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Oceanic Crust of Black Sea Basin Based on Seismic Data

V. B. Piip and A. P. Ermakov

Seismometry and Geoacoustic Department, Faculty of Geology, Moscow State University, Moscow, Russia
e-mail: piip@list.ru, ermakov@geol.msu.ru

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Abstract—Geological interpretation of seismic sections calculated using modern methods of processing data of deep seismic sounding of the 1960s was carried out. Images and quantitative characteristics of rift structures around Andrusov ridge and elements of the subduction zone in the southern frame of the Skiff plate were obtained. The location of structures in plan was determined.

Keywords: seismic interpretation, deep seismic sounding, Black Sea, tectonics.

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INTRODUCTION

In the period from 1956 to 1965 studies over a network of profiles using the method of deep seismic soundings (DSS) were undertaken in the Black See by researchers of the Shirshov Institute of Oceanology. The studies were aimed to investigate the deep structure of the Black Sea basin and area of the Black Sea crust that join its continental frame in the north. Profiles intersect the Black Sea basin in the southern, central, and eastern parts (Fig. 1).

Seismic sections along 17 profiles with a total length of more than 2900 km were generated based on these data by applying new processing methods. Recorded traveltime curves of refracted waves that are described in the literature [Goncharov et al., 1972; Stroenie zapadnoi..., 1972; Zemlya...,1975] were used as initial data for calculating seismic sections.

Images of a rift (paleorift and paleospreading) structure in the Andrusov ridge area were obtained at new sections. It was shown that the area of suboceanic crust of the Black Sea basin that joins the continental crust of the Skiff plate and regions of mountainous Crimea has characteristics that are typical of a subduction zone (probably, of paleosubduction and pseudosubduction).

NATURE AND TECTONICS OF THE BLACK SEA BASIN

The problem of the origin of the Black Sea basin has attracted many researchers since the end of the 19th century. In the last hundred or so years different researchers have offered many different hypothesis on the mechanism of its origin. Let us consider some of them:

(1) N.I. Andrusov [Andrusov, 1983], F.F. Osval'd [Osval'd, 1915], and B.F. Dobrynin [Dobrynin et al., 1922] described the Black Sea as giant hole in the Earth's crust (a graben) that appeared in Neocene–Quanternary ages over a wide area of land, i.e., Pontida;

(2) A.D. Arkhangel'skii and N.M. Strakhov [1938], V.A. Obruchev [1926], D.V. Nalivkin [1928], B.L. Lichkov [1933], and M.V. Muratov [1949] described the Black Sea as an "ancient geosyncline depression in a period of dipping";

(3) Since it was established that the "granite" layer is absent inside the inner areas of the basin [Gezhel'yants et al., 1958; Neprochnov, 1966] the hypothesis of the primarily oceanic (prior-geosyncline) origin of the basin was proposed. This hypothesis was developed by M.V. Muratov [1955], E.E. Milanovskii [1963], A.A. Sorskii [1962], A.L. Yanshin [1965], E.V. Artyushkov et al. [1980], and E.D. Sulidi-Kondrat'ev et al. [1980] who believed that the Black Sea basin was a relict of the oceanic crust that developed considerably more slowly comparing to adjusting structures. Other scientists [Dewey et al., 1973; Sorokhtin, 1974] assumed that the granite-free crust of the Black Sea was a remainder of the oceanic crust of the Tetis ocean of Early Mesozoic age.

(4) P.N. Kropotkin [1967] and Sh.A. Adamiya [1974] assumed the Black Sea to be a riftogenic structure that appeared in the Earth's continental crust and filled with Palaeogene volcanogenic–sedimentary formations;

(5) In [Finetti et al., 1988; Belousov et al., 1988] the idea of two-stage rifting was suggested. It is believed that the Large Caucasus basin was formed as a result of the first stage during the Lias–Dogger age. At the same time the Black Sea was a shallow basin. A

