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Collision Processes at the Northern Margin of the Black Sea

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Abstract—Extended along the Crimea–Caucasus coast of the Black Sea, the Crimean Seismic Zone (CSZ) is an evidence of active tectonic processes at the junction of the Scythian Plate and Black Sea Microplate. A relocation procedure applied to weak earthquakes ($m_b \leq 3$) recorded by ten local stations during 1970–2013 helped to determine more accurately the parameters of hypocenters in the CSZ. The Kerch–Taman, Sudak, Yuzhnoberezhnaya (South Coast), and Sevastopol subzones have also been recognized. Generalization of the focal mechanisms of 31 strong earthquakes during 1927–2013 has demonstrated the predominance of reverse and reverse–normal-faulting deformation regimes. This ongoing tectonic process occurs under the settings of compression and transpression. The earthquake foci with strike-slip component mechanisms concentrate in the west of the CSZ. Comparison of deformation modes in the western and eastern Crimean Mountains according to tectonophysical data has demonstrated that the western part is dominated by strike-slip and normal-faulting, while in the eastern part, reverse-fault and strike-slip deformation regimes prevail. Comparison of the seismicity and gravity field and modes of deformation suggests underthusting of the East Black Sea Microplate with thin suboceanic crust under the Scythian Plate. In the Yuzhnoberezhnaya Subzone, this process is complicated by the East Black Sea Microplate frontal part wedging into the marginal part of the Scythian Plate crust. The indentation mechanism explains the strong gravity anomaly in the Crimean Mountains and their uplift.

Keywords: Crimea, Black Sea, seismicity, earthquake mechanisms, collision processes, kinematic analysis, deformation regimes

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INTRODUCTION

The Greater Caucasus and the Crimea Mountains located at its northwestern continuation constitute a fold-and-thrust belt that formed in the Cenozoic at the southern margin of the East European Platform as a result of collision between Eurasia and the Africa–Arabian Plate [2, 53, 54]. Thus, the Crimean Mountains should retain traces of tectonic events related to the Cenozoic compression of the Greater Caucasus. The Main Caucasian Thrust, which marks the southern boundary of the Greater Caucasus orogen in Russia and Georgia, can be traced westward along the northern margin of the Black Sea, including the southern Crimean Peninsula (Fig. 1). The thrust position is marked by an active seismic zone stretching along the Crimea–Caucasus coast (Fig. 2): there, accumulated stress in the collision zone is released. The Crimea Orogen and the adjacent part of the Black Sea are characterized by a quite complex geological structure of the sedimentary cover and basement, as well as the deep crust [35, 43, 49, 52, 60, 65, 69, 70]. The thick (up to 48–50 km) crust of the Crimean Mountains neighbors the thin suboceanic crust of the Black Sea Basin [65, 96]. However, their structural relationships have not been studied sufficiently. The improvement in the understanding of regional geology and geodynamics would be also relevant for the development of high hydrocarbon potential of the area (e.g., the Subbotin, Abikha, and other deposits) of the area.

In order to collect additional information on the structure of the transitional zone between Crimea and the Black Sea, local seismic tomography of the Crimean Mountains and the adjacent sea is currently carried out, utilizing data from weak ($m_b \leq 3$) earthquakes. The first results of this work for the Kerch–Taman subzone have already been published [44]. Collected tomographic data on the parameters of earthquakes analyzed together with the focal mechanisms of strong earthquakes, the results of tectnophysic studies, and the results of structural analysis of the Crimean Mountains provide a unique opportunity to better understand the current geodynamics of the collision zone of the Crimea–Black Sea region.

SEISMICITY OF THE CRIMEA SEISMIC ZONE

The seismicity of the Crimea Seismic Zone (CSZ) was studied using data from weak ($m_b \leq 3$) earthquakes

