

SURVEYING WHITE SEA BOTTOM ROCKS AND SEDIMENTS WITH THE USE OF SEISMOACOUSTIC TECHNIQUES

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ABSTRACT. Geological, paleoclimatic and paleogeographic exploration in the Arctic Ocean usually encounters a number of natural constraints and difficulties. These are particularly awesome when close examination of glacial deposits is the task. Addressing this task invites techniques that work remotely. In the research below, the seafloor of the Kandalaksha Gulf of the White Sea is explored, employing the most promising of such techniques, seismoacoustics. Results: better knowledge of the geology of the study area; better knowledge of the seabed morphology of the study area; better knowledge of the structure and the surface relief of the crystalline foundation segment under the Velikaya Salma Strait; knowledge of dominant types of seismoacoustic response; knowledge of geological structures behind these types.

ПРОУЧВАНЕ НА ДЪННИТЕ СКАЛИ И СЕДИМЕНТИ НА БЯЛО МОРЕ ЧРЕЗ СЕИЗМОАКУСТИЧНИ ТЕХНИКИ

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РЕЗЮМЕ. Геоложките, палеоклиматичните и палеогеографските изследвания в Арктическия океан обикновено демонстрират редица природни ограничения и трудности. Това е особено очевидно при детайлното изучаване на ледникови отложения. За решаването на тази задача се прилагат дистанционни методи. В предложеното изследване е изучено дъното на Кандалакския залив на Бяло море с прилагане на най-ефективната методика в случая – сеизмоакустиката. В резултат е получено: по-добра информация за геологията на изучения район, по-добро разбиране за морфологията на морското дъно и по-добро знание за структурата и повърхностния релеф на сегмента от кристалинния фундамент под пролива Великая Салма, както и данни за доминиращите типове сеизмоакустични отражения, наред с информация за геоложки структури в дълбочина.

Geology of the study area

The modern White Sea is a basin with a rich and very complicated geological history. Tectonically, this basin is part of the encounter zone between the East European Platform and of the Fennoscandian Shield. The Kandalaksha Gulf in its northwest (Fig. 1) lies on the Mesoarchean-Paleoproterozoic structure known as the White Sea Shift Belt. In the period immediately after the Karelian tectonomagmatic cycle, the entire region was a single platform. In the Oligocene, it entered its neotectonic stage. (Baluev et al., 2004; Slabunov, 2009).

Geologically, there are two structural storeys beneath the seafloor of the Kandalaksha Gulf. The lower one, 8 km to 10 km thick, is crystalline bedrock of the Archean White Sea complex (mostly biotites, biotite gneisses, garnet-biotite gneisses, amphibole-biotite gneisses, amphibolites, granite-gneisses, alum shales and quartz rocks + multiple magmatic intrusions of varying nature and age). The upper one is a cover of sediment on this bedrock. This cover, in turn, consists of three layers. These are as follows (bottom-up): Riphean red sandstones, which fill avlakogenes in the foundation; southeastward terrigenous Vendian deposits; an almost

uninterrupted cloak of Pleistocene and Holocene deposits and sediments, which include glacial drifts, transitional glaciomarine sediments and purely marine sediments.

Past and recent geological and geophysical exploration has discovered particularly thick sediment layers in seabed troughs in the southeast of the Kandalaksha Gulf. The thickness there is over 150 meters in places. Overall, the geography and thickness of the Quaternary deposits closely reflects the pre-Quaternary surface of the seabed. The lower layers of the Quaternary deposit form what is termed the glacial deposit complex. At the base of this complex, characteristic glacial deposits are everywhere to be found. They usually consist of peripheral glacial moraine, which is the most widespread deposit type in the Kandalaksha Gulf.

This moraine, in turn, consists of clay-aleurolite sands peppered with pebbles and boulders. It has a low water content and a much higher density than other Quaternary deposits.



