the presence of frozen rocks (Krapivner, 2018), which are a fluid seal for free gas. These formations cannot be investigated with the resolution of seismic studies of the section to depths of up to 10 km using signal sources with frequencies up to 100 Hz.

The upper part of the section studies are carried out using seismic-acoustic systems based on sparker sources (frequencies up to 1000 Hz), profiler with frequency-modulated signals (frequencies from 2 to 16 kHz) or parametric profiler (Levchenko, Merklin, 2003). Detailed mapping of the upper part is also accompanied by multi-beam echo sounder, usually with the possibility of registering an acoustic field in a form similar to side-scan sonar and recording sound-scattering objects in the water column. The degree of geological certainty of the Pechora sea by seismic-acoustic methods is very high. In

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the course of these studies, in addition to the separation of Quaternary sediments into seismic stratigraphic complexes and seismic facies according to the characteristic features of the wave field, gas saturation facts were established in weakly consolidated rocks of the upper part of the section (Kostin, Tarasov, 2011; Rokos et al., 2001). It is indicated that accumulations of free gas are confined mainly to permafrost zones in the region of sea depths of 50-70 meters and smaller.

As a result of studies of the 13th cruise of the RV "Akademik Sergey Vavilov" (Institute of Oceanology of the Russian Academy of Sciences, 1998) (Levchenko, Merklin, 2003), many acoustic anomalies were identified in the Pechora sea associated with the migration of hydrocarbons from deep deposits into the upper part of the sedimentary section and into the zones of cryolithogenesis development. Accumulations of hydrocarbons in the form of gas lenses are observed in the Cretaceous complexes, the roof of which in the Pechora sea according to the frame network profiles 2008-2009 is located at depths of up to 300 meters (section KS1004, well Pomorskaya-1) (Kazanin et al., 2011). In the presence of tectonic dislocations (sections KS0928 and KS0932), hydrocarbons can migrate into the upper part of the section and into the water

column with the formation of the observed acoustic anomalies of various configurations depending on the relationship with the cryolithozone. A study of these phenomena associated with deep hydrocarbon sources was continued on the 38th cruise of the RV "Akademik Nikolaj Strakhov" (Institute of Oceanology of the Russian Academy of Sciences, Geological Institute of the Russian Academy of Sciences, 2018), the scheme of which is shown in Fig. 1. In this work, we used data from the SeaBat 8111 multi-beam echo sounder (Denmark) with a sonar mode and EdgeTech 3300 non-parametric profilograph (USA). In addition, materials of 2D CDP seismic reflection method were used.

Degassing in the marine extension of the Varandey-Adzvinzky structural zone

One of the areas of the 38th cruise of the RV "Akademik Nikolaj Strakhov" was the drilling site in 1995 at the "Bavenit" drilling ship (Bondarev et al., 2002; Bogoyavlensky, 2015) where a gas emission was recorded (Fig. 2). The position of the test site on tectonic structures is such that it covers thrust faults extending almost to the surface to extend the Varandey-Adzvinzky structural zone to the water area near the emergency well. When approaching the polygon, the

