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Crustal Structure in the Barents–Kara Region from Detailed Surveys by the Method of Deep Seismic Sounding. Paper 2

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Abstract—Seismogeologic sections for the Barents–Kara region along geotraverses 1-AR, 2-AR, and 3-AR with a total length of about 4000 km were obtained using the GODOGRAF software package developed at the Department of Seismometry and Geoacoustics of the Moscow State University. The data were travel times of refracted waves excited by approximately 100 sources along each traverse. This paper reports sections for the 3-AR traverse covering areas of the White Sea, Pechora Sea, and Kara Sea, and a geological interpretation of these. The sections cover depths down to 40–50 km and show basic crustal discontinuities, fold–thrust, rift, and paleospreading structural features, and paleosubduction zones. We characterize the possible character of the junction between the South Kara and North Kara basins. A geodynamic interpretation of the structures is provided for the Barents–Kara region.

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INTRODUCTION

Detailed seismic surveys were performed in 1995–2005 along geotraverses 1-AR, 2-AR, and 3-AR with a total length of about 4000 km within the framework of the Federal Program for establishing a network of geophysical traverses. The detailed surveys were carried out using reflected (CDP) and refracted (deep seismic sounding, abbr. DSS) waves.

Seismic sections were derived from travel times using the GODOGRAF software package developed at the Department of Seismometry and Geoacoustics, Moscow State University. The previous paper [Kunitsyn and Piip, 2008] reported interpretations for the traverses 1-AR and 2-AR. Here we give seismic sections along the traverse 3-AR in areas of the White, Pechora, and Kara seas down to depths of 40–50 km and a geological interpretation of these.

Major crustal discontinuities, fold–thrust, rift, and paleospreading structures have been identified in the sections. A paleosubduction zone has been reconstructed in the North Siberian Sill.

TECTONICS

The *South Kara basin* is a marine extension of the northern margin of the West Siberian plate. The basin is separated on the northwest, west, and southwest from the Barents and Novaya Zemlya plates by a series of arcuate faults. The South Kara and North Kara basins are separated by the North Siberian tectonic sill (Fig. 1). The basement of the South Kara basin is of Late Devonian age and is dissected by a set of narrow grabens in the middle. It is supposed that the spreading process in the Kara basin facilitated the generation of thrust structures in Novaya Zemlya during early Mesozoic time [*Ob"yasnitel'naya…*, 1996].

Magmatism has played a significant role in shaping the structure of the Barents–Kara continental margin and its basins. The Jurassic phase of tectonic activity due to plume magmatism led to rifting. The Cretaceous phase was related to the rift origin, its transformation into spreading with accretion of the Cretaceous oceanic crust, and extinction of the spreading center [Shipilov and Karyakin, 2008].

Geological evidence indicates that the *Pechora Sea basin* is an extension of the Timan–Pechora plate displaced westward along a series of along-coast normal–oblique faults. The basin is bounded in the north and northwest by a flexural normal-faulting zone. In the east, the basin is bounded by structures of the folded Pai Khoi–Novaya Zemlya fold belt. The basement of the Timan–Pechora plate consists of Neoproterozoic metamorphosed sedimentary rocks with effusive and intrusive formations.

The *White Sea Province* occupies the southwestern part of the area of study. It is situated within the east European Platform. The basin is a blade-shaped depression filled with waters of the White Sea. Two phases are distinguished in the evolution of the White Sea region, the aulacogen and the plate phases [Devdariani, 1985].

The Onega–Kandalaksha, Kerets, and Leshukon aulocogens originated along deep-seated faults during Riphean time. In the Vendian, the structural plan of the platform started undergoing a radical rearrangement due to right-lateral faults that have separated the Onega–Kandalaksha aulacogen into several grabens. The plate-motion phase during Vendian/Proterozoic time witnessed separation of the Baltic Shield and the Russian plate; this was a phase of low tectonic activity