Fig.1. Map of the studied area

Topping the glacial deposits is a complex constructed during the transitional and the thalassic stages. The lower part of this complex is seabed sediment forming a distinct layer, which is in places 20 meters thick. Bottom up, this sediment becomes finer and gives way to ash-gray clays and alewives. (Nevevskiy et al., 1977; Devdariani, 1985).

The upper layer of the Quaternary deposits consists of purely marine sediment. This layer, in turn, comes in two rather distinct sub-layers: The lower sub-layer is mostly clay from the most advanced stage of the post-glacial transgression. It marks a transition from glaciomarine to normal marine sedimentation conditions. The upper sub-layer is a granulometric spectrum reflecting the most recent geological and sedimentation conditions.

Geological history of the White Sea

The modern White Sea is a young basin formed just 10 to 12 ka at the very end of the Pleistocene. During the Valdai glaciation, it was filled with ice. During the Allerod, freshwater lakes appeared around its perimeter. Towards the end of the Allerod, the ice started to quickly disappear. Barents seawater flushed in, and the process of subglacial sediment

accumulation started. The sediment from that time is uniform in composition but widely varies in thickness. The sedimentation progressed against the backdrop of very complicated, varied and often conflicting tectonic movements that are so typical of the White Sea region. Besides the post-glacial isostatic rise of Scandinavia amounted to some 100 meters in the White Sea area. The basin's deglaciation spanned the Pre-Boreal and the Boreal times and did not end until the early Atlantic. The resulting seabed sediment is very complex structurally, diverse lithologically and varied chronologically and genetically. With the ice gone, including the surface one, the current sea stage of sediment accumulation started, in which sea currents and the biota played increasingly important roles (Nevevskiy et al., 1977; Devdariani, 1985; Rybalko, 2009; Polyakova, 2010). This was how the unstable geography and the unstable tectonics of the White Sea in the Quaternary period resulted in a sediment layer that is so complicated structurally, so diverse lithologically and so uneven in thickness.

There are five major stages of the late-glacial and post-glacial deposit and sediment accumulation in the White Sea: 1) the glacial stage, in which moraine was formed; 2) the glaciolimnetic stage (Allerod), in which the sediment came from

several freshwater lakes filled with glacial water; 3) the glaciolthassic stage (late Dryas), in which the sediment (abundant and mostly uniform silt) came from a mass of seawater hidden beneath a thick ice sheet; 4) the transitional stage (the pre-Boreal and the Boreal times); 5) the thalassic stage (the middle and the late Holocene), in which marine-type sediment accumulation reigned supreme.

Researches and results

In the period since 2001, DEKO Geofizika Ltd and the Geology Department of Moscow State University have been conducting research to gain a better insight into the geology and tectonics of the Kandalaksha Gulf and assess the condition of the marine environment in this sub-Arctic shelf area. In the period since 2003, seismoacoustic surveys have also been carried out. In the Velikaya Salma Strait, there were detailed seismoacoustic surveys and continuous seismoacoustic profiling, which involved the use of a sidescan sonar and video cameras. The sediment has also been sampled in a number of locations (Sorokin et al., 2009).

Past and recent geological and geophysical exploration has discovered particularly thick sediment layers in seabed troughs in the southeast of the Kandalaksha Gulf. The thickness there is over 150 meters in places. Overall, the geography and thickness of the Quaternary deposits closely reflects the pre-Quaternary surface of the seabed. The lower layers of the Quaternary deposit form what is termed the glacial deposit complex. At the base of this complex, characteristic glacial deposits are everywhere to be found. They usually consist of peripheral glacial moraine, which is the most widespread deposit type in the Kandalaksha Gulf. This moraine, in turn, consists of clay-aleurolite sands peppered with pebbles and boulders. It has a low water content and a much higher density than other Quaternary deposits.

