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The Deep Structure of the Earth's Crust beneath the White Sea Based on Seismic Data

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Abstract—New data on the deep structure of the White Sea have been obtained. An interpretation of traverses 510 km in total length is presented. It has been found that the area of the Black Sea that was surveyed with the traverses is characterized by a consolidated crust consisting of two layers. In the velocity sections, interleaving of horsts and grabens is sharply identified. In the central part of the sea, an isometric trough is found with sediments up to 7–8 km thick. The trough is surrounded by east- and northeast-striking ledges and faults. Rocks with anomalously increased velocities are found in the lower part of the sedimentary cover. The thickness of the upper crust is 5–7 km. The lower crust is of a complicated structure and is 30 km thick; it forms a large fold surrounded by rocks with decreased velocitys.

Keywords: seismic interpretation, deep seismic studies, the White Sea, tectonics.

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INTRODUCTION

The study of seas to the north of the European part of Russia has been continuing for more than 40 years. Despite the very great number of geological–geophysical studies, many issues concerning the deep tectonics of this region, which have a complicated structure, remain unsolved. New data that were obtained on the basis of traverses in the White Sea are considered here. Traveltame curves based on the traverses, obtained by the OAO Morskaya arkticheskaya geologorazvedochnaya ekspediciya by the refraction method were used as the initial materials for plotting of the sections. The interpretation results for seismic sections along the regional traverses of more than 510 km total length obtained by the refraction method are presented. The studies are aimed at revealing the deep structure of the crust in the considered region.

GEOLOGY OF THE REGION

The basin of the White Sea is located in the area of the joint between the Baltic Shield and the East European Craton at the location of the Riphean aulacogene, in a region that was repeatedly glaciated throughout the Quaternary. The basin was filled with water only at the end of the Late Pleistocene; therefore, its geologic structure and evolution were directly connected with the environment.

The nature of the White Sea basin is determined by its position on the eastern slope of the crystalline Baltic Shield in the shield–craton transitional zone. The predominance of upward tectonic movements accompanied by denudation caused the nearly complete absence of the Paleozoic–Mesozoic and Cenozoic sedimentary cover and discontinuity of the Quaternary cover in the northern and southwestern framing of the sea [Devdariani, 1985].

In a monograph by V.N. Zander [1972], the following aulacogene structures were identified within the White Sea on a map demonstrating the bedding depths of the Preriphean basement: the Onega–Kandalaksha aulacogene, within which the depth of the basement reaches 3000 m (in the mouth of the Bay of Kandalaksha), the Leshukonskii aulacogene, and the Lower Mesen' trough. Negative structures are divided by rises of the crystalline basement, namely, the Kuloi ledge and the Arkhangelsk horst.

According to V.E. Khain [1977], the geological evolution of the region can be subdivided into two stages, namely, aulacogene (Riphean) and plate (Vendian–Phanerozoic). Based on the stages that occurred, the plate stage, in its turn, can be subdivided into three substages: isolation of the Baltic Shield and East European Craton and the laying of the Baltic–Moscow syncline (Vendian); low tectonic activity with a predominance of upward movements (Cambrian–Early Paleogene); and the neotectonic substage and formation of the White Sea basin (mid-Paleogene–Holocene).

During geological interpretation of the data, the 3-AR traverse made by Sevmorgeo was considered, in addition to the M2, M4, and M5 traverses. Interpretation

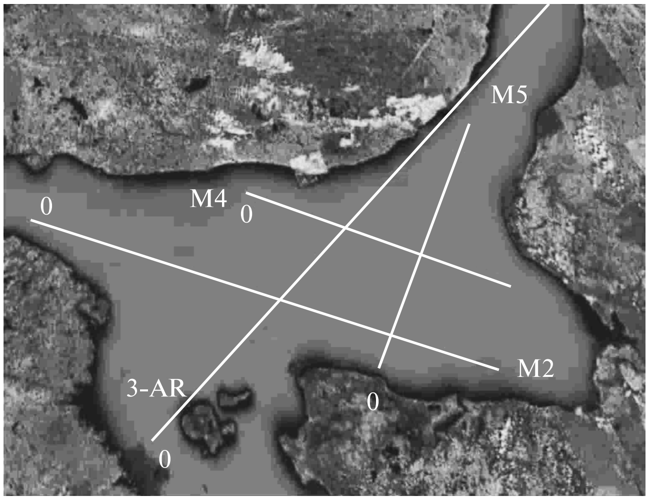

Fig. 1. The scheme of the traverse locations in the water area of the White Sea. Nulls designate the initial points of the traverses.

of this traverse was made previously [Kunitsyn and Piip, 2008a, 2008b].