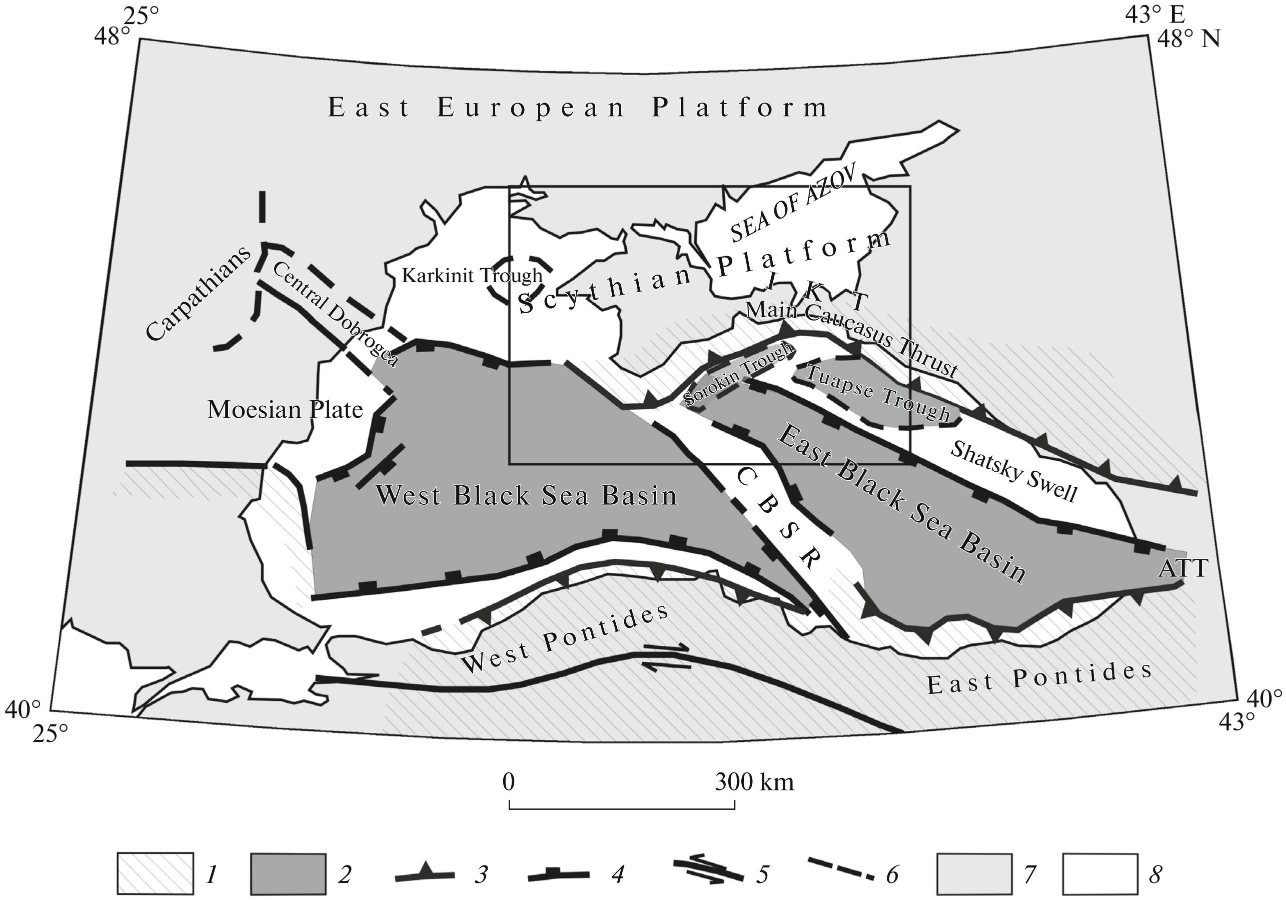

Fig. 1. Tectonic scheme of the Black Sea region. Rectangle highlighted by solid line denotes study area. ATT, Adjaro–Trialet trough; IKT, Indol–Kuban Trough; CBSR, Central Black Sea Rise. *1*, main area of Tertiary shortening-related deformation; *2*, suboceanic crust; *3*, main shortening zones; *4*, main extension zones; *5*, major strike-slip faults; *6*, contours of geological structures; *7*, onshore; *8*, offshore areas.

recorded during 1970–2013 by nine stations of the Crimea seismic network and by the Anapa station on the Caucasian coast (Table 1).

To acquire uniform seismic data, a seismic source relocation procedure has been used, based on the idea of minimizing the functional of residuals in the travel time of P- and S-waves in the given model of the medium [15]. The model presented in table 2 was applied as a reference: it is based on seismic tomography data [1, 16, 41] and reinterpretation of DSS profiles [70]. In this procedure, any data with random deviations exceeding the threshold values, which could be related to errors in estimating the time of phase initiation, have been omitted. Very weak earthquakes recorded by only two or three stations were not considered. Simultaneous use of P- and S-waves made it possible to increase the number of earthquakes subjected to relocation, with the number of phases changed from 6 to 16. In this study, the relocation algorithm was applied to earthquake parameter data for the CSZ in the period of 1970–2013 [32, 33].

The obtained spatial distribution of foci in the CSZ according to source depth is shown in Fig. 2. According to characteristic seismicity features, such as the density of foci, grouping in clusters and lineaments of a certain orientation, focal depth, etc., within the CSZ from east to west, four major subzones are recognized: Kerch–Taman, Sudak, Yuzhnoberezhnaya (Yalta–Alushta), and Sevastopol.

Fig. 2. Distribution of epicenters of weak earthquakes ($m_b \leq 3$) in Crimean seismic zone (CSZ) with corrected parameters. Focal depths are shown on the background of bathymetry and day surface relief. CSZ subzones (numbers in circles): 1, Sevastopol; 2, Yalta–Alushta (or Yuzhnoberezhnaya); 3, Sudak; 4, Kerch–Taman. Vertical cross section subzones: I-I', Yalta–Alushta; II-II', Kerch–Taman. Epicenters at depths of 1, 0–15 km; 2, 15–30 km; 3, 30–50 km; 4, >50 km. Black stars show strong earthquakes ($m_b > 3$) [41]; black triangles, seismic stations that recorded earthquake: ALU, Alushta; ANN, Anapa; DON, Donuzlav; FEO, Feodosiya; Keru, Kerch; SEV, Sevastopol; SIM, Simferopol; SUDU, Sudak; TARU, Tarkhankut; YAL, Yalta.