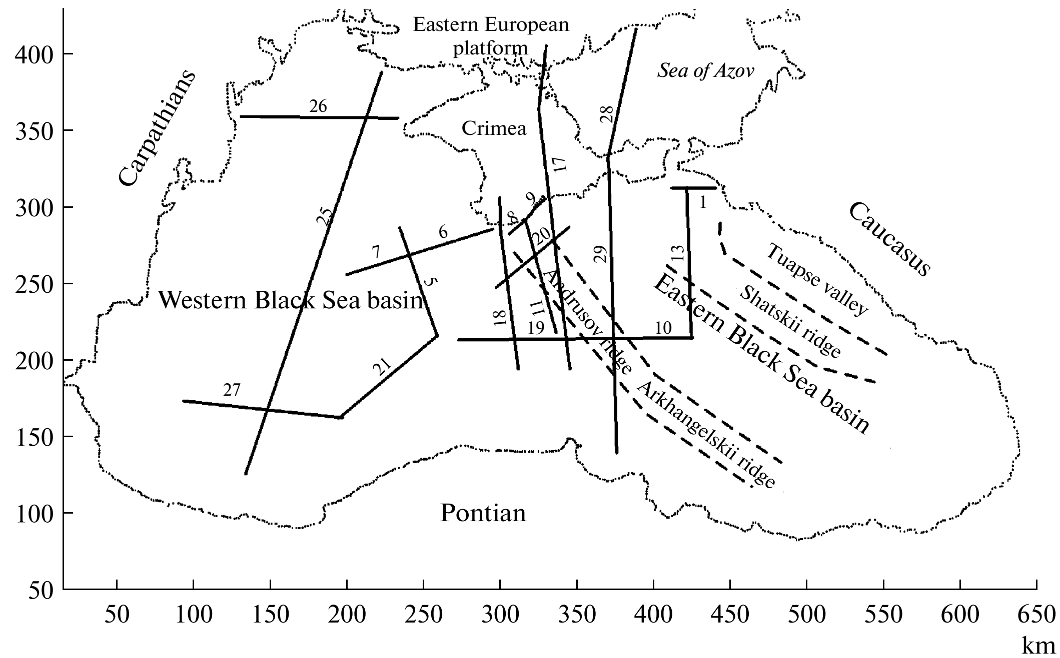

Fig. 1. Plan of DSS profiles.

deep basin was formed as a result of the second stage started in the Early Cretaceous age. At the same time, according to their opinion the western and eastern valleys were opened synchronously but developed in a different manner;

(6) The idea of reformation of the continental crust ("basification") with the formation of suboceanic crust in a deep basin of the Black Sea was considered by S.I. Subbotin et al. [1964], A.L. Yanshin et al. [1980], A.V. Shlesinger [1981], V.V. Belousov [1962], M.V. Muratov [1972], and others.

(7) E.V. Artyshkov [Artyushkov, 1993] believes that in the area of the Black Sea water area two separate relatively deep valleys (the western- and eastern Black Sea valleys) occurred in the continental crust. At the newest stage they rapidly sank, forming a single deep Black Sea basin, which currently exists. Within western- and eastern Black Sea valleys the continental crust experienced oceanization (eclogitization);

(8) Most geologists consider the Black Sea as back-arc basin that formed in the rear part of the Pontiiskaya island arc as a result of riftogenesis in the late Cretaceous. Such ideas can be found in a number of older and more recent papers [Adamiya et al., 1974; Zonenshain et al., 1986; Stroenie..., 1992; Kazmin, 1997; Kazamin et al., 2000; Bocaletti et al., 1974; Letouzey et al., 1977; Okay et al., 1994; Robinson et al., 1995, 1996].

Geological studies of the sediments of mountainous Crimea showed [Mileev et al., 2009] that this is a late Cimmerian folded–covering structure, which reformed at the Alpine stage by deuterogenic block movements. Overthrusts were formed during the subduction of the Tavricheskii basin under Skifiya.

The Black Sea is traditionally divided into three specific, from a tectonic point of view, parts, these are western, central, and eastern (Fig. 1). The western part includes the western-Black Sea basin and the Skiff and Mizii plates. The Central part includes the Andrusov and Arkhangelskii ridges and Sorokin depression. The eastern Black Sea valley, Shatskii ridge, and Tuapsinskii depression are located in the eastern part of the Black Sea. DSS profiles 17, 18, and 28 in addition to the Black Sea intersect mountainous Crimea and the Sea of Azov, including the Indolo-Kuban depression and Azovskii ridge within the limits of the Skiff plate.

MATERIALS AND METHODS

The conventional technique of mobile shotpoints and fixed registration points was used for seismic studies. For this technique the detail of the studies is generally determined by the number of registration points. Registration points were set at every 25–50 km and shots were made at an interval of 5–10 km. The traveltime curves recorded along profile 17 and on its extension on land are shown in the Fig. 2.