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The White Sea's bottom terrain is generally rugged. The Kandalaksha Gulf – its deepest part – is a narrow northwest-southeast depression with depths of over 100 m. In the study area, the bottom is generally 5 m to 90 m below the surface and drops to 150 m in places (map on Fig. 2). The shallowest parts (depths within 30 m) are in the west, near the Yermeyevsky and the Nilmogubsky thresholds, near the Olenevsky and the Veliky islands and near the Kindo cape, which continues as a shallow into the Velikaya Salma Strait. The deepest parts are in a central trough under this strait. The northern slope of the trough is much steeper than the southern one. Along the central axis of the trough are several more or less isometric (if viewed from above) depressions with depths of up to 100 m. Seismocomplexes identified by examining seismoacoustic response (bottom-up): 1) acoustic base; 2) glacial deposits; 3) postglacial and glaciomarine sediment; 4) late-postglacial sediment; 5) recent marine sediment.

Seismocomplex №1, palpable only as its roof. It is easily recognized by a uniform acoustic response with high reflectivity, significant diffraction and clear high-amplitude low-frequency equiphase axes. This complex comes in distinct blocks. Geologically, it is the roof of parent rock – granite-gneisses from the Archean.

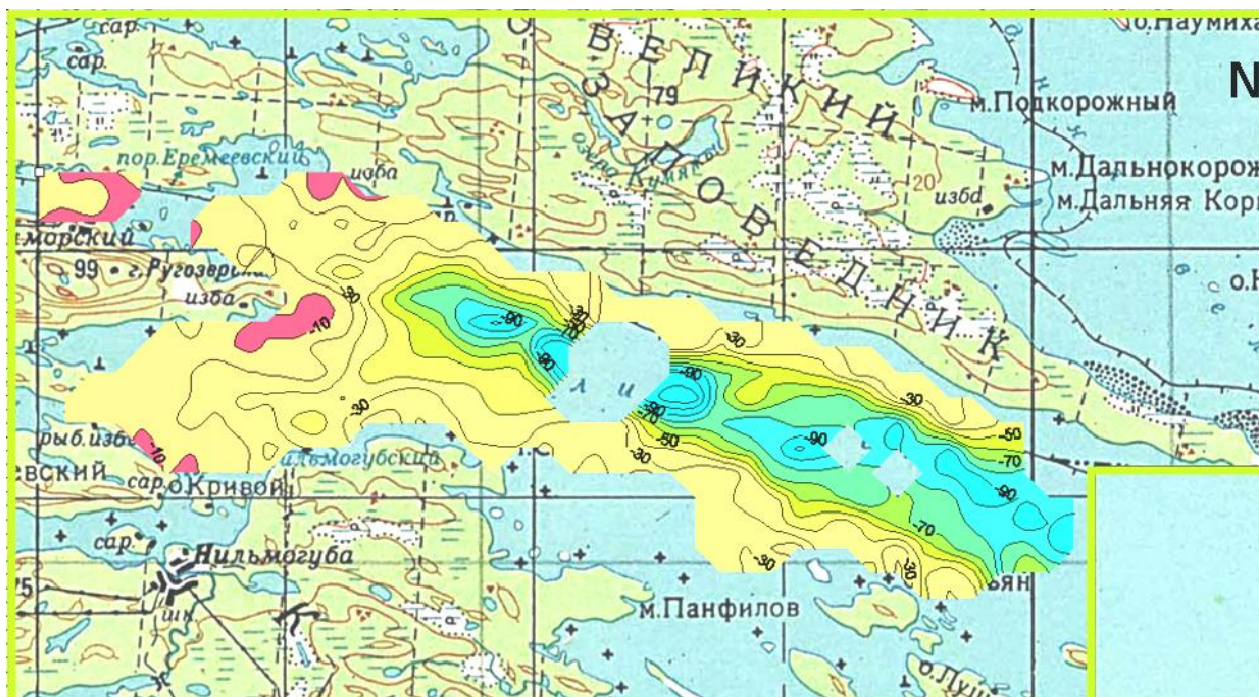


Fig. 2. Bottom surface of the study area

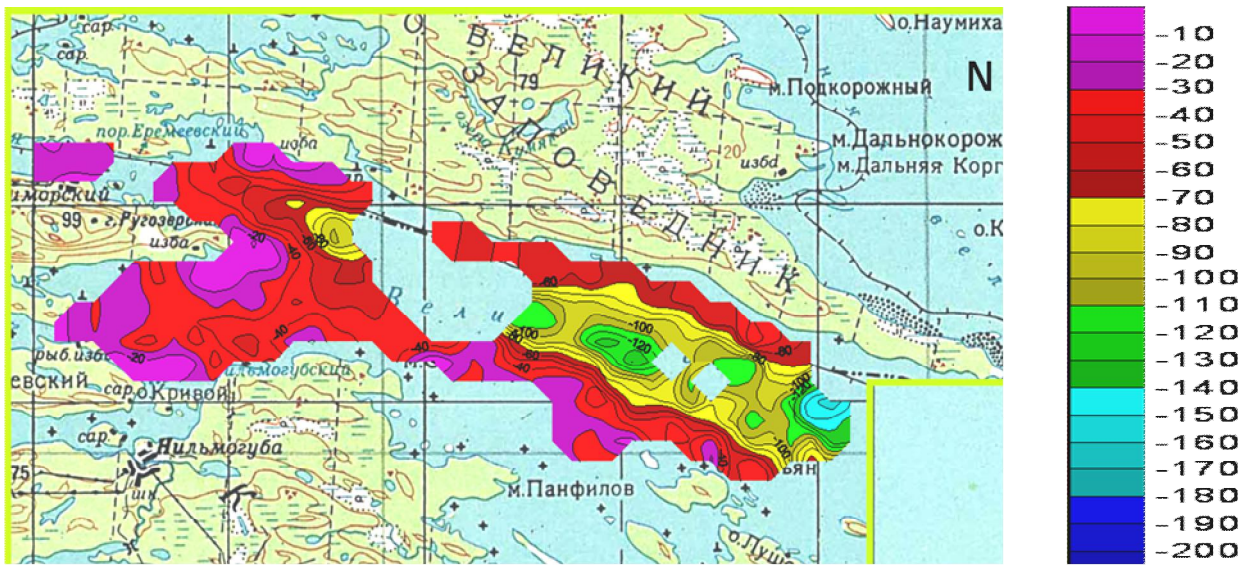