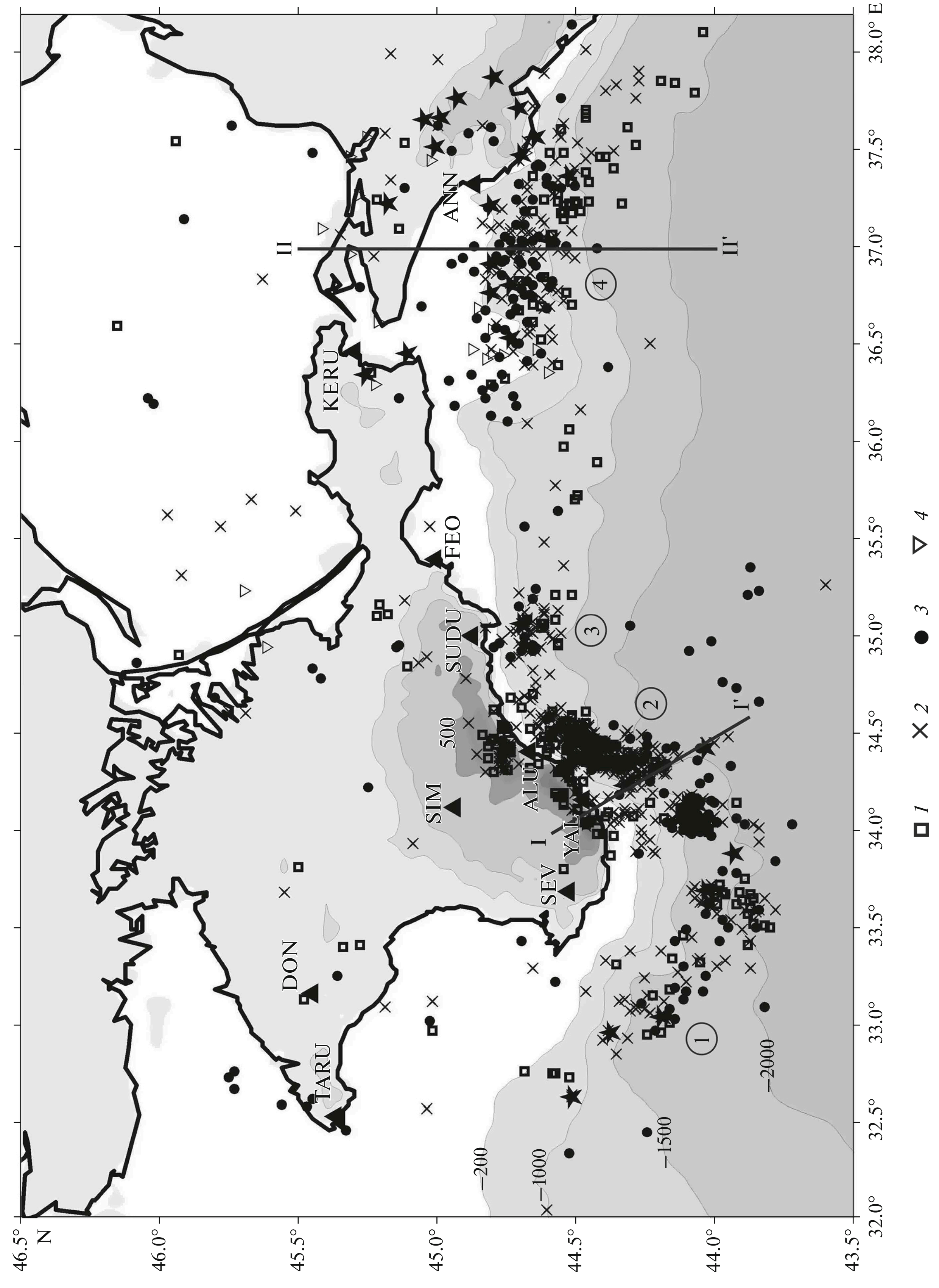
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Table 1. Seismic stations of Crimea

No	Station		Opening Date	Beginning of digital recording	Coordinates		
	name	code			φ°, N	λ°, E	h_y, m
1	Feodosiya	FEO	11.10.1927	06.09.2006	45.02	35.39	40
2	Yalta	YAL	13.03.1928	05.07.2000	44.48	34.15	23.6
3	Simferopol	SIM	14.05.1928	25.06.2000	44.95	34.12	275
4	Sevastopol	SEV	28.06.1928	03.09.2006	44.54	33.68	42
5	Alushta	ALU	03.10.1951	19.07.2006	44.68	34.40	61
6	Sudak	SUDU	18.10.1988	29.07.2006	44.89	35.00	108
7	Kerch	KERU	19.05.1997	06.03.2007	45.31	36.46	50
8	Tarkhankut	TARU	11.07.2012	11.07.2012	45.38	32.53	0
9	Donuzlav	DON	04.1998		45.45	33.10	80

The Kerch–Taman subzone of foci is located at the continental slope south of the Kerch and Taman peninsulas. Quite strong earthquakes with magnitudes of $m_b = 4–6$ are generated in this subzone: their foci are situated in the lower crust and upper mantle [44]. Those foci cluster deepens northward at about 30°. Thus, the deepest (70–90 km) hypocenters are located at the very north of the Kerch and Taman peninsulas (Fig. 2, 3).

In the Sudak subzone, with a small number of earthquakes clustered at the continental slope to a depth of 35 km there is a similar to the Kerch–Taman subzone tends to get deeper northward. Between the Sudak and Kerch–Taman subzones within a zone at λ ~ 35.2°–36°, abrupt weakening of seismicity up to its complete disappearance south of Feodosiya is observed. This may be related to a strong negative velocity anomaly, revealed by seismic tomography [14] and interpreted as a weak layer incapable of earthquake generation.