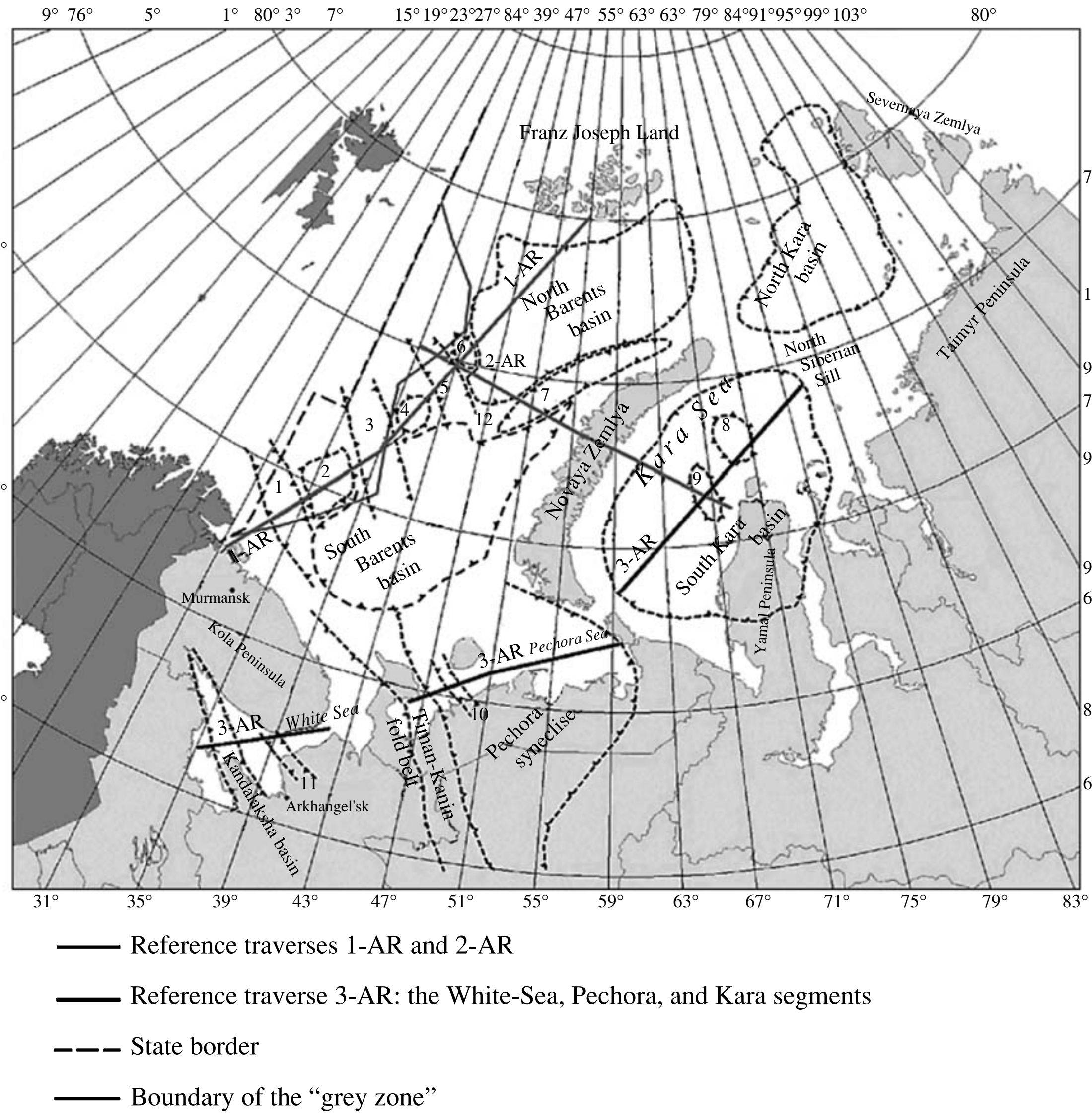

Fig. 1. Tectonic scheme of the region with indication of regional traverses 1-AR, 2-AR, and 3-AR after [*Stroenie*…, 2005]: (*1*) West Kola depression, (2) Fedynskii dome, (*3*) Demidovo aulacogen, (*4*) Fersman dome, (*5*) Malygino graben, (*6*) Vernadskii rise, (*7*) Admiralteiskii ridge, (*8*) Skuratovskii rise, (*9*) Rusanov rise, (*10*) Oksino graben, (*11*) Kerets graben, (*12*) Ludlova saddle.

dominated by uplifting. Since the middle of the Paleogene, the region was subsiding, resulting in generation of the White Sea basin and submergence in sea water.

STUDY TECHNIQUES

Detailed seismic surveys using reflected and refracted waves in various modifications were carried out along the traverse 3-AR (Fig. 1) about 2000 km long.

Deep seismic sounding used air-gun sources and ocean bottom stations as receivers. The stations were deployed at intervals of about 40 km, seismic wave excitation was done at a step of about 250 m. The deployments provided travel time recording of deep refracted and reflected waves to distances of 200–300 km.

In the processing of seismic data, the researchers used a kinematic modeling within the framework of various velocity models, as well as constructed wave images (dynamic sections) of reflectors and refractors. We used a new method, different from the accepted tools, in data interpretation; as a result, we derived deeper sections providing more detail and informative sections.

HOMOGENEOUS FUNCTION METHOD FOR TRAVEL TIME INVERSION

The technology of this method is based on the properties of homogeneous functions. The velocity sections were derived using the GODOGRAF software technology developed at the Lomonosov Moscow State Uni-