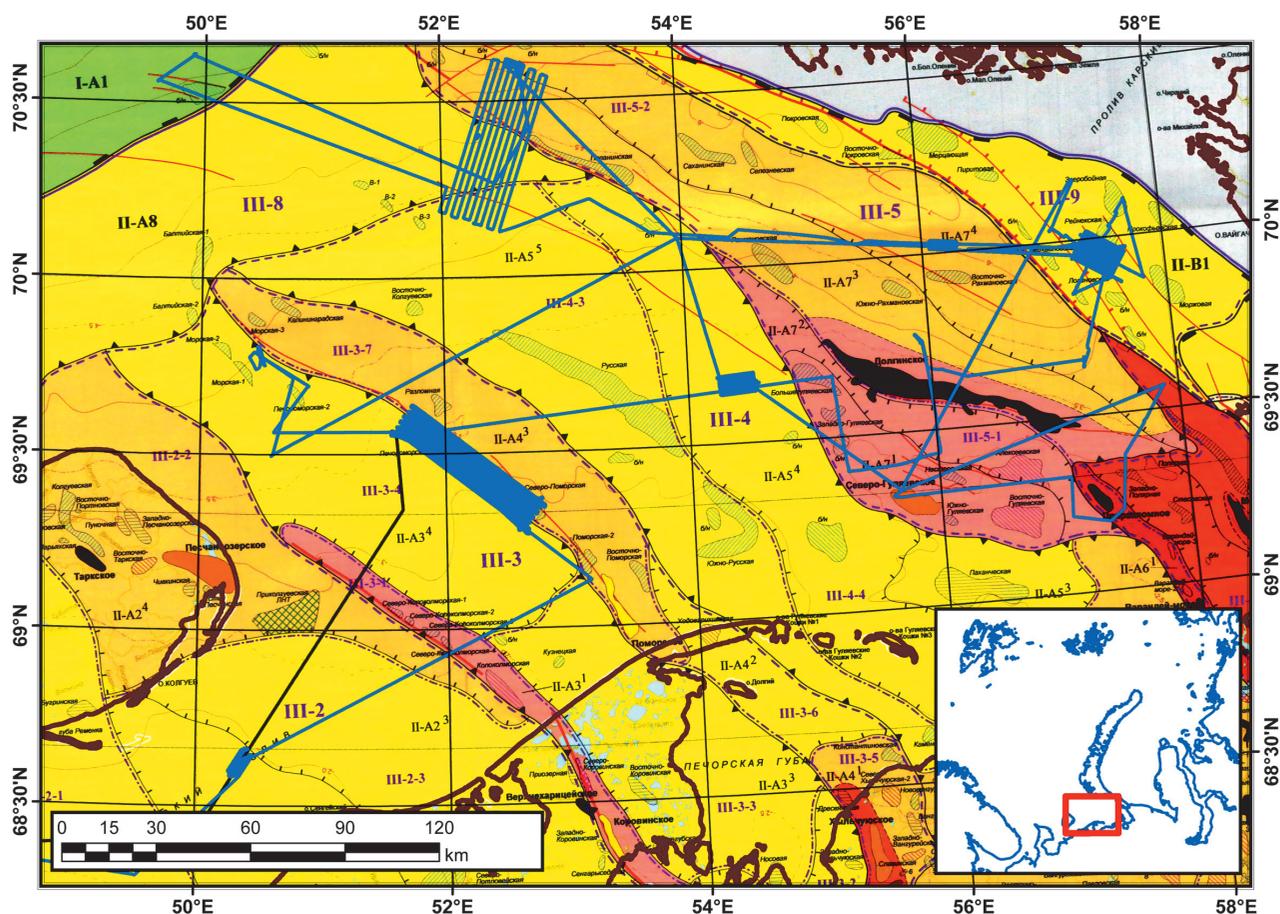


Fig. 1. Scheme of the 38th cruise of the RV "Akademik Nikolaj Strakhov" (Institute of Oceanology of the Russian Academy of Sciences, Geological Institute of the Russian Academy of Sciences, 2018). Seismic acquisition profiles are shown with a blue line. The oil and gas forecast map from the set of the State geological map R-39-40 of the 3rd generation (State geological map..., 2013) was used as a topographic basis. In the inset – the position of the main plane table within the Barents sea.

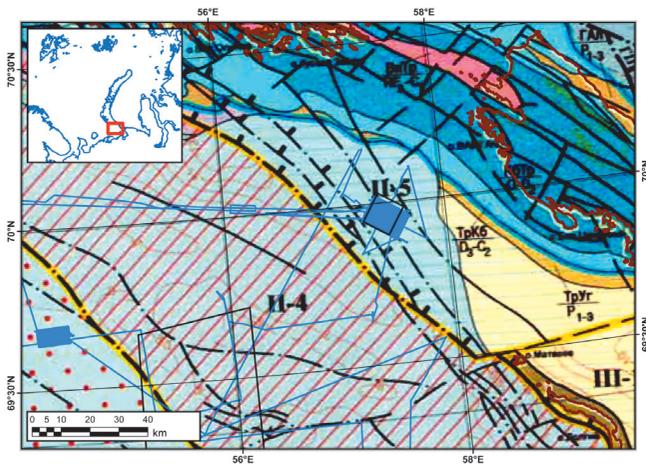


Fig. 2. Scheme of the 38th cruise of the RV “Akademik Nikolaj Strakhov” (Institute of Oceanology of the Russian Academy of Sciences, Geological Institute of the Russian Academy of Sciences, 2018) and the polygon (black square) in the drilling area in 1995 at the “Bavenit” drilling ship (Bondarev et al., 2002; Bogoyavlensky, 2015), located on the marine extension of the Varandey-Adzvinsky structural zone. As a topographic base, a tectonic map from the set of the State geological map R-39-40 of the 3rd generation was used (State geological map..., 2013). In the inset – the position of the main plane table within the water area of the Pechora sea.

seismic section of CDP 078917 was crossed (Fig. 3), in the upper part of which an anomaly of the “bright spot” type is visible above the sheared thrust structures of the Varandey-Adzvinsky zone. The fluid nature of the anomaly is unquestionable due to a sharp increase in the amplitude of the negative phase in the anomaly

and an inversion of polarity in the northeastern edge of the anomaly. Let us note that, judging by the section, the source of fluid is thrusting complexes, which lie with the northeast bearing azimuth, which, according to the data of (Sobornov, 2018), can be of the Early Paleozoic age and be a source of upward migrating hydrocarbons. Jurassic-Cretaceous complexes with clayey rocks lying on the eroded surface can be fluid-resistant, but small dislocations of the bottom of sedimentary complexes at a depth of about 600 ms in this area form channels for fluid to leak into the overlapping Jurassic-Cretaceous complex and Quaternary sediments.