OBSERVATION AND INTERPRETATION METHODS

Seismic studies within water areas are carried out using nonexplosive sources only. The most widespread sources are pneumatic sources.

The main object of the work is the study of the section of the sedimentary cover and crystalline basement. Marine seismic works using the refraction method were carried out with the use of autonomous bottom seismic stations (ABSS) of the Gnom-07 hardware complex (manufactured by FGUP Tekhmorgeo) that performed signal receiving and recording.

Excitation of elastic vibrations was made by two pneumosources of the PPI-M type every 2 min, which corresponds to a 250-m distance at an average boat speed of 4 knots.

The M2, M4, and M5 traverses were made in the *Geofizik* in 2007 (Fig. 1). In the M2 traverse, bottom stations were installed every ten kilometers, at a traverse length of 140 km; in the M4 traverse, the distance between stations was 8 km on average and the length was 130 km; the length of the M5 traverse and the distance between stations in it were 140 and 9–10 km, respectively.

The method of homogeneous functions was used for the purpose of processing, interpretation, and plotting of the seismic sections. This method is used to invert traveltame curves into a two-dimensionally heterogeneous velocity section. The method is based on the local approximation of the real velocity distribution by a continuous homogeneous arbitrary power function, which grows monotonously as the polar angle increases [Piip, 1991; Piip, 2001].

Initial models were not used during the construction of the sections. Sections along all the traverses were calculated independently; therefore, comparison of velocity curves in the points of traverse crossings gives an indication of how precise the determination of the velocity values is.

The GODOGRAF program was used during the construction of the sections; this is universal software for the interpretation of systems of refracted wave traveltame curves. The interpretation process is completely automated. Refracted wave traveltame curves were used as initial data. The identification of refracted waves from various refraction interfaces in traveltame curves from various sources is not required if it is implemented automatically. The program enables one to construct velocity sections, horizontal deep cross sections, curved surfaces (for example, the relief of dividing interfaces), and sections of physical parameter distribution.

The sections resulting from the homogeneous function method are presented in the form of velocity values calculated in rectangular mesh points. Such a representation is often referred to as a “grid model.” Numerous programs have been developed for the visualization of grid models. In particular, a surface with highlighted relief is used. Owing to the fact that sections calculated by the homogeneous function method contain information concerning dividing interfaces and faults, this representation appears to be very convenient for the automatic visualization of dividing interfaces in sections. At this highlighting, first and second type interfaces, inversion dividing interfaces, and tectonic failure are visualized. First type interfaces are those where a velocity of waves increases in a downward direction. Upon light penetration from the top, interfaces where velocity increases are highlighted in a traverse as bright lines; interfaces where velocity decreases (inversion interfaces) are seen as dark lines. The second type of interfaces is used for changes in the velocity gradient. An increase in the gradient is shown in the sections with highlighted relief as bright zones; a decrease in gradient is shown as dark zones. Faults and tectonic failures are shown as dark or bright lines depending on their slope and direction of motion.

Sections with a lighted relief of the velocity field can be conveniently combined with velocity isolines in order to trace the manner in which the velocity changes along the dividing interfaces. Additionally, sections are viewed as velocity fields where velocity values are indicated with colors.

Such a representation of the sections helps one to analyze and interpret the obtained data.

THE RESULTS OF THE GEOLOGICAL INTERPRETATION OF SEISMIC SECTIONS

The refracted wave traveltame curves observed along the M2 traverse are shown in Fig. 2. Interpolation was used to supplement the system. Thick lines indicate the observed traveltame curves; thin lines indicate those that were supplemented using interpolation. For the purpose of interpolation between traveltame curves, the representation of the system in the form of an equal offset section [Piip, 2001] was used. During calculation of the section, traveltame curves from all the receiving stations were used (Fig. 2).

In the other traverses, observation systems of nearly the same detail were obtained. The seismo-geological section along the M2 traverse is exhibited in Fig. 3. Isolines are drawn with a step of 0.25 km/s. The distance between isolines is inversely proportional to velocity gradient; hence, values of velocity gradient in a section can be estimated visually.