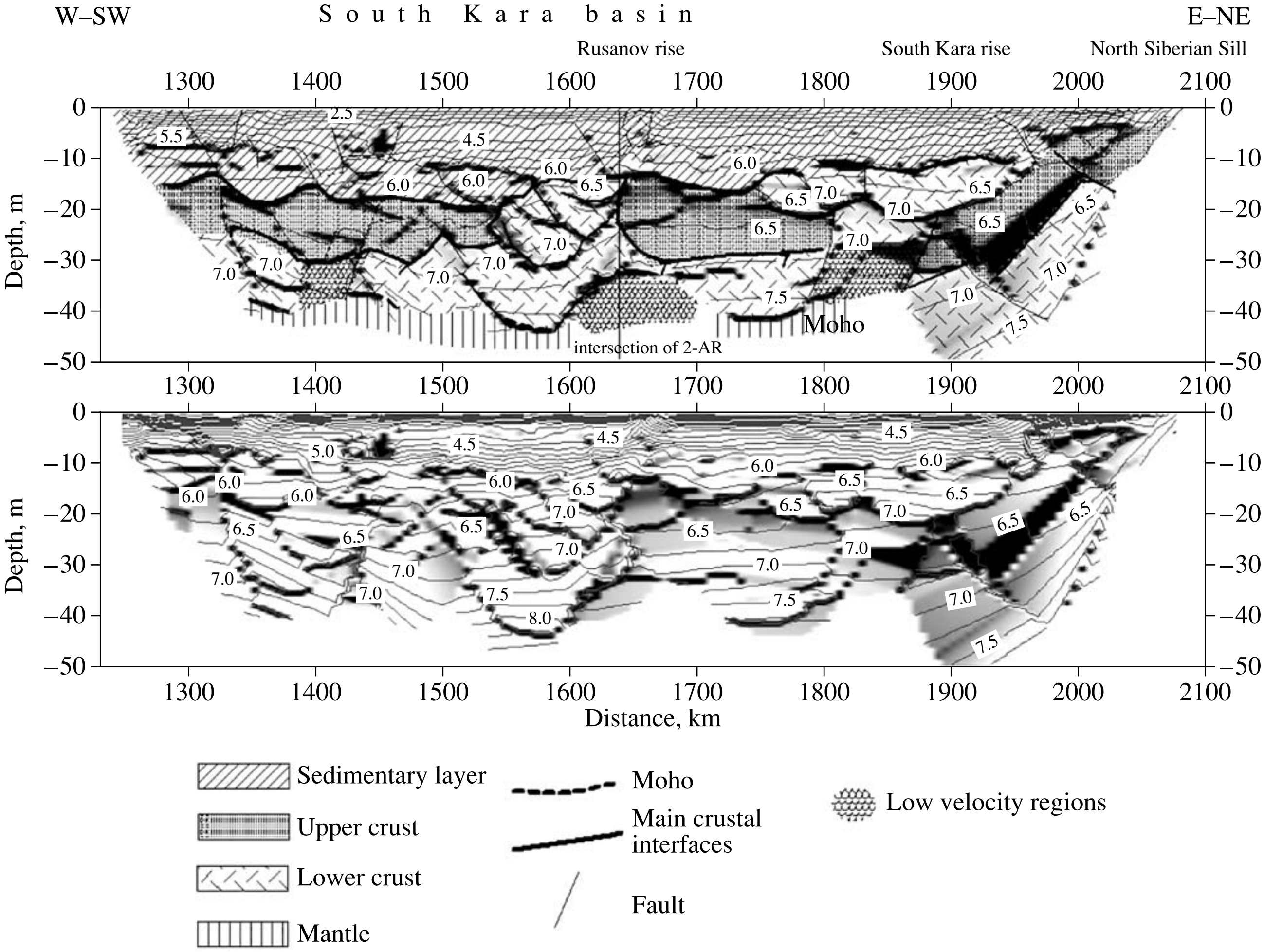

Fig. 2. Seismic section along the traverse 3-AR. Kara Sea: section with a geological interpretation (top) and automatically calculated section (bottom). Thin solid lines are isolines of seismic velocity. Velocity values are shown by numerals. The shading corresponds to the value of velocity gradient. The velocity isolines are at intervals of 0.2 km/s.

versity. The theory of the method and the software technology were discussed in [Piip, 2001; Kunitsyn and Piip, 2008].

The following basic criteria for identification of layers, interfaces, and structures were used in geological interpretation. The leading criterion for attribution to crustal layers consisted of the velocities that characterize parts of the section. Discontinuities were found from the presence of contrasts in velocity or a velocity gradient in the velocity field. Velocity values provide a more accurate indication of the material composition of a layer, while the gradient characterizes the degree of consolidation in the rock sequence. Numerous previous investigations by the homogeneous function method revealed that the top of the basement is frequently an inversion discontinuity, and the velocity inside the basement near its top is about 5.8 km/s on the average. The sedimentary layer is characterized by higher velocity gradients. The velocity in the upper consolidated crust varies in the range of 5.8–6.5 km/s. The velocity in the middle crust may vary between 6.4 and 6.6 km/s. The velocity range in the lower crust is 6.5–7.8 km/s. We also paid attention to the following property of the main crustal layers: there is a network of faults inside each layer, and the faults do not generally intersect the main discontinuities.

GEOLOGICAL INTERPRETATION OF THE SECTIONS

The 3-AR traverse consists of three segments; it intersects the Kandalaksha and Kerets grabens in the White Sea basin, the Sengeiskii dome and the Khorei-Ver basin in the Pechora Sea, and then it passes across the South Kara basin, and terminates near the North Siberian Sill. The sections we derived along this traverse reach a depth of over 50 km (Figs. 2, 3).