Figure 4 shows the sub-latitudinal section obtained by the EdgeTech 3300 profilograph in the frequency range 2-6 kHz through the area of boreholes 480 and 481 (Bondarev et al., 2002). In the amplification mode tuned to the bottom reflectors, it can be seen (Fig. 4A) that there was degassing in the central part of the section, according to the data (Bondarev et al., 2002). It is represented by an acoustically transparent record that does not show signs of acoustic stratification. In the amplification mode tuned to visualize the sound scattering objects in the water column (Fig. 4B), it can be seen that no anomalies of seismic acoustic recording are observed above this zone. This indicates that, most likely, after a well penetrated through frozen rocks 23 years ago, the free gas accumulated in the vicinity of the drilling zone entered the water column and the plastic frozen environment closed its channel. Acoustic stratification of the Quaternary deposits is present in the western part of the section. The presence of local anomalies of the “bright spot” type in individual recording segments

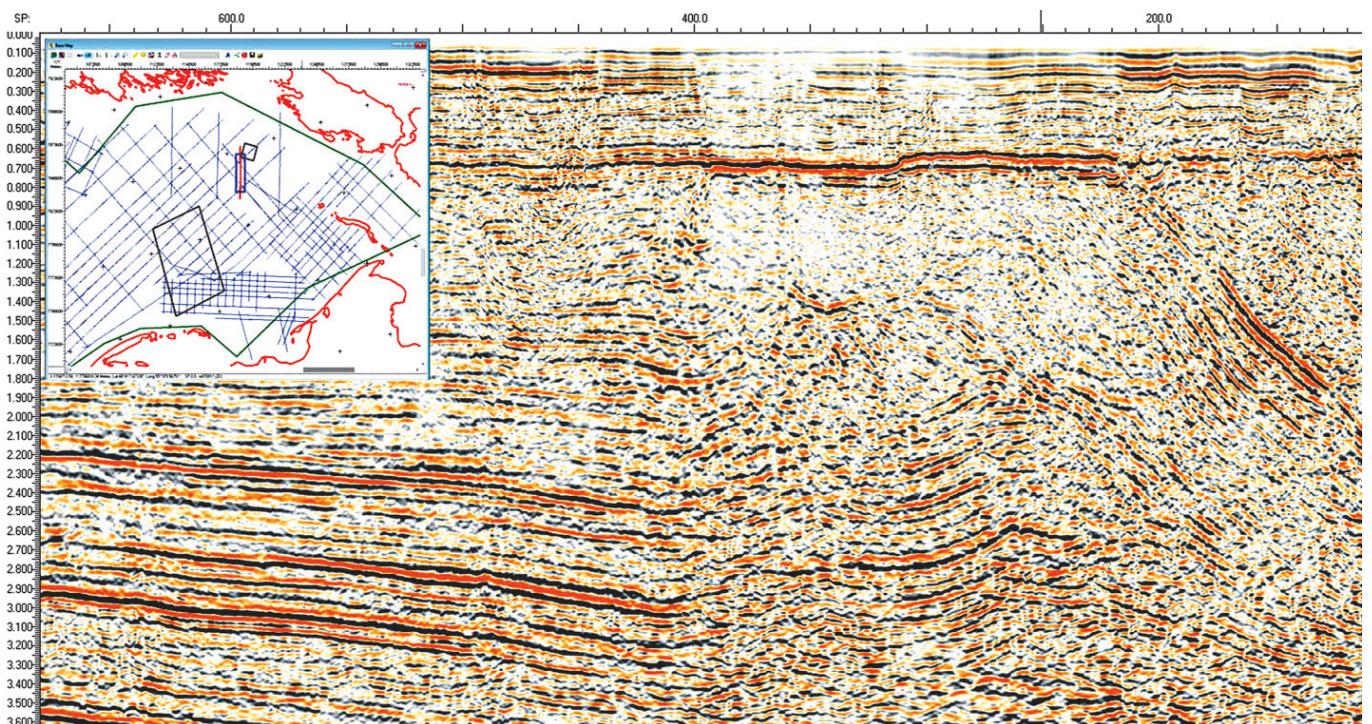


Fig. 3. A fragment of a section of the CDP 078917 (position on the inset). Vertical – seconds, horizontal – CDP assembly number in increments of 50 m.