The Yalta–Alushta (Yuzhnoberezhnaya) subzone is known for producing a majority of earthquakes and is characterized by their maximum density. Their foci are located within a zone running along the Black Sea continental slope (λ ~ 34°–34.7°) partly overlapping shelf and adjacent part of the Crimean Mountains (see Fig. 2). With a complicated character of seismicity distribution in the subzone, some regularities are recognized. The deepest foci (H = 35–50 km) are located about 50 km south of the Yalta station. Between Yalta and Alushta, the foci are mainly concentrated in a layer at a depth of 10–25 km. Thus, along the Yuzhnoberezhnaya subzone, a tendency is observed where foci rise to the northeast along the shoreline. In the cross–section normal to the shoreline, there is a general tendency of foci getting shallower northward (or to the northwest) toward the southern coast of Crimea at an angle of 17°–18° (see Fig. 3). This ascent of the foci is a feature that requires a tectonic explanation.

Table 2. Reference velocity model, applied for the relocation procedure

Z, km	Vp, km/s	Vs, km/s
0	5.4	3.2
10	5.6	3.3
20	6.1	3.6
35	6.6	3.8
35	7.5	4.3
90	8.0	4.5

The foci of the Sevastopol NW-striking subzone are located orthogonally to the Yuzhnoberezhnaya subzone and concentrated in a narrow zone 35–40 km width occurring at the foot of the continental slope (see Fig. 2). Notably, foci in this subzone are distributed approximately uniformly along the interval of depths of 0–40 km.

The longitudinal cross–section of the entire CSZ shown in Fig. 4 most clearly demonstrates the revealed differences in the seismicity of the two subzones: the Yalta–Alushta subzone with earthquake foci down to 50 km deep, plunging southward, and Kerch–Taman subzone with foci down to 90 km and a dominant dip northward.

Localization of the earthquakes foci within the continental slope (see Fig. 2) limited to a depth of 90 km (Fig. 3, 4) may suggest their relationship with a heterogeneity of the lithosphere and collision processes at the plate boundary. This is well demonstrated in the Free Air gravity anomaly map (Fig. 5). The foci of the Sevastopol, Yalta–Alushta, and Sudak subzones are located within the gradient zone corresponding to the transition from the Crimea gravity maximum (its southern end can be traced southward in the sea to about φ = 43.7°) to the negative gravity field offshore. The majority of Kerch–Taman subzone earthquakes are confined to a positive band-shaped anomaly at the shelf, connecting the Crimea maximum to the positive anomaly of the North Caucasus, while the latter borders the negative field of the Tuapse Trough (see