The *Kara Sea*. In the Kara region, the 3-AR traverse begins in the area of the North Kara Sill, intersects structures of the South Kara basin (including the Rusanov rise), and terminates at the southern tip of Novaya Zemlya. The seismic section derived automati-

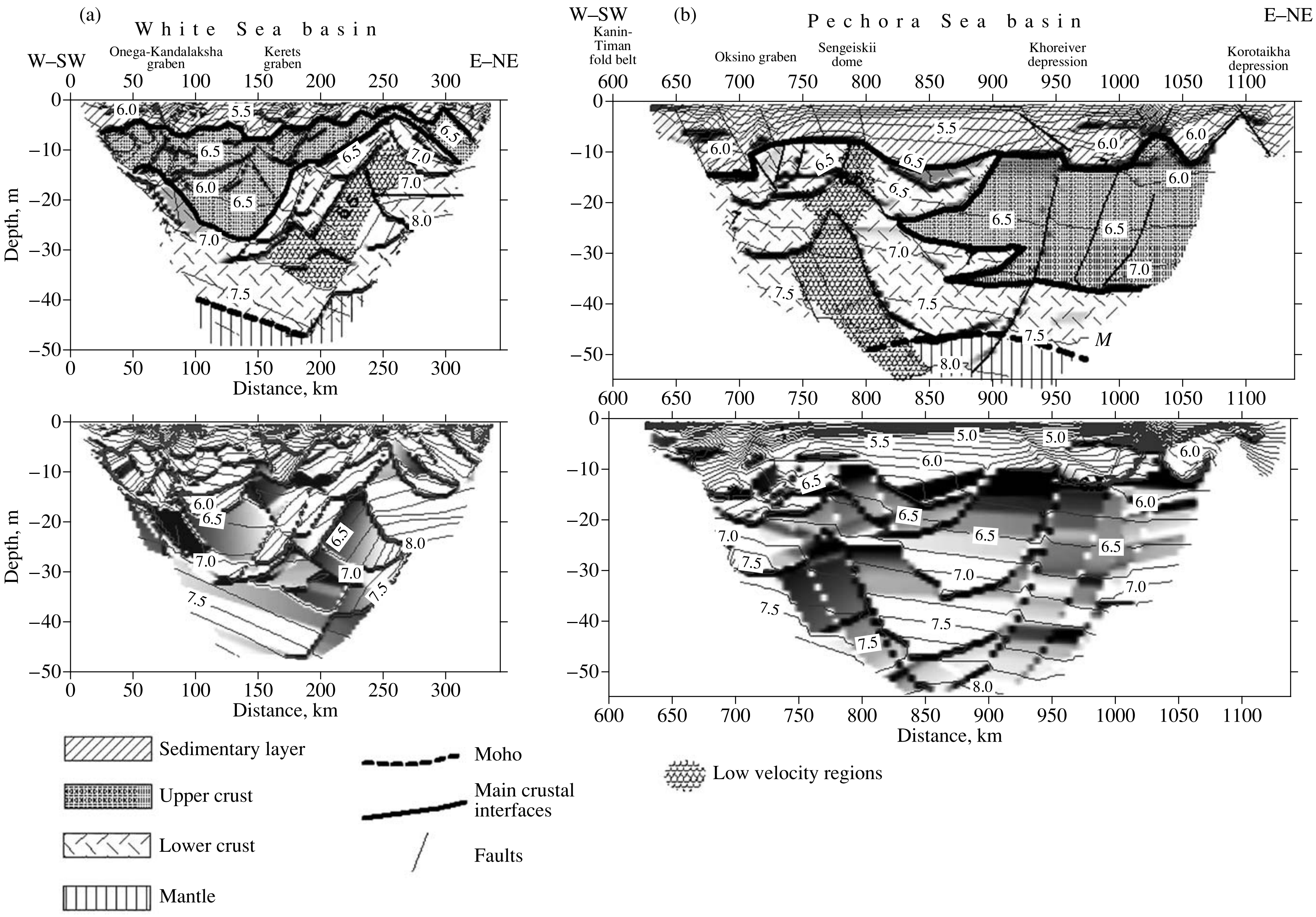

Fig. 3. Seismic sections along the traverse 3-AR. (a) White Sea, (b) Pechora Sea. Top: sections with geological interpretations, bottom: automatically calculated sections. Thin solid lines are isolines of seismic velocity. Velocity values are shown by numerals. The shading corresponds to the value of velocity gradient. The velocity isolines are at intervals of 0.2 km/s.

cally is shown in Fig. 2 below, while above this is the section with a geological interpretation.

The South Kara basin is characterized by a thick sedimentary succession as thick as 15–18 km. The sediments are thinner in the Rusanov rise area (8 km). In places, the sediments are divided into two sublayers: an upper, high-gradient one with velocities as high as 5.7 km/s and a lower sublayer, of considerable thickness, having velocities between 5.5 and 6.2 km/s and a low velocity gradient.

The structure of the South Kara consolidated crust seen in the section shows that a backarc basin may have existed there, since structures are identified in this section that can be interpreted as a paleosubduction zone and paleospreading centers.

The consolidated crust in the South Kara basin generally consists of two layers, in a similar manner to the North Barents basin [Kunitsyn and Piip, 2008]. The consolidated crust has a thickness of approximately 30 km.