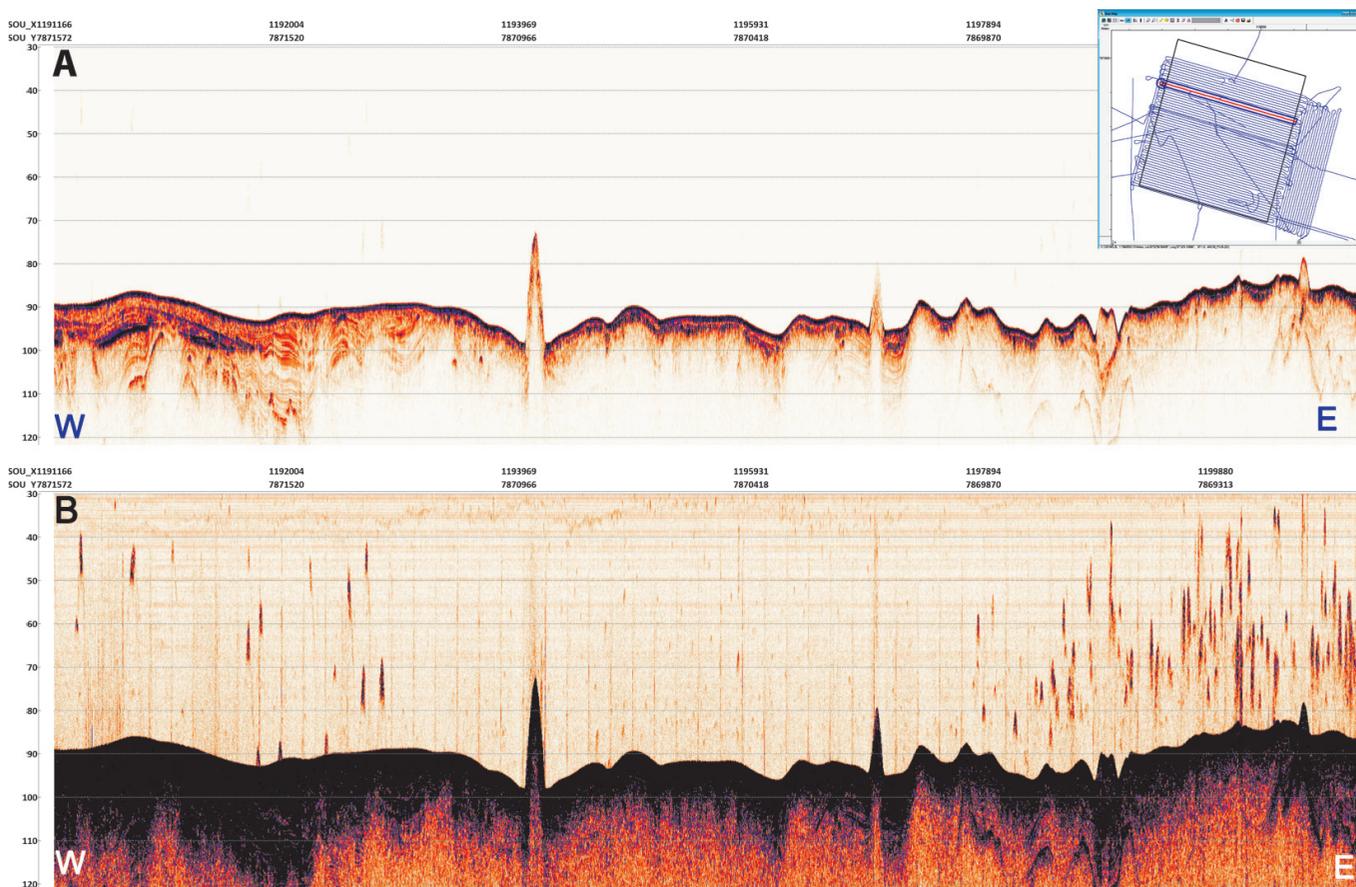


Fig. 4. Section ANS38-P3-26 obtained by EdgeTech 3300 profilograph in the frequency range 2-6 kHz (the position of the section within the polygon of Fig. 2 is shown in the inset). Vertical – milliseconds from the surface, horizontal – UTM37 meters. A – a section with gain in the range of bottom reflectors, B – a section with gain for the isolation of sound-scattering objects in the water column.

indicates the accumulation of gases in this part of the section. The presence of rare sound scattering objects in the water column, both rootless, without anomaly binding to the bottom, and root, traceable from the upper sound diffuser to the bottom, shows a slight degassing from the bottom sediments, which is not catastrophic. This is evidenced by the presence of undisturbed “bright spots”. In the eastern part of the section, there are much more signs of degassing, but there are no record of anomalies in sediments. Thus, there are various stages of degassing processes – accumulation with the formation of “bright spots”, degassing through a system of natural channels, accompanied by attenuation of the amplitude in the anomalies, and catastrophic man-made degassing.

Records of water column anomalies obtained by the sonar mode of a multi-beam echo sounder at a frequency of 100 kHz (Fig. 5) show a similar distribution of sound scattering objects along the same profile. Since the swath angle across the vessel’s movement is 150 °, sound scattering objects located on the side of the profile line fall into the record. In addition, the backscattered signal from the head parts of the sound scattering objects in the water column and from the root parts of the sound scattering objects is noticeably more efficient. The latter can be seen in the enlarged inset in the western

part of the profile, which shows the ground origin of sound-scattering anomalies. Due to the large band of sonar sounding, unlike the profilograph, the assembly of anomalies from a wide shooting band is recorded. Fig. 6 shows examples of scattering data from the areas of the polygon adjacent to ANS38-P3-26 containing root and rootless sound-scattering objects. The examples show the ground genesis of the contrasting hydrophysical conditions that form the scattered signal, and are an indicator of the deep degassing processes in the area of work.

Degassing in the Varandey-Gulyaevsky tectonic block

Degassing in the Varandey-Gulyaevsky tectonic block (Fig. 2, block II-4 on a topographic basis) (State geological map..., 2013) has deep roots. Figure 7 shows a fragment of the CDP section 078681, in which at a depth of about 500 ms a bright spot with an increased amplitude of the negative phase is distinguished under the bottom of the Jurassic-Cretaceous complexes. This indicates fluid accumulation under the reflector. In several places on this section, and in particular on the presented fragment between gathers 150 and 200 above the reflector, heaving mounds are observed