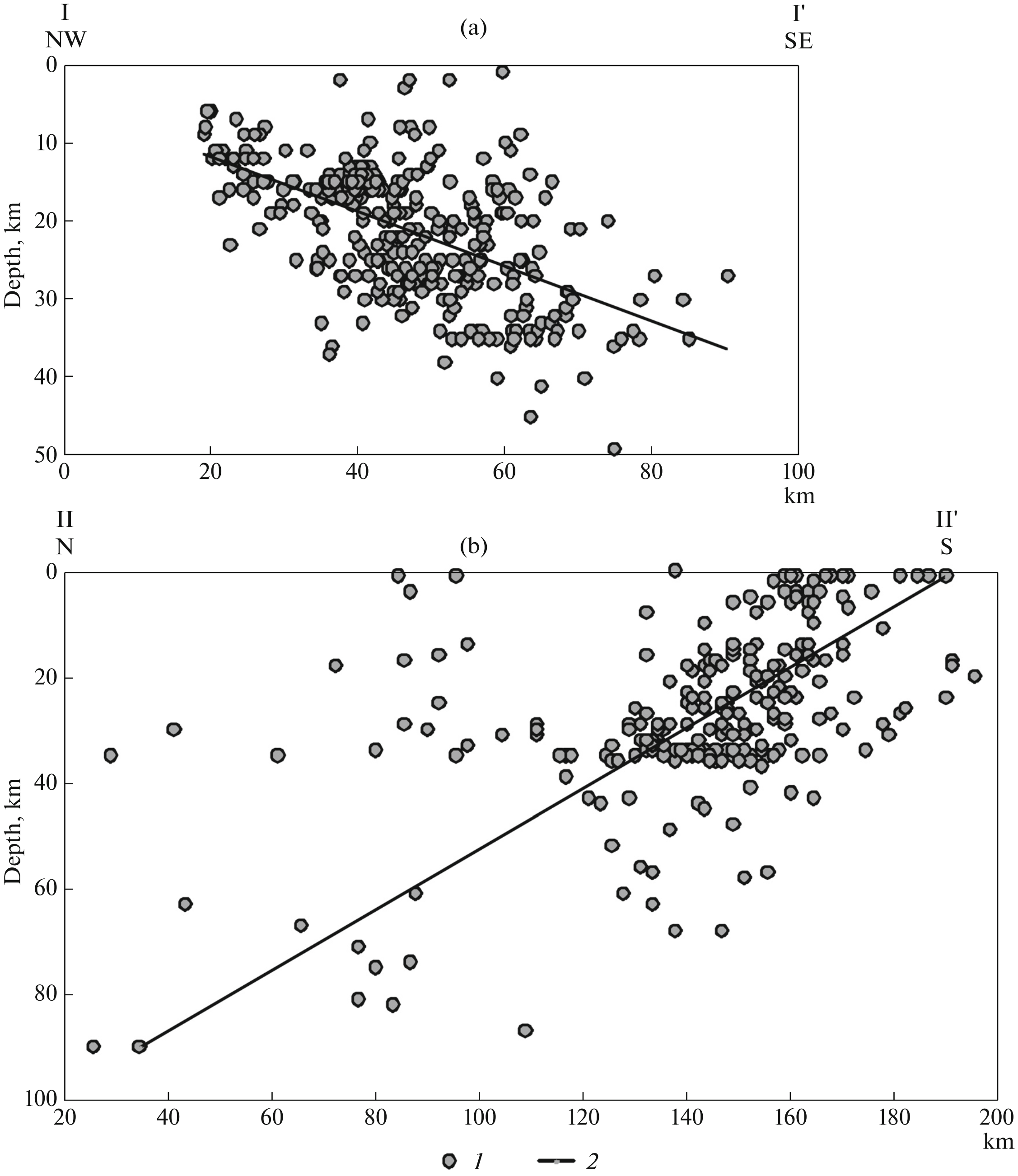

Fig. 3. Distribution of foci depths of weak earthquakes. Subzones: a, Yalta–Alushta (cross section I-I'); b, Kerch–Taman (cross section II-II'). *1*, earthquake foci; *2*, trend line.

Fig. 5). This implies the presence of two plates with different rheological properties: the continental Scythian Plate with the Crimea Orogen in the south and the Black Sea Microplate with thin suboceanic crust. The seismic zone clearly marks the collision region between the two plates. On the other hand, the foci distribution in Figs. 2–5 testifies to the specific features of modern collision processes in two branches of the seismic zone: the Yuzhnoberezhnaya (Yalta–Alushta) and Kerch–Taman subzones.

FOCAL MECHANISMS OF STRONG EARTHQUAKES

Solutions of focal mechanisms of strong earthquakes, based on dislocation theory [8], makes it possible to reconstruct the direction of movement along nodal planes, which correspond to faulting planes, as well as to reconstruct the orientation of the main axes of normal stress released in a focus at the moment of an earthquake.

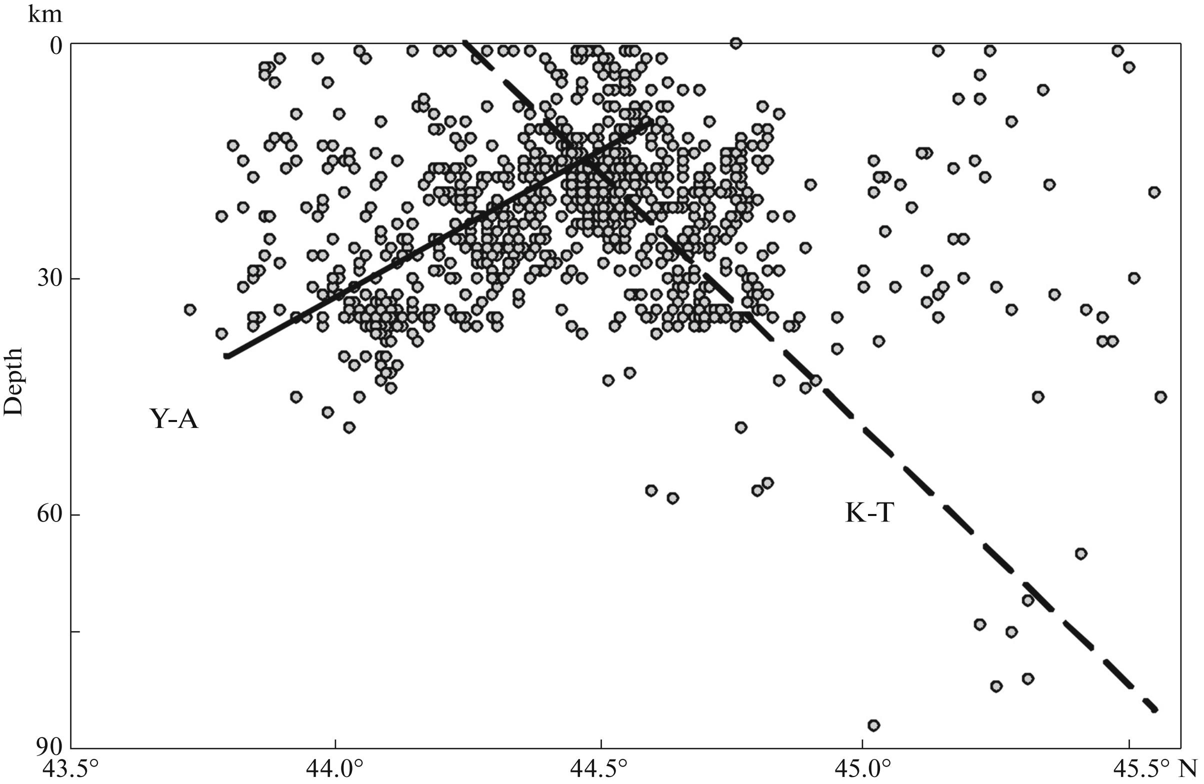

Fig. 4. Meridional cross-section of all foci of the Crimean seismic zone. Marked branches: Y–A, shallow Yalta–Alushta plunging southeast; K–T, Kerch–Taman with dip to the north. Legend, see Fig. 3.

During perennial seismological studies carried out by the staff at the Seismology Department of the Institute of Geophysics of National Academy of Sciences of Ukraine (now the Institute of Seismology and Geodynamics of Vernadskii Crimean Federal University), the focal mechanisms of the strongest earthquakes ($M \geq 4$) that have struck the Black Sea region, including the CSZ, have been solved. In this study, the focal mechanism solutions of 31 earthquakes that occurred during 1927–2013 [12, 30, 31] have been classified and analyzed.