By using the example of the M2 traverse, the principles of layer identification can be illustrated. The consolidated crust in the White Sea basin generally has a two-layer structure.

Three layers are identified in all the traverses made in the White Sea, viz., sediments, the upper crust, and the lower crust. Every layer is characterized by a certain approximately stable interval of velocity values. This interval is 3–6.4 km/s for the sedimentary cover, 6–7 km/ s for the upper consolidated crust (basement), and 6.4–8 km/s for the lower crust. The velocity gradient has certain predominant values in every layer. The velocity gradient in the sedimentary cover is characterized by higher values. In the case where the velocity in the upper layer is higher than in the lower one, the layers are divided with continuous inversion interfaces.

Faults form an autonomous system in every layer and do not cross dividing interfaces.

The ***M2 traverse*** goes near the axis of the Onega–Kandalaksha graben. The depth of the obtained section reaches 20 km.

The *sedimentary cover* within this traverse is characterized by a higher velocity gradient. The velocity varies from 3 km/s near the roof to 6.4 km/s near the base of the layer. In the western part of the traverse, in the stakes from 0 to 70 km, the thickness of the layer is reduced to 1–3 km. Here, the step of the basement (of the upper crust's roof) is observed. In the central part of the traverse, sediments are immersed to the depth of 7 km. In the stakes in the interval of 160–180 km, a narrow depression of less than 20 km width and up to 8 km depth is distinguished. The graben is expressed in the sharpest way within the basement.

Rocks with a high velocity (6.4 km/s) occur in the lower part of the sedimentary cover. Risen and sunken blocks are interleaved in the sedimentary cover.

The *upper crust* (basement) is traced at depths from 2 to 7 km. The velocity varies along a vertical line from 6 to 7 km/s. The layer's thickness is about 5 km. The behavior of faults is chaotic.

The lower crust is sharply identified in the traverse and has an ordered structure. The depth of the roof of the layer varies from 7 km in the west to 10 km in the east. velocity values vary from 6.4 to 7.7 km/s. The layer is an interleaving of the blocks with a 10–30-km width and dips southeastwards at about 30°. The blocks are divided with listric faults that dip southeastwards and have a common end at depths ranging from 20 to 15 km.

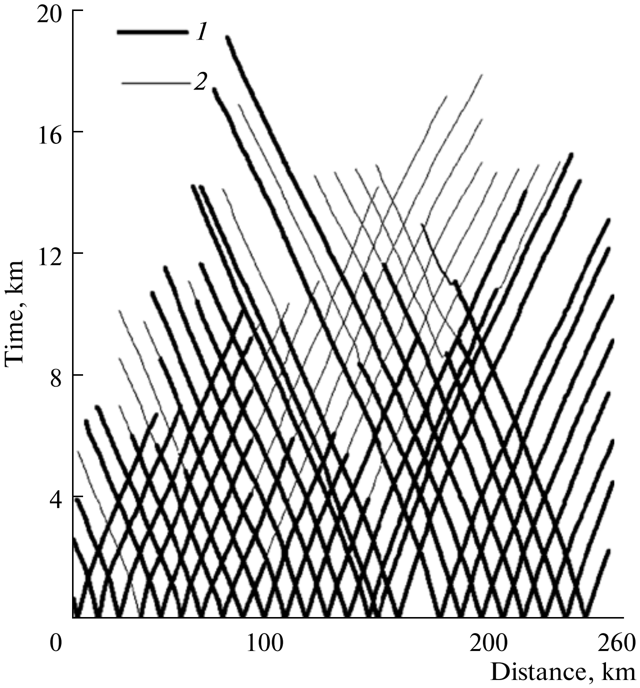

Fig. 2. The system of observed (*1*) and interpolated (*2*) refracted wave traveltame curves along the M2 traverse.

The ***M4 traverse*** (Fig. 4, bottom left) goes approximately 50 km to the north of the M2 traverse and crosses the Keret' graben along its axis. The depth of the obtained section is 16 km.

The *sedimentary cover* within this traverse characterizes the Keret' graben structures. The velocity in the layer varies from 3 km/s near the roof to 6.6 km/s in the base. In the northwest of the traverse in the interval of stakes from 0 to 70 km, the thickness of the layer is reduced to 3 km. Here, a step of the basement is observed. In the sedimentary cover, horsts and grabens are sharply expressed. In the central part of the traverse, sedimentary deposits are immersed to the depth of 7 km. In the lower part of the sedimentary cover, the rocks with a very high velocity (up to 6.6 km/s) are bedded.