Seismogeological sections were generated and the velocity and general characteristics of the main layers of the Earth's crust were achieved based on results of data interpretation carried out in the 1970s.

For the sections described in [Goncharov et al., 1972; Stroenie zapadnoi..., 1972; Zemlya..., 1975] it was assumed that the waves that are recorded in the first arrivals are primary waves. The sections were generated using the method of time fields with the values of average velocity. The media was assigned as horizontally layered with thick subhorizontal layers and constant velocity within one layer. Using this kind of media it is impossible to obtain information on the inner structure of the layers of section, velocity gradient distribution in layers, and interface boundaries with considerable dip angles (above 15°). Sharp lateral alteration in the section was shown as changes of the structural block. The section that was generated largely depended on the individual decision of the interpreter, as the identification and matching waves from one boundary of the interface at traveltime curves from different shotpoints were carried out manually.

THE NEW INTERPRETATION TECHNIQUE

For the interpretation of these data, a method of homogeneous functions is applied, which was used here for the interpretation of both the engineering seismic survey data and the data of regional studies based on refracted waves. The method is based on local approximation of the real velocity distribution by homogeneous functions of two coordinates [Piip, 1991; Piip, 2001].

Interpretation using the method of homogeneous functions is an automatic procedure. It does not require any initial model, i.e., prior information on the section structure. Identification of waves concerning to different boundaries at traveltime curves for different shotpoints is carried out automatically.

GODOGRAF software, which is used for inversion systems of traveltime curves of arbitrary-form refracted waves (first arrivals), was used for interpretation. Thus, relief-based seismic sections and velocity horizontal maps for any horizontal level within the depth of areal studies were automatically generated.

In the area of the Black Sea at some DSS profiles an insufficiently detailed observation system was obtained, as sources were located along the profile non-uniformly, thus, for processing, interpolation of traveltime curves system was used to calculate traveltime curves in additional sources. It was suggested that seismic media between sources changes linearly in a lateral direction.

Sections obtained using the method of homogeneous functions are sections for which the velocity is calculated in nodes of a rectangular network, i.e., a grid model. These sections may be represented as surfaces or sections with lighter relief. This is very convenient for the visualization of interface boundaries in sections. In this case, boundaries of the first and the second kind, inversion interface boundaries, and tectonic faults are recognized. Boundaries of the first kind are boundaries at which velocity steeply increases downwards. These boundaries are outlined in the section with shaded relief as light lines. Boundaries where the velocity decreases steeply (inversion boundaries) are drawn as dark lines. Boundaries of the second kind

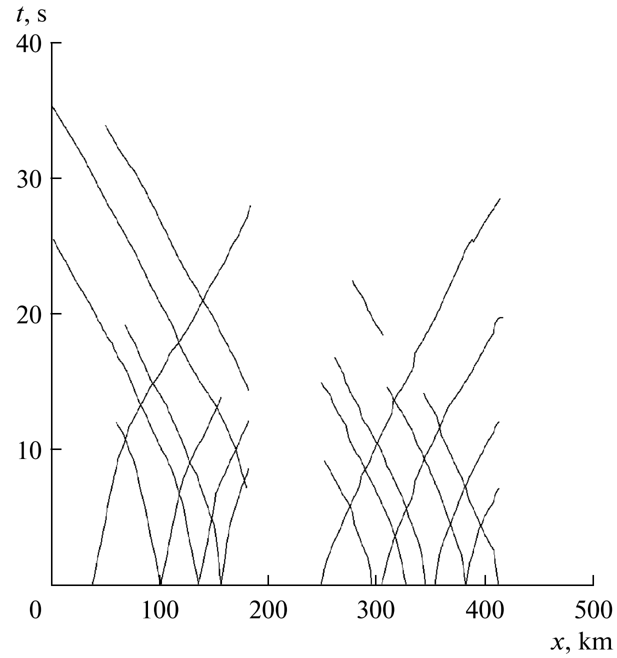

Fig. 2. Observed traveltime curves of first arrivals of refracted waves along the profile 17.

are boundaries at which the velocity gradient changes sharply. Increase of the velocity gradient is shown in the section with the shadowed relief as light-colored areas and a decrease of the gradient is shown as dark-colored areas. The boundaries of the layers, as a rule, run concordantly with velocity isolines. Faults intersect them and are shown in the sections with shaded relief as light-colored and dark-colored lines depending on the inclination. Let us note that for more convenient visualization seismic sections are often shown in a distorted scale with visually larger dip angles of faults.