Depending on the orientation of the main axes of the stress tensor, all the mechanisms are subdivided into four groups, corresponding to reverse-fault, strike-slip, normal-fault and normal–reverse-fault deformation regimes (Fig. 6b). The reverse-fault regime is characterized by subvertical orientation of the extension axis σ_3 (or minimal principal stress); the strike-slip regime- by the same orientation of the intermediate stress axis σ_2, while for the normal-fault regime, the maximum stress axis σ_1 has a subvertical position. A real mechanism can be attributed to the reverse-fault, strike-slip, or normal-fault regime under the condition of deviation of the σ_3, σ_2, and σ_1 axis, respectively, for less than a 45° angle from vertical. The normal–reverse-fault regime was earlier determined [20] and characterized by orientation of the extension and maximum stress axes at a 45° angle to a horizontal plane. One of the nodal planes in this type of mechanism is oriented vertically, while the other one is horizontal. The stress field of normal-reverse type has been reconstructed for the Kerch Peninsula subhorizontal fault zone (detachment) in Sarmatian (Messinian) limestone: it has been referred to as “related to movements along the horizontal plane” [13]. For brevity, it is further referred to as “overthrust” (Fig. 6b).

Analysis of the orientations of the principal stress axes in the foci (Fig. 6a) shows that most of the mechanisms (16 events or 52%) are related to the reverse-fault deformation regime with predominance of the horizontal compression axis in the foci (see Fig. 6b). The normal–reverse-fault deformation regime is second in abundance and found in seven (22% of the total) foci with hypocenters at depths of 15–33 km. The normal-fault and strike-slip deformation regimes are present in equal proportions (four or 13%). Comparison of the mechanisms with structures shown in the depth map of the crystalline basement shows some regular patterns in their spatial distribution. Five reverse-fault mechanisms (foci nos. 2, 10, 17, 24, 28 in Fig. 6a and Table 3) form a compact group confined to the margins of the Tuapse Trough and the adjacent region of the Greater Caucasus. The mechanisms revealed for the foci within the Kerch–Taman (nos. 3, 5, 25) and the Indolo–