The *upper crust* (basement) is traced in depths ranging from 3 to 7 km. velocity varies along a vertical from 6 to 7.4 km/s. The thickness of the layer is about 5 km. The behavior of the faults signifies the presence of overthrusts and covers in the upper crust.

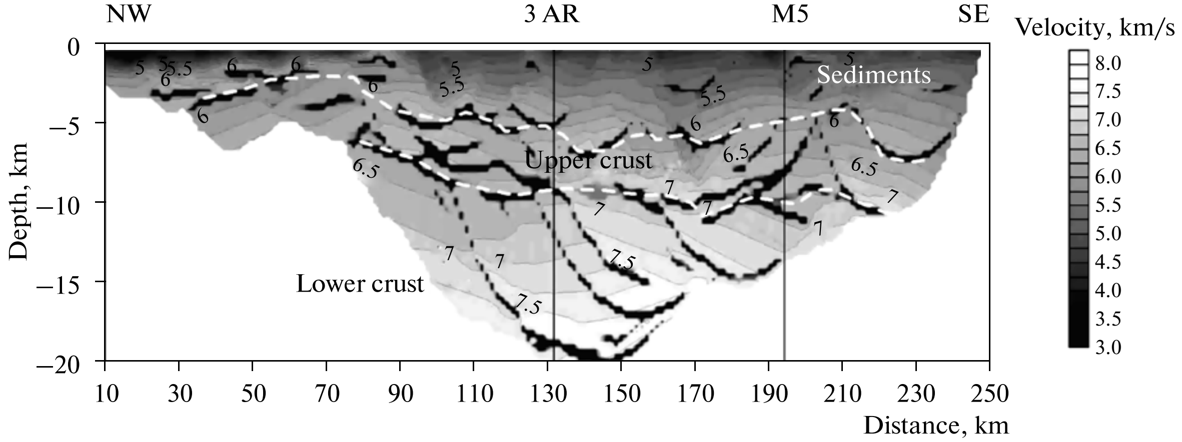

Fig. 3. The seismo-geological section along the M2 traverse. The step of the velocity isolines is 0.25 km/s. The dividing interface between the crustal layers is shown as a white dashed line.

The *lower crust* in this section is seen only within a very limited domain and is characterized by decreased velocity, which varies from 6.4 to 7.4 km/s.

The ***M5 traverse*** travels in a northeastern direction in the central part of the White Sea and crosses the M2 and M4 traverses; its length is about 130 km.

The resulting seismo-geological section is exhibited in Fig. 4 on the top right. The isolines are drawn with 0.2-km steps. The structures of the Keret' graben are distinguished in the section.

The *sedimentary cover* is characterized by a higher velocity gradient. The velocity changes from 3 km/s in the roof to 7 km/s in the base. High velocity layers (up to 7 km/s) in the base of the sedimentary cover are thrusted over each other in a northeastern direction. The thickness of the thrusts is 2–3 km. Relatively low-velocity deposits 1–1.5 km thick are bedded between the thrust slabs. The depth of the graben is 10 km.

The thickness of the *upper crust* (velocity is 6–6.2 km/s in the roof and 7.2 km/s in the base) varies along the traverse from 2 to 7 km. A trough filled with high-velocity rocks was identified in the central part of the traverse, beneath the Keret' graben at the base of the upper crust. The behavior of the faults signifies a compression environment.

The *lower crust* in the traverse is located in the interval of depths of 8–12 km.

The ***3-AR traverse***. The most detailed observation system in the considered region was obtained in the 3-AR traverse. Thus, the section is very detailed and complex. The section with its geologic interpretation is given in Fig. 4 at the bottom and in [Kunitsyn and Piip, 2008b].

The *sedimentary cover* in the section is characterized by sharply varying thickness. Several depressions and ledges form a syncline and fill the Onega–Kandalaksha graben. Sedimentary rocks have the highest thickness in this graben (6 km).

Between the Onega–Kandalaksha and Keret' grabens (stakes in the interval of 80–170 km), at depths of 15–27-km, the *upper layer* of the consolidated crust reaches a thickness of 10 km. The eastern portion of the upper crust is complicated by several east-dipping tectonic failures. The thickness of the upper layer of the consolidated crust is significantly decreased here and becomes less than 3 km in the area of the stake at 250 km.