Fig. 3. Bedrock surface of the study area

Fig. 3 is our map of parent rock terrain in the study area. The crystalline foundation reaches the modern sea bottom in just a handful of places. In all other places, it is covered by younger complexes. The foundation's roof is 5 m to 210 m below the sea surface. The shallowest parts – within 30 m of the sea surface – are in the western segment of the study area. The deepest parts are in a graben-like structure stretched along the main axis of the Velikaya Salma Strait. The southern slopes of this graben are much steeper than the northern ones. Along the central axis of the graben are depressions dropping to 170 m below the sea surface.

Seismocomplex №2, made of glacial deposits. It is recognized by a chaotic seismic response with very high-amplitude positive short equiphase axes. As seen on seismoacoustic profiles, both the roof and the sole of this complex are very uneven. Geologically, this complex is most probably moraine from the Valdai glaciation (Europe's latest).

The moraine because its continental origin has a much higher acoustic reflectivity than the marine sediment above it.

Seismoacoustic profiling with towing speeds between 1.800 m/s and 3.000 m/s (average 2.600 m/s) allowed us to map the bottom moraine (Fig. 5). The latter is quite widespread across the study area, but there are places where it is absent. In some places, the moraine is in direct contact with seawater. Generally, however, it is blanketed by younger complexes.