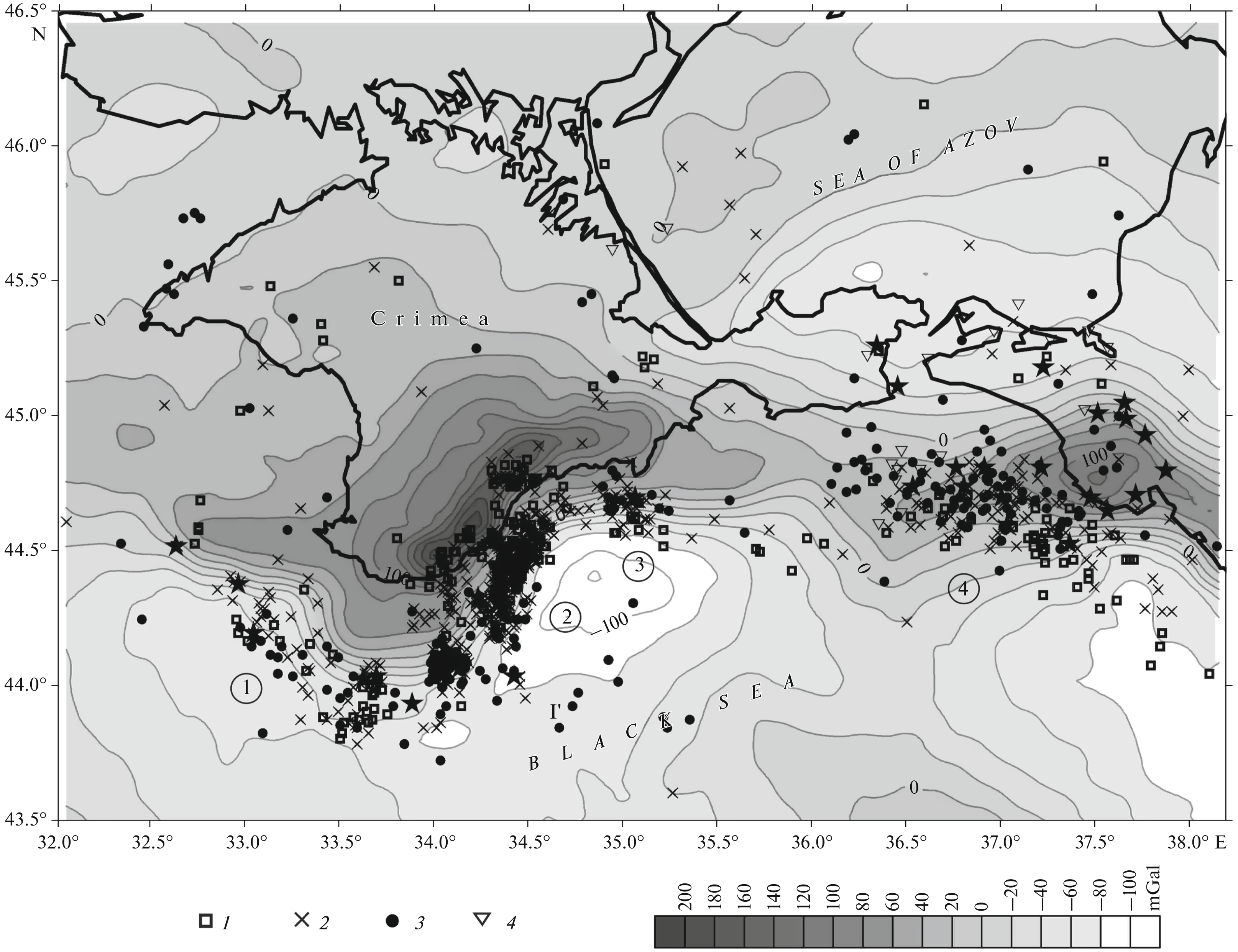

Fig. 5. Distribution of epicenters of weak earthquakes ($m_b \leq 3$) in the Crimean seismic zone on the background of Free Air gravity anomalies, EGM2008 reference model [57]. Symbols, see Fig. 2

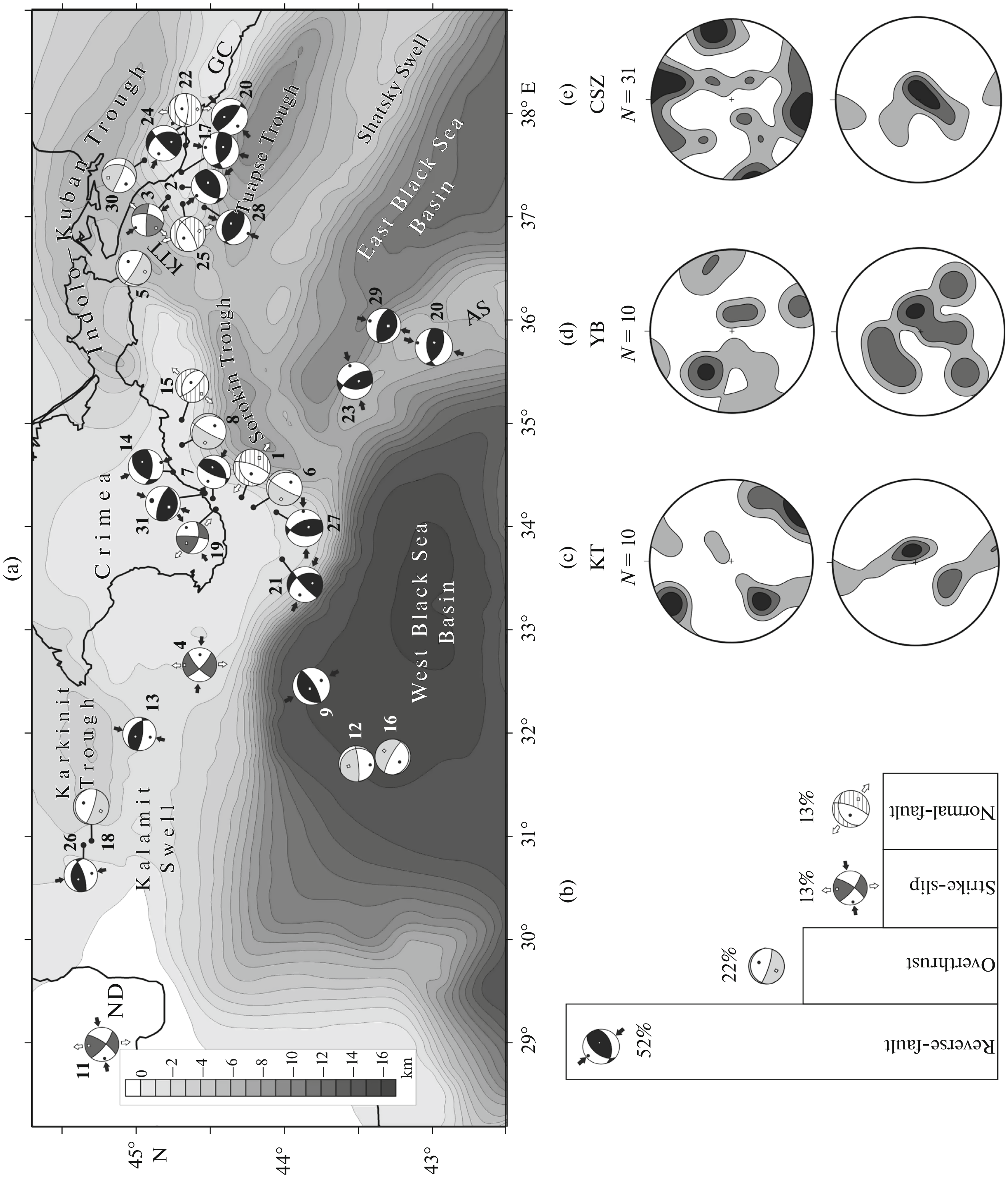

Fig. 6. Spatial distribution and typology of earthquake focal mechanisms in the Crimean seismic zone: (a) epicenters of strong earthquakes and their corresponding mechanisms on background of crystalline basement depth [35]; (b) percentage of different types of earthquake mechanisms; (c–d) stereograms constructed on lower hemisphere with orientations of axes of compression and extension in foci of subzones: (c) Kerch–Taman (KT); (d) Yuzhnobertezhnaya (YB); (e) all mentioned mechanisms in CSZ. GC, Greater Caucasus; AS, Andrusov Swell; ND, North Dobrogea; KTT, Kerch–Taman Trough.

Table 3. Parameters of focal mechanisms of strong earthquakes in the Black Sea northern coastal area.