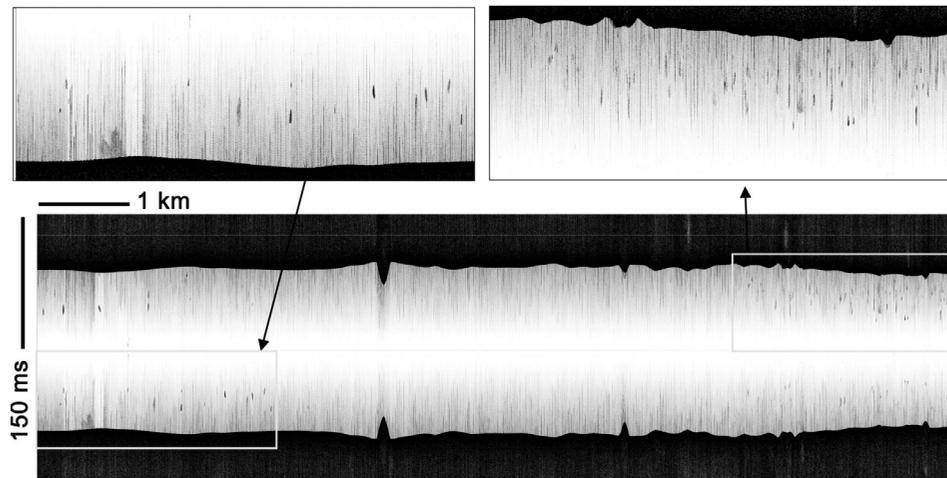


Fig. 5. Section ANS38-P3-26 according to the sonar mode of the SeaBat 8111 echo sounder, similar to side-scan sonar without applying the procedure for eliminating the water column. The inset shows sound-scattering objects in an enlarged view. This section contains interference from an electric spark source.

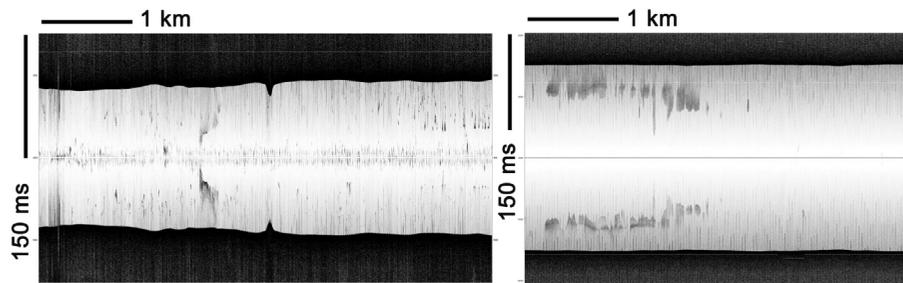


Fig. 6. Examples of sonar mode data for the SeaBat 8111 echo sounder from areas adjacent to ANS38-P3-26 without the use of the water column removal procedure containing root and rootless sound-scattering objects.

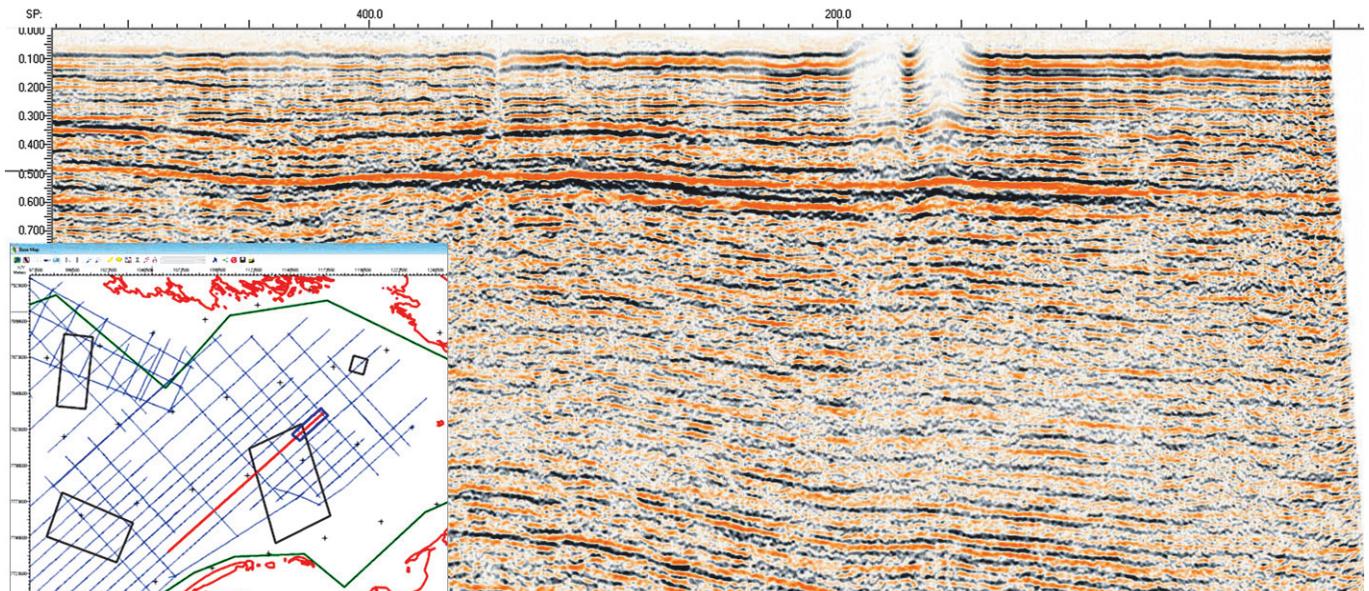


Fig. 7. A fragment of the section of the CDP 078681 (position on the inset). Vertical – seconds from the surface, horizontal – CDP assembly number in increments of 50 m.