A section with lighted relief was generally superimposed on a velocity section to trace how the velocity changes inside of the layer. The velocity section is transparent when the sections are superimposed. Geological interpretations of the velocity sections and the deep cross-section map are carried out by an interpreter by matching boundaries of the first and the second kinds with the geological boundaries using geological and geophysical information obtained using other methods.

THE DEEP STRUCTURE OF THE ANDRUSOV RIDGE

In the most detail, the rift structure referred to the Andrusov ridge was imaged in the section along profiles 28, 29, 17, 19, 10, and 18 intersecting this structure. These profiles are characterized by a representative system of observations. The observed traveltime curves along profile 17 are shown in Fig. 2. The length of the traveltime curve reaches 200 km.

In sections that were obtained within the suboceanic crust we outlined sedimentary layer I (velocity increases with depth from 2 to 6 km/s, the gradient is high), layer II (velocity increases from 6 to 7 km/s), and layer III (velocity increases with depth from 7 to 8 km/s).

The depth of the bottom of the sedimentary layer in the area of Andrusov ridge is on average 9.5 km; it increases at the Black Sea basin to 12–15 km and decreases to 2 km and less near the Crimean coast. The seismic boundaries near velocity levels of 4 and 5 km/s are outlined inside the sedimentary layer, which is shown at profiles as consistent low-inclination layers. The thickness of the consolidated crust in the area of the Andrusov ridge (layers II + III) is approximately 10 km.

The rift structure in all three sections (Fig. 3) is clearly defined and has a classic form. In the central part of the rift structure a mantle rise occurs with anomalously low velocity (7–7.5 km/s) and an amplitude of 5–10 km down to a depth of 20–23 km. Faults inclined to the rift axis and located at its sides limit the blocks of crust that are uplifted and moved apart from the axial rise of the anomalous mantle. The upper boundary of layer II, which is uplifted or dipped in the area of the axial mantle anomaly, is sharply outlined in the velocity field. In the peripheral parts of the rift structure layer III is underlain with very high-velocity (up to 9 km/s) and high-gradient layers (oceanic mantle ?). A sharp inversion boundary at a depth of 23–25 km separates the flank part of the rift from the normal mantle, where the velocity increases with depth to 8 km/s with a gradient of approximately 0.125 s^{-1}.

In the profile 19–10 (Fig. 3 b) only the western part of the rift structure is shown, as in the eastern part of the profile the length of the recorded traveltime curves is not sufficient.

In the northern part of the sections of parallel profiles 17 and 28–29 (Fig. 3a and 3b) in points (p) 200–250 km and 300–320 km, respectively, the Sorokin depression is outlined; this is located in the region of sea and land contact. The velocity inside the depression increased slowly and reaches 7 km/s at a depth of 25 km. Further northwards in the region of mountainous Crimea at profile 17 (Fig. 3c) and in the region of Kerchenskii peninsula at profile 28–29 (Fig. 3a) blocks (layer III and mantle) of oceanic crust are traced; these blocks are outlined by typical values of velocity, velocity gradient, and thickness. In the section of the profile 17 these layers sharply (at an angle of 30°–40°) plunge in the direction of the Crimea and Skiff plate. These structures can be considered as some confirmation of subduction (paleosubductuin) of the Black Sea lithosphere under Crimea, taking the possible very complex structure of the studied region into consideration.

In the area of the Skiff plate in the section of the profile 17 (Fig. 3b) at p 320–400 km, a subhorizontal layer of thinned continental crust was outlined. Here the thickness of the sedimentary strata is approximately 5 km. The thickness of the upper crust varies from 5 to 10 km and the lower crust with a thickness of 10 km at a depth of 20–22 km is underlain with mantle with a velocity that increases with depth from 8 to 9 km/s.

The profile 28–29 (Fig. 3a) in the northern part intersects the Sea of Azov (Skiff plate) with an anomalously thick (up to 40 km) two-layer crust. The thickness of the crust decreases sharply in the direction of the eastern-European platform. The lower crust in the upper part has an anomalously low velocity of 6 km/s. The thickness of the sedimentary formations is approximately 5 km [Ermakov, 2005].