In the eastern part of the traverse, on the side of the North Siberian Sill, the thin (10–15 km) lower crust descends under the thicker crust of the basin from a depth of 15 km down to 35–40 km. It is divided by transverse faults into rectangular blocks. The uppermost block has a structure similar to that of a paleoaccretionary wedge. The lower and the upper crust within that structure (the second and third layers of paleooceanic crust) are separated by a layer that is parallel to them and which has a lower velocity gradient; possibly, it is an image of a fault plane. In the mantle (at distances of 1800 to 1900 km), the hypothetical paleosubduction zone is terminated by a region of relatively lower velocity with a series of nappes having higher seismic velocities above. The nappes have been truncated by the sedimentary layer. These are possible traces of magmatism or a paleospreading zone.

A complex structure has been identified in the Rusanov rise area (distances of 1540 to 1640 km); in our opinion, it has features typical of a spreading center. Blocks of increased velocity typical of the lower crust (6.5–7.8 km/s) are uplifted from the mantle directly under the sedimentary layer. These structures have features typical of spreading zones; their dimensions are about 50 by 10 km. The crustal blocks form large overthrusts along listric faults dipping at 12°. The lower part of that zone, at depths of about 30 km, contains a mantle high with an abnormally low seismic velocity, 0.2 km/s, below that in the host rocks. Magmatic occurrences have been identified previously in the Kara region by geological mapping and by geological and geophysical surveys in marine sedimentary complexes [Shipilov and Karyakin, 2008]. The section we have obtained is probably relevant to the spreading as envisaged by I. Gibson and A. Gibbs. This kind of spreading proceeds by "emplacement of dikes and surficial basaltic effusions: the wedging effect of the dikes controls the spreading, while the subsidence under the basaltic load generates fan-like monoclines on both sides of the axial zone" [Khain, 2005].

The sedimentary layer in the southern part of the study area (distances of 1300 to 1650 km) is divided by numerous, variously striking faults into blocks 50–100 km in extent. According to geophysical data, there are alternating-sign linear magnetic anomalies in the area, which are also related by many researchers to the possible presence of rift systems and paleospreading, e.g. [Aplonov, 1998]. This confirms our hypothesis that the structure identified in the central part may be a paleospreading center.

The upper crust in the Kara Sea (distances of 1300 to 1650 km) has lower values of velocity gradient and lower velocities near the top (below 6 km/s). The sedimentary layer in that locality may contain, in a similar manner to the North Barents basin, a set of asymmetrical rifts after Wernike [Kunitsyn and Piip, 2008], providing evidence of an extensional environment in the area.

The consolidated crust in the Kara basin differs in its structure south and north of the Rusanov rise: the crust in the southern zone is divided into blocks by faults of varying strikes and lengths and is thinner. The area of the crust north of the Rusanov rise has a simpler structure, containing as it does few tectonic faults.

Large zones of abnormally low velocity were identified in the lower crust of the South Kara basin. The Moho has been found at depths of about 39–42 km along several segments of the traverse.

The *Pechora Sea*. In the Pechora Sea sector, the traverse passes through the Oksino graben, the Sengeiskii dome, the Khorei-Ver basin, and terminates in the Korotaikha basin.

Sedimentary layers were identified from velocity values (approximately below 6 km/s) and high velocity gradients (Fig. 3). The sedimentary successions are the thickest, up to 10 km, in the Oksino graben and the Khorei-Ver basin. In the central part of the traverse, including the Sengeiskii dome, the basement top lies at a 6-km depth. Fault structures (possibly rift ones) have been identified in the sediments in the eastern and western margins of the basin. They show in the sections as zones bounded by large faults and divided by numerous tectonic faults of varying dip and length. Gravity and magnetic anomalies were observed in the area of these objects judging by geophysical evidence [*Ob"yasnitel'naya*…, 1996].

The section has an interface at depths of 13–14 km where the velocity gradient is much lower (the top of the upper crust). This is thought to be an interface between different folded complexes (greenschist and gneissic (?)) [*Ob"yasnitel'naya*…, 1996].

The western half of the traverse, similarly to the section of the South Kara basin, has a structure with features typical of a paleospreading center (with distances of 740 to 850 km). There is a region of lower seismic velocity rising from the mantle toward the base of the sedimentary layer (at a depth of about 10 km). The