with a visible drop in the instantaneous frequency of the reflectors and acoustic brightening. They are probably confined to the places where the fluid breaks to the surface in an area accessible for mapping by a high-frequency profilograph. This record indicates the local rise of weakly consolidated sedimentation under

the influence of gases. The reason for the formation of these structures in one place or another is small local heterogeneities and tectonic dislocations in the Jurassic-Cretaceous sediments (horizon B), or deeper faults covering the section before the Paleozoic (Kazanin et al., 2011).

On the fragment of section ANS38-P2-04 (Fig. 8), located next to section CDP 078681, rare manifestations of acoustically stratified sediments with anomalies “bright spot” were found, over which ruptures along the horizon at a depth of about 10 ms are root sound-scattering objects in the water column. The observed configuration of the sound-scattering objects has the shape of gas flares, which in some cases have a root width of about bottom up to 100 m. The obtained wave field pattern indicates intense degassing processes that form gas caps in the upper part of the section, breaking into the water column in the weakened zones with the formation of characteristic sound-scattering objects.

Degassing in the frame of the Khoreyver block

The Khoreyver block (Fig. 9, index II-3 in the inset) westward passes into the mobile zone of increased permeability of the earth’s crust (State geological map..., 2013), in which seismic-acoustic records with signs of degassing are traced. On the border of this block with the Murmansk-Kurentsov block in the northwestern part of the works (Fig. 1), a depression of the bottom topography with an amplitude of up to 20 meters is distinguished, which, according to the data (Krapivner, 2018, Fig. 5.11) marks the distribution of the paleorus channel. The intersection of this bottom structure is shown in section 9. Directly outside the zone, a structural feature of the sedimentary section is the presence of depression, the formation of which led to an inclined occurrence of clay sediments, initially deposited horizontally. This is indicated by the presence of angular disagreement on the eastern side of the depression. The cause for the depression

formation could be an impulse of intense degassing, which continues at present, as evidenced by the “multi-level” bright spots observed in the section. On the other hand, the trigger for this catastrophic process could be neotectonic activity with a tensile component, along the axis of which the paleo-channel was oriented. The formation of depression was multistep, since erosion section of the inclined layers in the eastern part is observed, and the sediments that seal it in the depression itself have the same inclination configuration. The channel adapted to depression led to the accumulation in its axis of a horizontally layered stratum saturated with bright spots.

Note that in the section of Fig. 9, bright spots are located either in the central part of clay sediments, or with an angle of incidence to the depression axis above the diamicton roof, below which the wave field is acoustically transparent. This suggests that the source of fluid is deep sedimentary complexes, breakthroughs of which are found in places where the integrity of the Quaternary sediments is impaired.

Section ANS38-038 (Fig. 10), which, according to the tectonic map (State geological map..., 2013) intersects the buried fault, contains intense anomalies formed by free gas and having the form of “flat” and “bright” spots. The strong randomization of all underlying reflectors and the complete loss of coherence of the acoustic foundation most likely indicates that fluid breakthroughs come from deeper horizons than the foundation. Also, there is a deflection of the reflectors and the formation of a characteristic depression, subsequently leveled by sedimentation. In addition, we note increased amplitude along the reflectors with a slope suitable for depression,