WESTERN BLACK SEA BASIN

The section along profile 25 (the length of the profile is 495 km) (Fig. 4) characterizes the structure of the western Black Sea basin [Dzhaniashvili et al., 2005].

The profile started at the Kefken cape (Turkey) intersects the deep western Black Sea basin, the Karakinitskii graben within the Skiff plate, and finishes near Herson city at the boundary with the western European platform within the northwestern shelf of the Black Sea. To build a section along profile 25, all traveltime curves from 20 registration points were used; the maximum length of the traveltime lines reaches 200 km.

The southern (with oceanic crust) and northern (with continental crust) parts considerably differ in their structures.

The southern part of the section within the western Black Sea basin is characterized by subhorizontal layers. In the section, clearly outlined sedimentary strata (layers I, II, and III), the Moho boundary, and the upper mantle are outlined. The depth of the lower boundary of the sedimentary layer in the southern part of the section is 11 km and further the sedimentary layer starts dipping in the northern direction reaching a depth of 12 km. The velocity inside the next layer II increases with depth from 6 to 7 km/s. The thickness of the layer is 6–9 km. The upper boundary of layer III is drawn at the boundary of the interface near the velocity level of 7 km/s. The thickness of the layer is insignificant and is less than 4 km, which is typical of the oceanic crust. This layer is underlain by a normal mantle, where the velocity increases with depth from 8 to 9 km/s at a depth of 30 km. The Moho boundary is clearly defined.

In area p 150 km a complex structure is outlined, whose upper part has the form of an uplift or ridge. The upper boundary of layer III in this area is faulted and was not traced. The faults have a southern dip at an angle of 25°. Below this structure an anomalous mantle with a low velocity (of about 7 km/s) is recog-