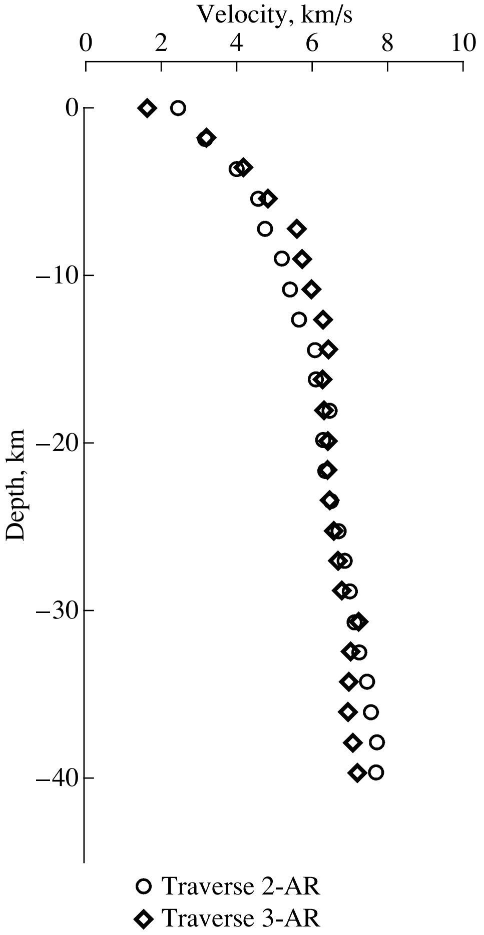

Fig. 4. Plots of vertical velocity profiles along the line of intersection of the 2-AR and 3-AR traverses.

region is surrounded by crustal blocks with velocity values typical of the lower crust or the basaltic layer of oceanic crust, with the blocks having been pushed apart from the center of the region along listric faults. The blocks are 50–100 km in horizontal extent and 10–15 km thick. We identified no upper crust in the area of that structure.

There is a thick (25 km) upper crust with lower velocity gradient in the east of the traverse at distances of 900 to 1100 km; the crust is divided by rectilinear faults into blocks.

The Moho mostly lies at depths of 43–46 km.

The *White Sea*. The most detailed observations in the study area were made on that segment of the traverse across the White Sea basin. Accordingly, the section derived there is a very detailed and complex one. Taken as a whole, the platform crust within the traverse forms a large complex fold whose layers are cut by numerous linear faults.

The sedimentary layer (Fig. 3) has a strongly variable thickness. Several nearly parallel layers form a syncline, filling the Onega–Kandalaksha graben. The sedimentary layer is the thickest (7 km) in the graben. The upper layer of the consolidated crust is the thickest (up to 22 km) at depths of 15–27 km between the Onega–Kandalaksha and Kerets grabens (distances of 80 to 170 km). The eastern part of the upper crust is complicated by several tectonic faults striking east. The upper layer of consolidated crust is considerably thinner, less than 5 km, around a distance of 250 km.

The lower crust is thick. There are zones of lower velocity within the layer. The structure may be characterized, as a whole, as a fold-thrust structural feature. In the lower layer of the fold, in the lower crust (velocity 6.5–7.8 km/s), thrust structures were identified. Such structures are usually generated during crustal movements, which are accompanied by the appearance of a plastic zone followed by generation of a fold complicated by an overthrust. The center of the fold contains rocks of lower seismic velocities. Such regions are stippled in the section. The fold-thrust structures in the crust of the White Sea basin have amplitudes as large as 10–15 km and lengths up to 200 km. Similar structures have been detected along the 1-AR traverse within the Barents plate [Kunitsyn and Piip, 2008].

The lower crustal layer has a uniform thickness over the traverse, about 20 km. The Moho is at depths of 43–45 km.

RELIABILITY OF THE SECTIONS

The velocity uncertainty can be estimated from the extent to which the velocities are consistent along the line where the 2-AR and 3-AR traverses intersect, considering that the sections were calculated absolutely independently [Kunitsyn and Piip, 2008]. A comparison of vertical velocity profiles is shown as a plot in Fig. 4. The rms deviation is 0.24 km/s.

The best agreement between the velocities along the line of traverse intersection was recorded at depths of 15–33 km, with the difference being below 0.2 km/s. The average difference for depth ranges of 7–15 and 34–40 km is 0.5 km/s. There are velocity jumps, but the plots generally have similar slopes in both plots at depths of 6–7, 15, and 33 km. Considering that the sections along the traverses across and along the trend of structures were calculated independently, the results show satisfactory agreement.

The theoretical travel times were calculated using the Firstomo program developed by the Sevmorgeo Company. The technology for this program is based on seismic tomography. The theoretical and observed travel times are fairly consistent, the rms deviation is within 0.5 s, the rays provide a good coverage on the section and penetrate through the entire depth of the section (Fig. 5).

A GEODYNAMICAL MODEL OF THE REGION

The velocity sections and seismogeologic sections beneath the Fersman and Fedynskii rises along the 1-AR traverse [Kunitsyn and Piip, 2008] and in the area