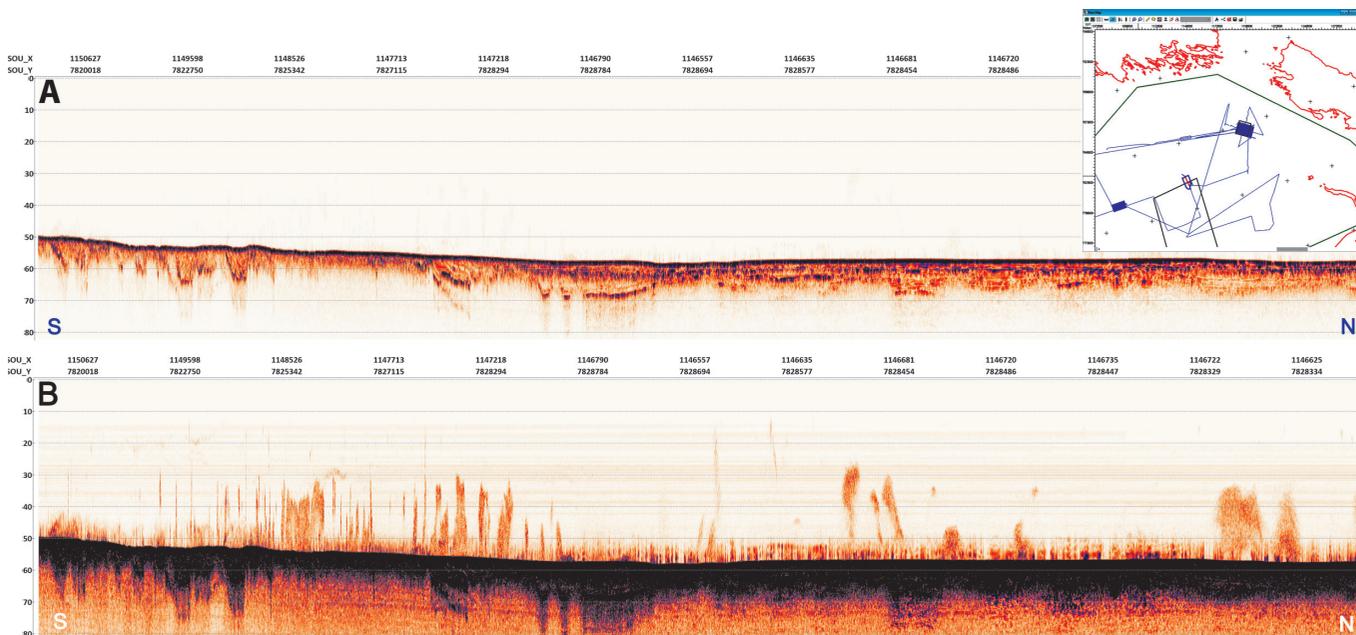


Fig. 8. Section fragment ANS38-P2-04 (section position shown in the inset). Vertical – milliseconds from the surface, horizontal – UTM37 meters. A – a section with gain in the range of bottom reflectors, B – a section with gain to isolate the SRA in the water column.

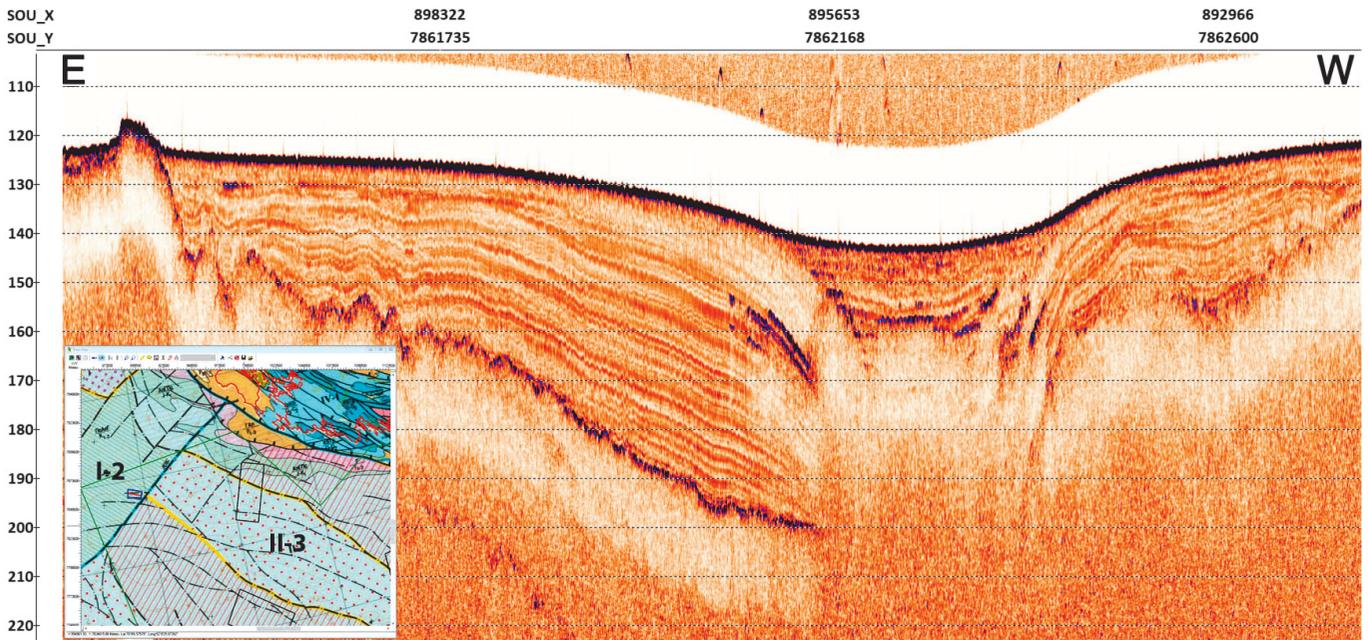


Fig. 9. Section fragment ANS38-014 (section position shown in the inset). Vertical – milliseconds from the surface, horizontal – UTM37 meters. The automatic gain control window is 40 ms long. In the inset, a tectonic map from the set of the state geological map R-39-40 of the 3rd generation (State geological map..., 2013) was used as a topographic base. I-2 – Murmansk-Kurentsovsky block. II-3 – Khoreyver block.

which indicates a fluid migration upstream. An elevation is formed on the eastern flank of the depression, exceeding the level of the undisturbed horizon. This indicates that a disjunctive dislocation was formed under compression. In the west of the section (Fig. 10), buried pockmarks were noted, under which low-contrast gas pipes are traced.