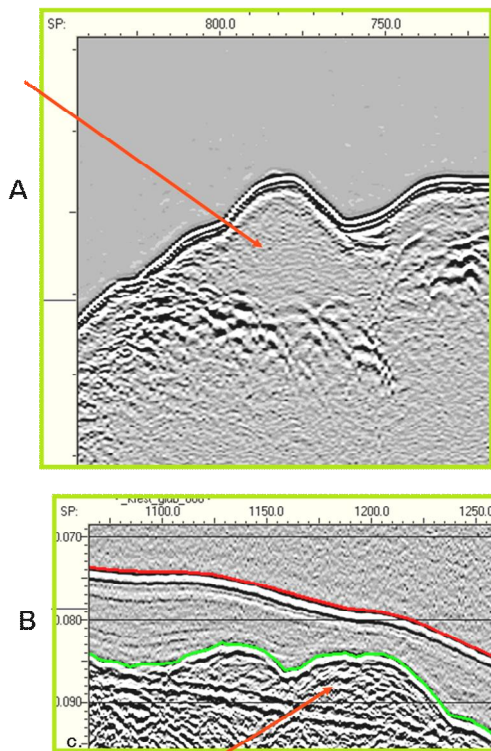


Fig. 4. Seismic response from bottom moraine (seismocomplex № 2): a) acoustically transparent (fragment of Profile p_208); b) chaotically irregular (fragment of Profile pr_08)

Within the study area, the moraine is at its most pronounced along the northern slope of the graben-like structure under the Velikaya Salma Strait. According to Yevzerov (2005), the Valdai glaciation supplied what is now the Kandalaksha Gulf with a glacier in the form of a tongue. The northeastern and the southern boundaries of this erstwhile tongue are marked by thick peripheral moraine belts. Indeed, our exploration discovered underwater drift beds 30 to 40 m thick along the northeastern shore slope of the Velikaya Salma Strait. They are apparently part of the southwestern peripheral moraine of the glacier, with an estimated age of 10 thousand years (Yevzerov, 2005). Further up, there are three more sedimentary seismocomplexes, each showing angular discrepancy with the lower one.

Seismocomplex №3, detectable by low-amplitude chaotic seismic records with weakly pronounced equiphase axes. This complex most likely consists of glaciolacustrine sand and clay deposits. They cover the moraine or, in places with no moraine, the crystalline foundation. They are not widespread, occur locally and fill depressions in the underlying layer (or layers). They also show very weak stratification compared with the upper seismocomplexes. Their thickness is under 5 m

above the moraine and up to 15 m in depressions on the crystalline foundation (Fig. 6).