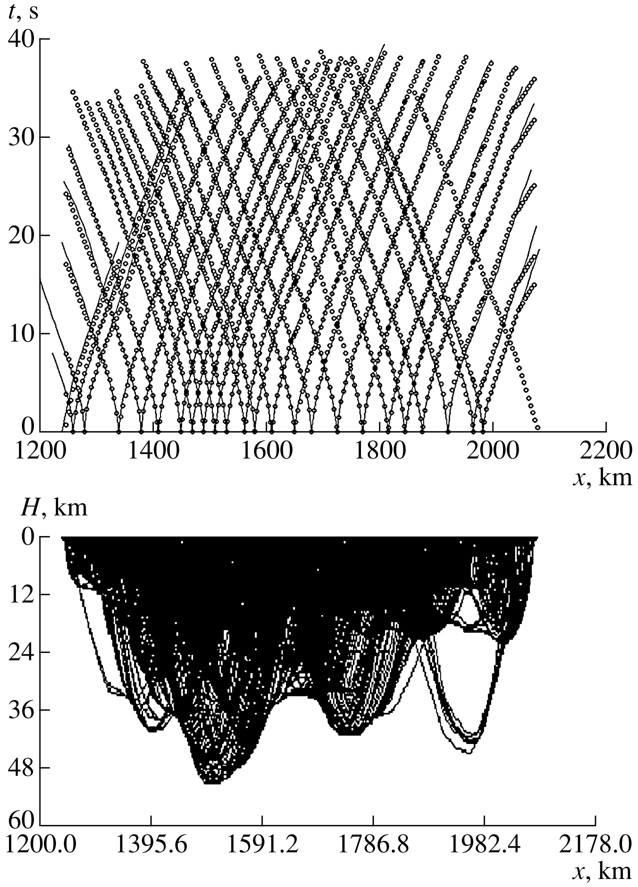

Fig. 5. Comparison of travel times observed on the 3-AR traverse (solid lines) with calculated times (circles). Below are seismic rays calculated when solving the forward problem.

of the Admiralteiskii megaridge along the 2-AR traverse reveal features of practically identical structure (Fig. 6). At moderate depths (15–30 km), one notes deformed, high-velocity, domelike features everywhere with regions of lower velocity under these features within the lower crust that are possibly relict magma chambers. The structure identified beneath the Admiralteiskii rise can be interpreted as a paleospreading center. Paleospreading regions may also exist beneath the Fersman and Fedynskii rises, as well as in the West Kola depression area. These features crossed by the 1-AR traverse are situated practically on the extension of the Atlantic rift within the Caledonian orogen [Breivik, 2002] (Fig. 7). It is noteworthy that the consolidated crust is thicker than usual in the central part of the Barents region. A spreading axis extends between Greenland and Scandinavia and extending farther east toward the Barents region [Lobkovskii et al., 2004]. Seismic investigations have shown that an abnormally thick (up to 40 km) oceanic crust has formed in the region [Coffin and Eldholm, 1992]. A similar crustal thickness was recorded in the Fedynskii and Fersman rises.

The three spreading centers, below the Fersman and Fedynskii rises and in the West Kola depression area, are not very far from each other (about 200 km) suggesting that they could belong to a common major paleospreading axis (Fig. 7). Transform faults and strike–slip faults may be found between these centers, coinciding with known depressions and grabens that separate the rises. The Admiralteiskii megaridge and the Fersman dome have very similar structures, suggesting that these are segments of a single paleospreading ridge torn apart by a transform fault in the area of the Ludlov saddle that separates the North and South Barents basins. In the opinion of S.V. Aplonov, the transform fault extends farther east as far as Novaya Zemlya [Aplonov, 1998].

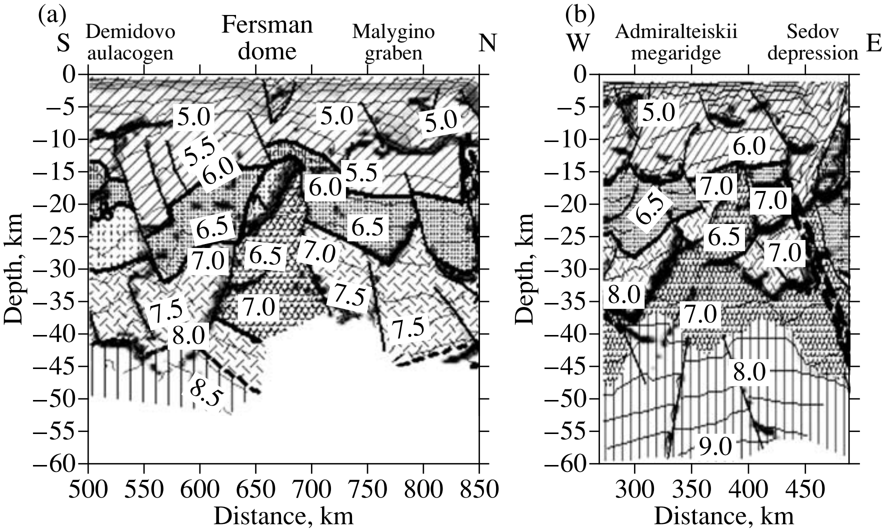

Fig. 6. Comparison of seismogeologic sections in the area of the Fersman dome (a) and Admiralteiskii megaridge (b). See Figs. 2 and 3 for the legend. Thin solid lines are isolines of seismic velocity. Velocity values are shown by numerals. The velocity isolines are at intervals of 0.5 km/s.