The *lower crust* has a significant thickness. Lowered velocity zones are traced within its limits. The lower crust has a folded-thrust structure. Thrust structures are identified in its lower part (with a velocity of 6.5–7.8 km/s). Similar structures are usually formed during motion of the crust; this process is accompanied by the appearance of a ductile zone, and then, with the formation of a fold that is complicated by a thrust. Rocks that are distinguished by lowered velocity values (6.2–6.8 km/s) occur in the center of the fold and at its periphery. The amplitude of the fold-thrust structure in the lower crust of the White Sea basin is 10–15 km and the length of the structure is up to 200 km. Analogous structures are traced along the section of the 1-AR traverse made in the Barents Plate [Kunitsyn and Piip, 2008a].

The thickness of the lower layer of the crust is about 20 km. The Moho discontinuity is found at depths of 43–45 km.

MAPS OF CROSS SECTIONS

In order to trace the spatial structure of the crust, we combined the data of the traverses and constructed horizontal velocity cross sections for various depths. The resulting cross sections characterize only the central part of the White Sea, because the traverses form a sufficiently representative network only in this area.

Cross sections were made for various depths and with various steps. In the final version, the levels of

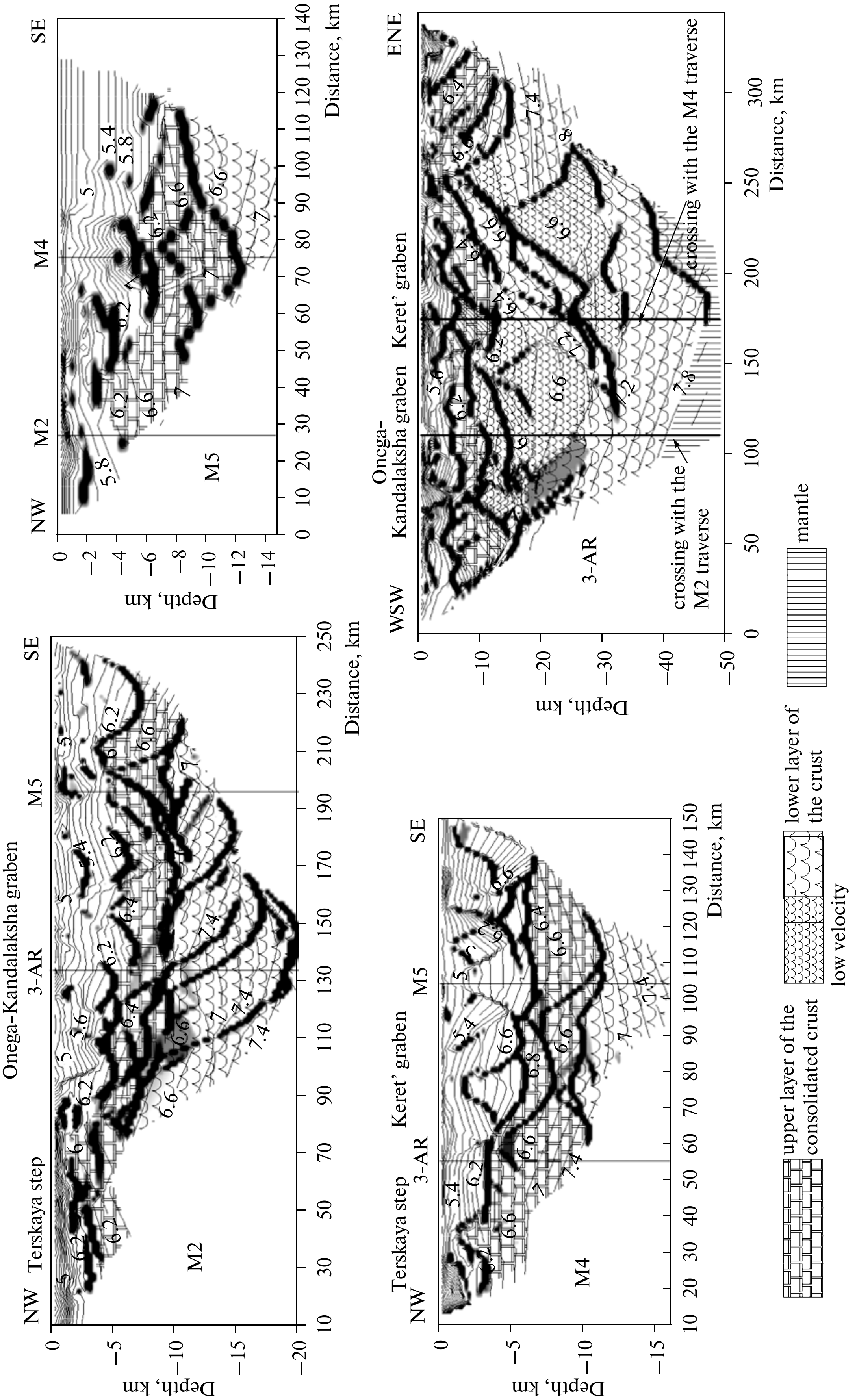

Fig. 4. The seismo-geological section along the traverses in the White Sea. The names of the traverses are written on sections. The step of velocity isolines is 0.2 km/s.

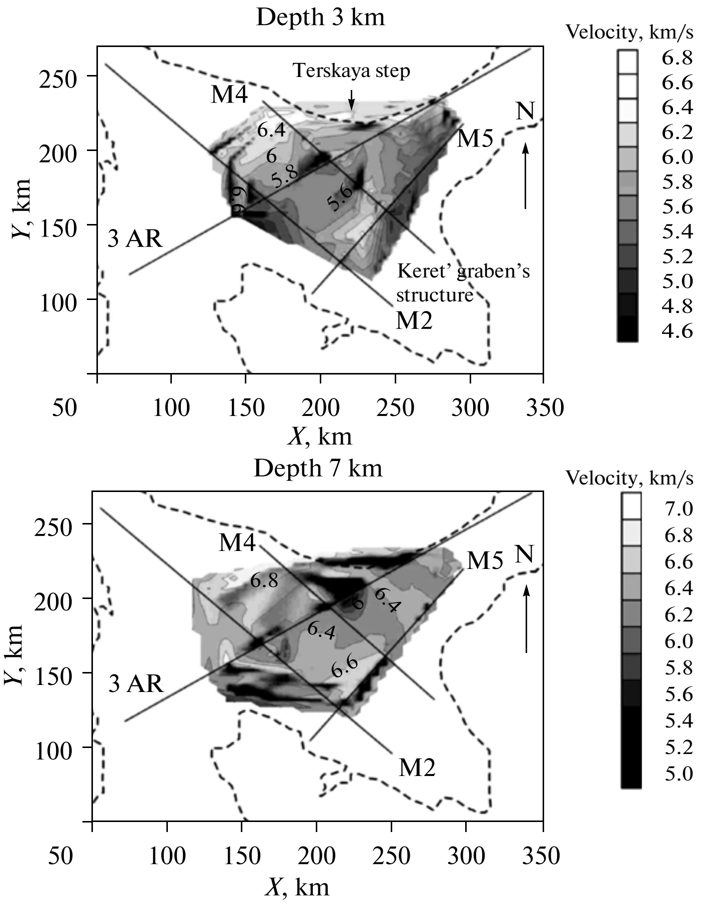

Fig. 5. Horizontal velocity cross section maps for 3 (top) and 7 (bottom) km depths. The step of velocity isolines is 0.2 km/s. The dashed lines mark the White Sea coast line.

3 and 7 km were chosen. There, the cross sections characterize the graben structures in plan.

The *3-km level* (Fig. 5 top) is located in the sedimentary cover. Figure 5 demonstrates the velocity section, which is combined with the map demonstrating the velocity field's relief with the step of isolines of 0.2 km/s and velocity scale. Here, the graben structures and faults that divide them are visible. Faults are seen as dark lines. As the velocity grows with depth, high-velocity domains (bright) are ledges, and low-velocity ones (dark) are depressions. In Fig. 5, interleaving of high- and low-velocity blocks is seen. In the area of the M4 traverse, two northeast-striking grabens of approximately the same size are traced. The grabens are divided by a horst with a width of about 25 km. In general, the section is an isometric depression 100 × 100 km in size, surrounded by northeast-, east-, and north-striking ledges.