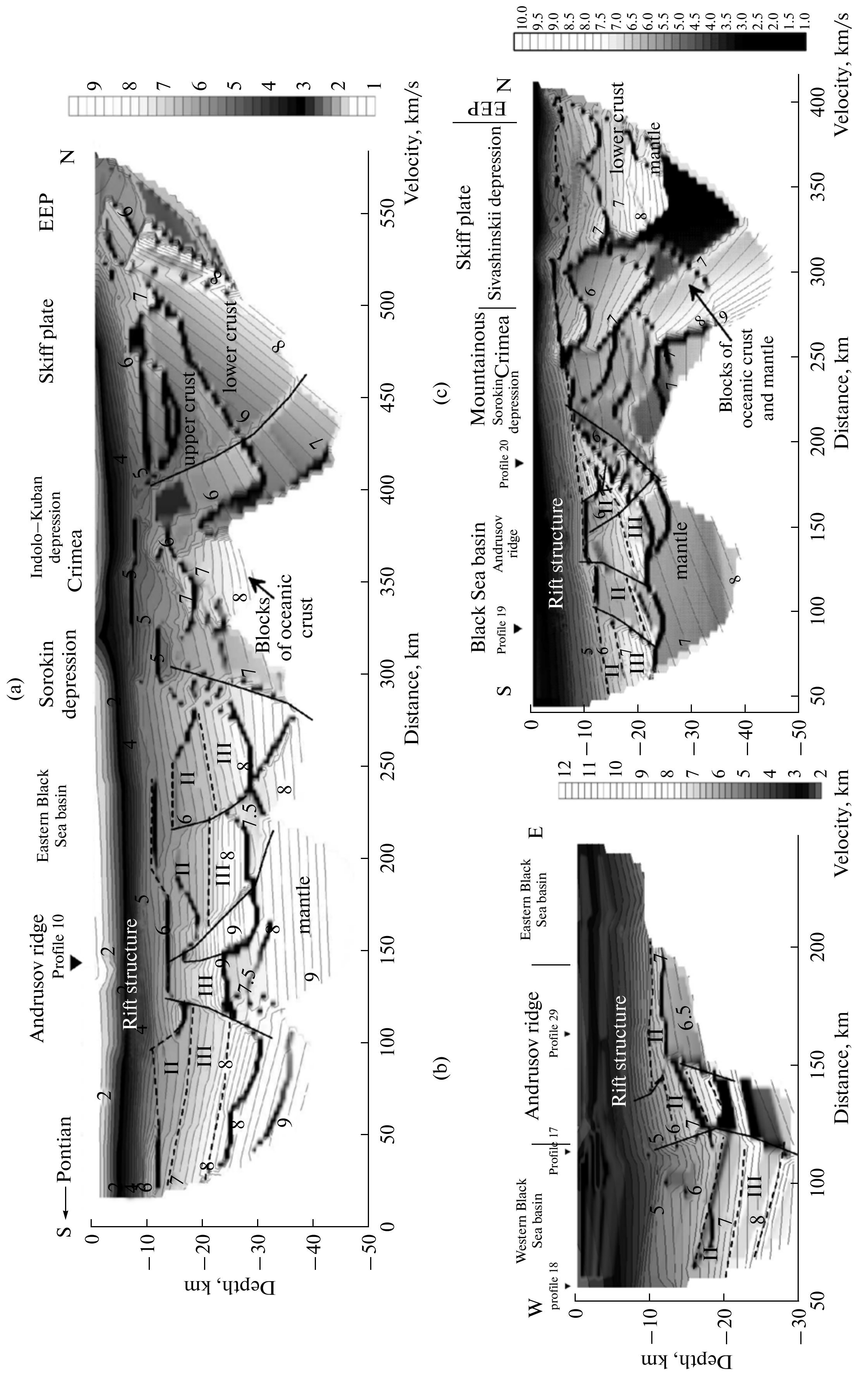

Fig. 3. Seismic sections along profiles intersecting Ansrusov ridge: a, a section along profile 28–29; b, a section along profile 19–10; c, a section along profile 17. Solid lines show tectonic nonconformities, dashed lines show the boundaries of layers. Contour interval is 0.25 km/s.

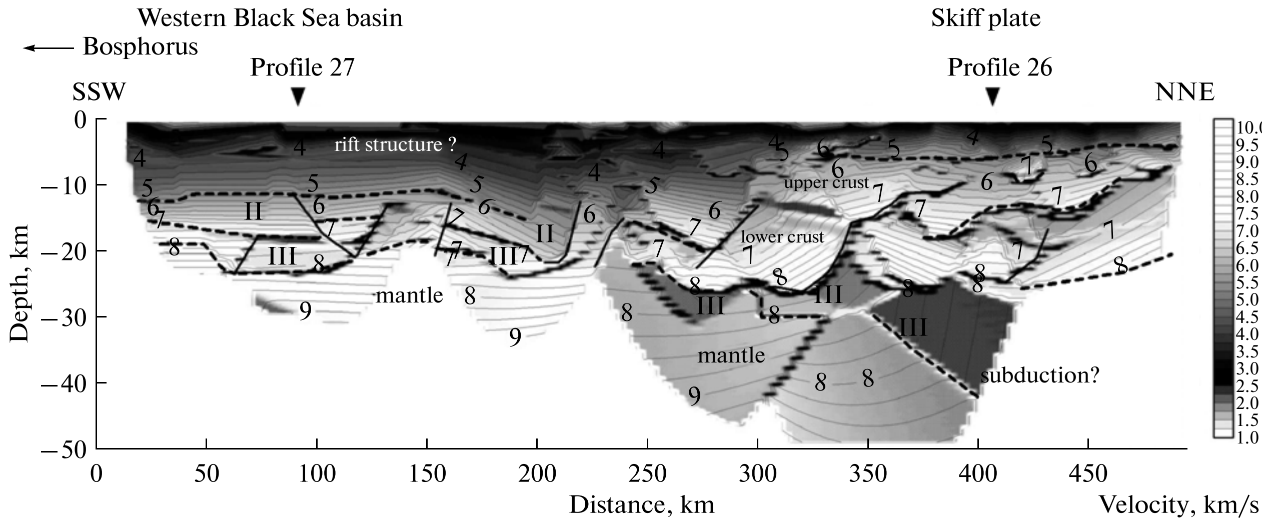

Fig. 4. Seismogeological section along the profile 25. The cross section of the velocity isoline is at 0.25 km/s. Legend, see Fig. 3.