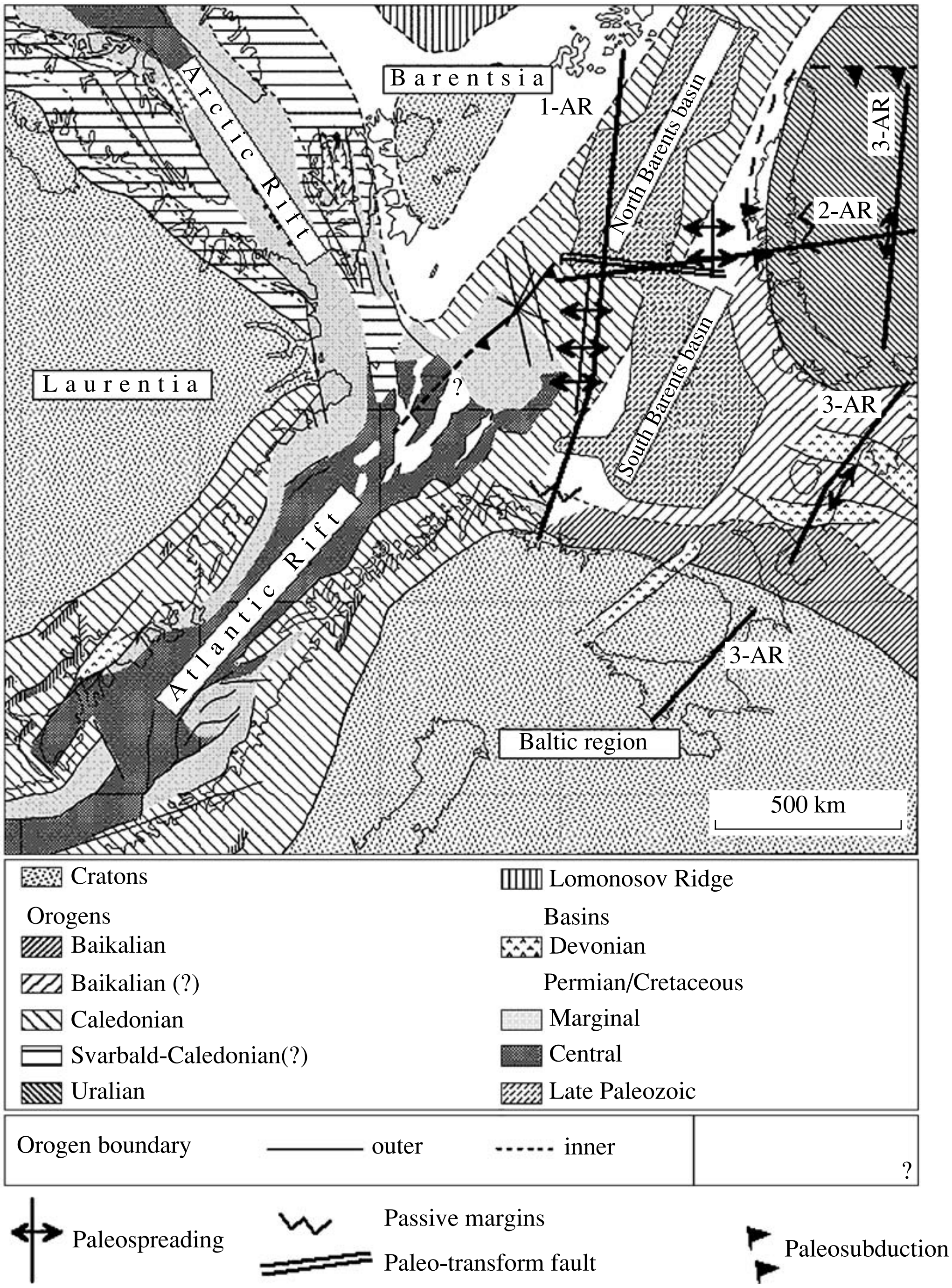

Fig. 7. Scheme of the Barents region and adjacent areas after [Breivik et al., 2002] showing tectonic elements derived when interpreting the sections along the 1-AR, 2-AR, and 3-AR traverses.

A suture zone has been identified between the Malygino graben and the North Barents basin [Kunitsyn and Piip, 2008], which can be viewed as the area of a paleotransform fault.

Paleospreading centers are present in the western Pechora Sea basin and in the middle of the South Kara basin. All the paleospreading features identified in the present study occur on basement highs.

The southern part of the Barents region in the Baltic Shield area, as well as the eastern termination of Novaya Zemlya, have structures corresponding to the type found in a passive continental margin.

The lower crust of deep sedimentary basins in the study area has been thinned, separated into blocks by faults, and is underlain by a low-velocity upper mantle. This may imply that subsidence was occurring there as a result of crustal extension rather than crust eclogitization.

CONCLUSIONS

(1) The data we have obtained on the structure of the South Kara basin provide evidence of a possible former backarc basin that existed there. A subduction zone could have existed in the area of the North Siberian Sill and a spreading center, in the middle of the basin.

(2) A major feature has been identified in the western Pechora Sea basin, in the upper and lower crust; the feature is interpreted there as a paleospreading center.

(3) A large fold–thrust feature has been identified in the crust beneath the White Sea basin, suggesting a former compressional environment in the continental margin area.

(4) Features have been identified in the area of the Central Barents rises, as well as in the Admiralteiskii rise, which are thought to have been segments of a common paleospreading ridge torn apart by the transform fault in the Ludlov saddle area.

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