Synthesis

Mapping of free gas manifestations in acoustic anomalies in the water column and in seismic-acoustic anomalies in the upper part of the section forms an additional indicator of tectonic activity and the frame of the fault network. Apparently, fluid flows from deep horizons in which deposits of industrial importance are

formed. Comparison of the seismic-acoustic survey with the data of the deep CPD sections shows that the fluid in the upper part of the section first accumulates under the bottom of the Jurassic-Cretaceous sedimentary complexes, which are a fluid-resistor located on older eroded complexes. Small local disturbances in fluid uptake lead subsequently to the uplift and redistribution of free gas in the Quaternary complexes. The latter are characterized by strong variability of thickness and lithology, and also contain frozen areas, which, along with clay deposits, are fluid-resistant. Natural or artificial violation of its integrity leads to gas discharges into the water column from near-surface accumulations in the form of “bright spots” on the record. Mapping of sound-scattering objects in the water column shows degassing

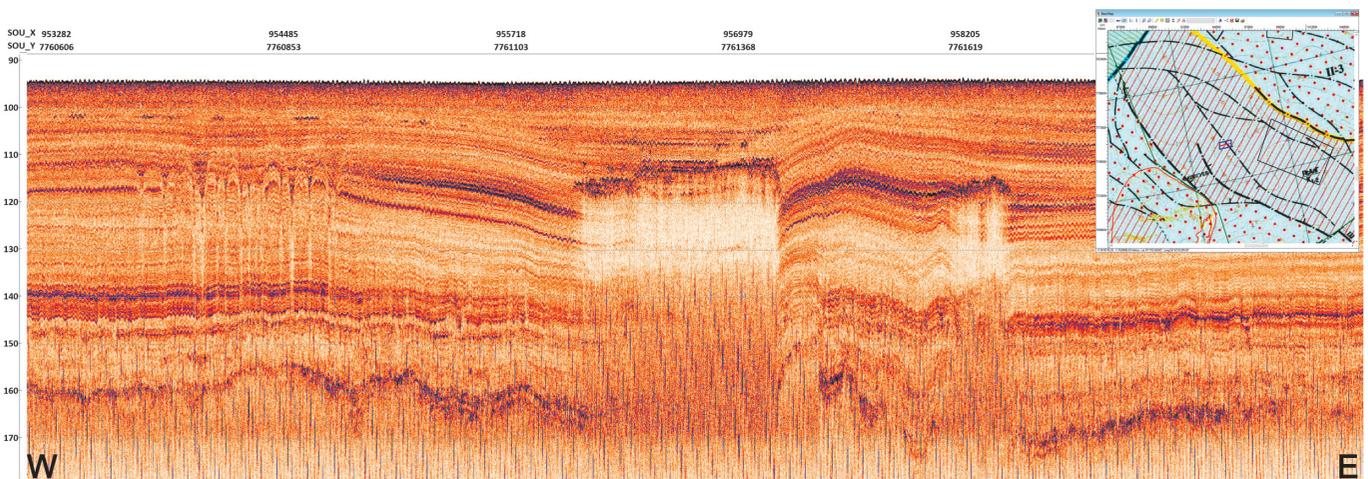


Fig. 10. Section fragment ANS38-038 (section position shown in the inset). Vertical – milliseconds from the surface, horizontal – UTM37 meters. In the inset, a tectonic map from the set of the state geological map R-39-40 of the 3rd generation (State geological map..., 2013) was used as a topographic base. II-3 – Khoreyver block.

areas, which are usually located above deep faults that displace ancient complexes up to the Paleozoic. This fault network also determines the distribution of paleochannels within the Pechora sea. The “bright spots” of free gas in the Quaternary complex have a diverse shape, sometimes multi-tiered, sometimes tilted, and gas breakthroughs into the water column occur, as a rule, near the edges of these anomalies.

A systematic mapping of the phenomena considered – sound-scattering objects and bright spots – is a necessary element in preparing the area for industrial operation. The features of the mapping technique of time-varying formations of sound-scattering objects are described in (Sokolov et al., 2017).

Conclusion

Let us formulate brief conclusions.

1. Free gas from deep sources forms two-level accumulations near the bottom surface of the Pechora sea – near the base of the Jurassic-Cretaceous complexes occurring on eroded older complexes disturbed by the fault network and in impermeable zones of the Quaternary sediments.

2. The tectonic, lithological, and thermal heterogeneities of the Quaternary sediments lead to the release of gas into the water column and the formation of abnormal sound-scattering objects, monitoring of which shows the state of permeability and activity of the stratified environment on which engineering is being conducted.

3. Seismoacoustic recording of the studied phenomena of degassing in the water column has the configuration of root sound-scattering objects, and in the upper part of the section there is a set of bright and flat spots with different slopes, sometimes with a multi-tiered structure. Anomalies in the water column are usually concentrated near the edges of the anomalies in the Quaternary sediments.

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Arctic shelf, the transition zone from the Pacific Ocean to Eurasia, certain regions of the Atlantic and Indian Ocean, the seas of Russia” (headed by S.L. Nikiforov), digitization and interpretation of anomalous objects in the Quaternary are performed partially in the framework of the topic of state assignment No. 0135-2019-0069 of the Geological Institute of the Russian Academy of Sciences “Dangerous geological processes in the World Ocean: connection with the geodynamic state of the crust and upper mantle and the latest movements” (headed by A.O. Mazarovich).

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