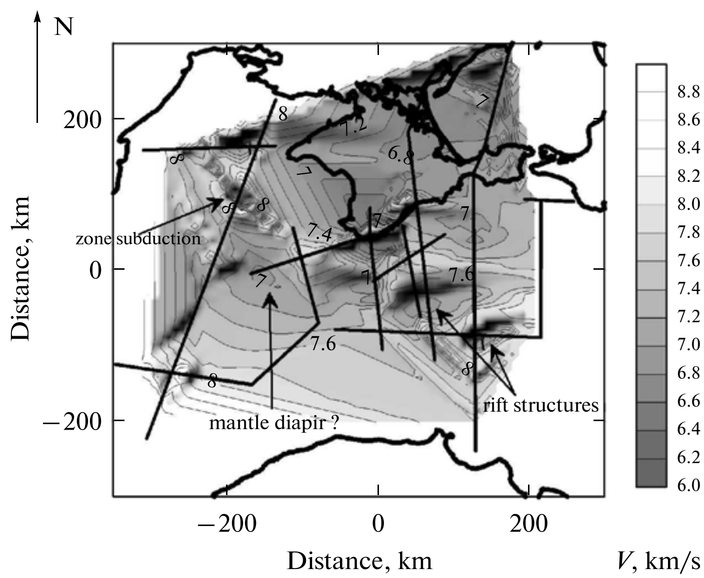

Fig. 5. Velocity map-slice at a depth of 23 km. The section of the velocity isoline is 0.2 km/s. profiles DSS are shown in black solid lines.

nized. In general, the structure has rift features. This structure is a deep reflection of the Polshkov uplift, which is located to the west of the profile. In this zone of the Black Sea crust adjoining the Skiff plate (p 160–290 km) all three layers (I, II, and III) smoothly dip in the north direction, deform near p 200 km and are divided into separate blocks by faults with both northern and southern dips (dip angles are approximately 30°–45°). The sedimentary deposits in this zone are also deformed and are located at a depth of 14 km; this is probably a result of accretion. Further northwards, layer III makes a step-by-step plunge in the northern direction down to a depth of 40 km at p 400 km below the structures of the Skiff plate. Here the mantle of the upper part has low velocity (<8 km/s). According to the location of the subcontinental crust and upper mantle, the area of contact between the Black Sea crust and Skiff plate may be considered as a subduction zone (probably, paleosubduction or pseudosubduction).

The northern part of the section (Skiff plate) is presented by a thinned continental crust. Here the sedimentary layer, upper and lower crust, and Moho boundary were outlined. The Skiff plate crust has folded structure.

The sedimentary layer of the continental crust of the Skiff plate is thin (<5 km) compared to the thickness of sedimentary formations in the Black Sea.

Upper crust (near upper boundary velocity is 5 km/s) and lower boundary (velocity is from 6.5 to 8 km/s) from folds and covers [Ermakov, 2005].

LOCATION OF THE OUTLINED STRUCTURES IN THE PLAN

The technology for building sections with the method of homogeneous functions allowed us to generate horizontal velocity map-slices over the area of studies according to the results of our investigations. These maps are visualized in the same way as sections and allow one to see the positions of structures in the plan.

A horizontal velocity map-slice at a depth of 23 km was made at the level of the Moho boundary, i.e., the upper boundary of the mantle. In the map (Fig. 5), which is the velocity field at a level of 23 km that is superimposed on a relief map of the velocity surface, the rift structures in the area of Andrusov ridge are clearly defined. The flanks of the rift structures and valleys are areas of low-velocity mantle anomalies, which caused rift formation and are clearly observed at the map. Along the Andrusov ridge, three approximately similar in strike rift structures in a northeastern direction are outlined.

In the western part of the sea structures connected with the subduction zone of the northwestern strike are seen. In the central part of the western-Black Sea basin in the tops of the mantle a low-velocity anomaly is traced (velocity is <7 km/s); probably, this is a mantle diaper.

The reliability of the velocity sections was studied by solving the direct problem. The estimates that were obtained correspond to modern requirements for the precision of section design [Ermakov, 2005; Dzhaniashvili et al., 2005].

The degree of coincidence of velocity curves in lines crossing points (survey ties) is one of the criteria for estimating the reliability of the generated seismic sections, as all seismic sections are generated independently. For lines that cross points, the curves changed their velocities with depth and in general they have a satisfactory coincidence in every diagram. The average deviation of the velocity curves is 0.2 km/s.

CONCLUSIONS

Based on the results of a new interpretation of seismic data that the DSS obtained automatically in the 1960s, without any prior information on the structure of the media, images of the quantitative characteristics of series of rift structures in the area of the Andrusov ridge and elements of a subduction zone of the Black Sea lithosphere under a Skiff plate and mountainous Crimea were obtained in cross sections and in plan.

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