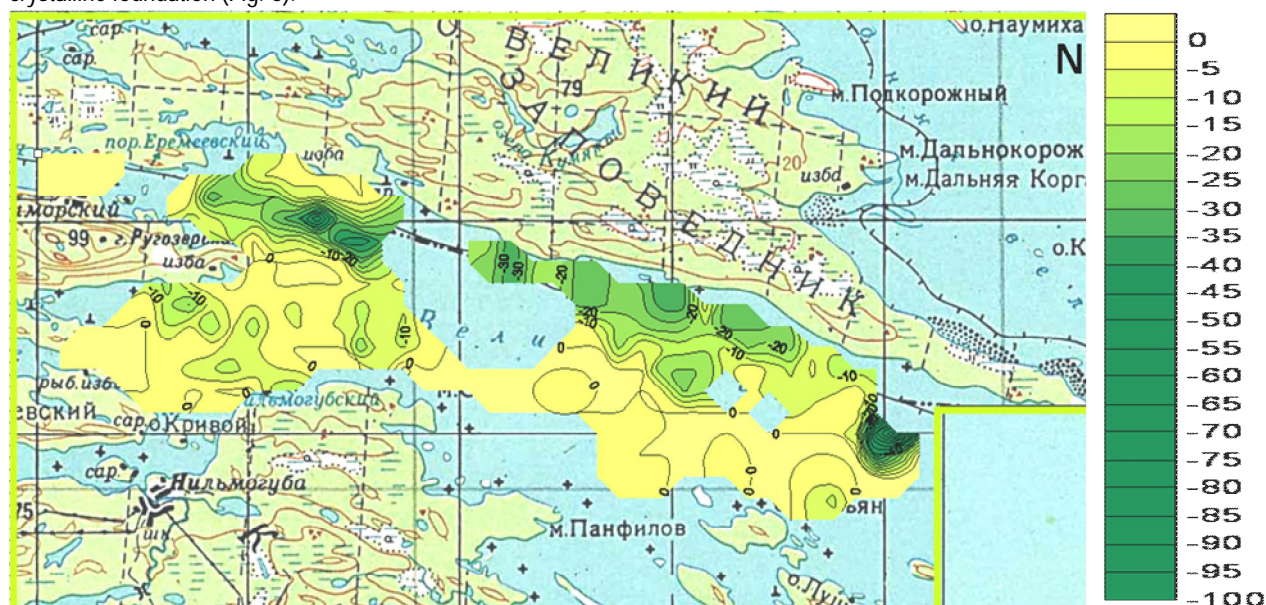


Fig. 5. Moraine thickness map



Fig. 6. Generalized thickness map of the supra-moraine sediment layer

Seismocomplex №4 covers *Seismocomplex №3* with sharp directional discrepancy. It is detectable by a distinctly stratified seismoacoustic record, which closely follows the underlying terrain. Its thickness is between 1 m and 10 m. It most probably consists of late-postglacial terrigenous fine sediment.

South of Cape Kindo, *Seismocomplexes №3* and *№4* are very well differentiated and separated from each other by a clear high-amplitude boundary. In other parts of the Velikaya Salma Strait – with the total deposit and sediment layer of up to 50 m – there is no clear seismoacoustic differentiation between *Seismocomplexes №3* and *№4*, and we lump them together with *Seismocomplex №5* into what we term *the supra-moraine layer*.

Seismocomplex №5 consists of the most recent marine sediment – a very thin layer of silt with varying thickness. It overlays the lower seismocomplexes with directional discrepancy. Our techniques discover this sediment exclusively in depressions. Direct sampling reveals the presence of a 10- to 15-cm layer of highly liquefied silt at the top of the recent sediment profile (Sorokin, 2009).

Fig. 6 shows a generalized thickness map of the supra-moraine sediment layer. The speed of sound in seawater presumed at 1,600 m/s.

Conclusions

The principal results are as follows: improved knowledge of the geology and tectonics of the area; improved knowledge of the sea bottom surface of the Kandalaksha Gulf (this sea

bottom surface usually follows the one of the underlying bedrock surface); a map of the sea bottom surface of a significant part of the Gulf; improved knowledge of the structure and the surface of the underlying bedrock under the Velikaya Salma Strait; typology of seismographic records in the Strait; geological identification of these types; the spatial distribution of these record types; a systematized compendium of all seismoacoustic data from the Kandalaksha Gulf. A close examination of recent and earlier seismographic records from the study area enabled us to identify the following seismocomplexes (bottom-up): 1) the acoustic bedrock; 2) the glacial deposit complex; 3) the post-glacial and the glaciomarine sediment complex; 4) the most recent marine sediment complex.

Detailed seismoacoustic profiling allowed our team to gain a better insight into the geological structure of the White Sea Basin. The complicated history, geology and tectonics of this basin make it an excellent proving ground in which to hone techniques for interpreting seismoacoustic data from glacial shelf areas. The types of seismographic records identified in the White Sea are probably yardsticks for exploring shelf seabed in other Arctic seas. Seismoacoustic methods are very useful for researching Cainozoic sediments in these seas. Such exploration produces a wealth of knowledge about the surface terrain of the bedrock and also about the vertical structure (usually highly complicated) of the Quaternary sediments in Arctic basins. It also largely eliminates the need for direct sampling of these sediments. The exploration techniques developed and tested out in the White Sea are almost certainly applicable to the wider Arctic Ocean and other marine basins.

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