The cross section for the 7-km depth is shown in Fig. 5 at the bottom. The depth of 7 km approximately corresponds to the roof of the basement. Two mutually shifted grabens occur in the M4 and M2 traverses. The velocity within the grabens is 6–6.2 km/s. The filling deposits in the depressions have a velocity of 6.4 km/s. The depressions have a north strike. In general, a large depression was identified at this depth; it is surrounded by northeast- and east-striking ledges and faults.

THE RELIABILITY OF THE SECTIONS

The reliability of the sections and errors of velocity determinations were studied by comparison of velocity curves in the lines of traverse crossings. The rms deviation of the velocity curves does not exceed 0.2 km/s. It is seen from the graphs in Fig. 6 that the peculiarities (changes in inclination angles, which indicate changes of the dividing interface) are the same in different traverses.

The traverses travel within the limits of the large geologic structures that were identified previously. These structures were also displayed in the sections. The main results concerning geology, which were obtained for the first time, deal with the deep parts of the crust, where other methods yield either a low level of detail, or insufficient reliability. As a result of these studies, the structure of the consolidated crust was generalized and analyzed. The processing and interpretation of the seismic information obtained in the

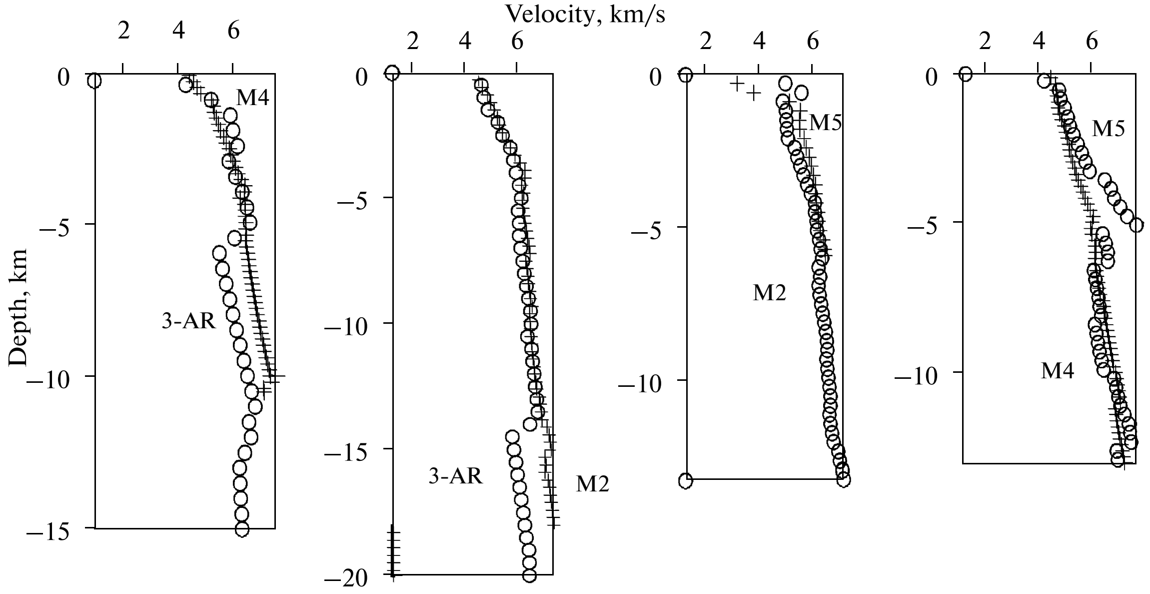

Fig. 6. Comparison of velocity curves in the crossings of traverses. The names of the corresponding traverses are written on the graphs.

White Sea region by the refraction method enabled us to identify new features of the region's deep structure. These results demonstrate the high efficiency of the method under the conditions of a detailed observation system and the complex heterogeneous structure of the shelf of Russia's northern seas (based on the example of the White Sea).

CONCLUSIONS

1. The White Sea region, through which the traverses travel, is characterized by a consolidated crust that consists of two layers. The thickness of the upper crust is 5–7 km. The lower crust has a complex structure and forms a large fold surrounded by low-velocity rocks; the thickness of this layer is up to 30 km.

2. Interleaving of horsts and grabens is clearly seen in the velocity section along the traverses; the positions of these structures are known from previous studies.

3. A trough was found in the central part of the sea, where the thickness of sedimentary deposits reaches 7–8 km. The trough is surrounded by east- and northeast-striking faults. Sediments with anomalously high velocitys are bedded in the lower part of the sedimentary cover.

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