No	Date	Latitude, N	Longitude, E	Depth, km	Azimuth and dip of contraction axis, *P*	Azimuth and dip of intermediate axis, *N*	Azimuth and dip of extension axis *T*	Deformation mechanism	Structural position
1	11.09.1927	44.3	34.3	15	263/62	28/17	125/22	Normal fault	Continental slope, South Crimea (SC)
2	12.07.1966	44.7	37.3	55	325/5	233/19	69/70	Reverse fault	Tuapse Trough
3	22.07.1972	44.8	37.2	19	325/8	68/57	230/32	Strike–slip	KT Trough
4	06.08.1972	44.6	32.7	15	90/28	265/62	359/2	Strike–slip	Continental slope, West Crimea (WC)
5	20.02.1973	45.03	36.52	25	50/50	298/18	195/35	Overthrust	KT Trough
6	1955–1975	44.2	34.2	15	134/54	29/11	292/34	Overthrust	Continental slope, south Crimea (SC)
7	1955–1975	44.5	34.3	5	301/29	204/13	92/58	Reverse fault	Continental slope, (SC)
8	1955–1975	44.7	34.8	20	134/54	29/11	292/34	Overthrust	Continental slope, South-Eastern (SE) Crimea
9	17.04.1975	43.83	32.44	46	147/27	57/1	325/63	Reverse fault	WBSB
10	03.09.1978	44.4	38	20	236/23	139/18	14/60	Reverse fault	Tuapse Trough
11	13.11.1981	45.27	29.01	11	254/1	159/78	244/12	Strike–slip	North Dobrogea
12	03.03.1986	43.52	31.69	18	188/30	81/26	318/48	Overthrust	WBSB
13	02.04.1988	44.98	32.01	13	188/10	94/22	301/66	Reverse fault	Kalamit Swell
14	02.07 1990	44.78	3453	14	160/8	254/28	55/61	Reverse fault	Mountain Crimea
15	16.08.1990	44.7	35.06	28	81/67	317/14	223/19	Normal fault	Continental slope, South-Eastern (SE) Crimea
16	25.07.1991	43.3	31.7	30	215/55	118/5	24/35	Overthrust	WBSB
17	27.08.1992	44.72	37.44	24	14/17	277/23	136/61	Reverse fault	Greater Caucasus
18	29.03.1992	45.3	31	33	35/48	302/2	210/42	Thrust	Karkinit Trough
19	22.11.1996	44.51	34.16	10	61/16	173/52	320/34	Strike–slip	Mountain Crimea
20	09.06.1997	43.03	35.73	33	192/3	283/15	91/74	Reverse fault	Andrusov Swell
21	18.10.1998	44.05	33.68	22	304/29	53/32L	181/45	Reverse fault	Continental slope, (SC)
22	08.08.1999	44.71	37.71	37	27/77	268/7	176/12	Normal fault	Greater Caucasus
23	04.03.2001	43.6	35.37	20	74/9	342/17	192/71	Reverse fault	Andrusov Swell
24	09.11.2002	44.82	37.7	29	113/10	14/41	213/48	Reverse fault	Greater Caucasus
25	13.03.2005	44.72	37.14	4	240/59	78/29	344/8	Normal fault	KT Trough
26	07.05.2008	45.34	30.95	5	172/0	82/1	172/90	Reverse fault	Karkinit Trough
27	12.04.2009	44.16	34.23	20	82/2	352/13	181/76	Reverse fault	Continental slope, (SC)
28	05.10.2007	44.56	37.08	18	205/9	297/12	78/75	Reverse fault	Tuapse Trough
29	17.03.2011	43.39	36.13	31	20/18	289/7	183/71	Reverse fault	Andrusov Swell
30	10.12.2012	44.83	37.54	24	232/30	117/36	350/39	Overthrust	Indolo–Kuban Trough
31	15.10.2013	44.55	34.35	7	16/27	108/6	209/62	Reverse fault	Mountain Crimea

Serial number corresponds to number of earthquake mechanism in Fig. 6; WC–West Crimea; WBSB–West Black Sea Basin; KT–Kerch–Taman trough; SC–South Crimea.

Kuban troughs (no. 30) are related to the strike-slip, normal-fault, and normal–reverse types.

Three reverse - type mechanisms (nos. 7, 14, 31 in Fig. 6a and Table 3) are located in the central part of the Yuzhnoberezhnaya subzone at the maximum bend in the coastline and the narrowest shelf of the East Black Sea Basin. To the south and east of them, two normal-fault (nos. 1, 15) and two normal–reverse-fault (nos. 6, 8) mechanisms revealed. Reverse-fault and strike-slip mechanisms (nos. 4, 13, 21, 26, 27) are located in the northwestern and northern shelf of the Western Black Sea Basin (WBSB). The Andrusov swell is characterized by a compression deformation regime, revealed in foci nos. 20, 23, and 29. Within the deepwater part of the WBSB, two centers with normal–reverse-fault mechanisms and one with a reverse-fault mechanism have been identified (see Fig. 6a).

The orientation of the compression and extension axes has been statistically determined for ten mechanisms of the Kerch–Taman subzone and ten mechanisms the Yuzhnoberezhnaya subzone, which form compact clusters. The Kerch–Taman group is characterized by NW and SW orientation of the predominantly subhorizontal compression axes (Fig. 6c) and close to the vertical extension axis. In the Yuzhnoberezhnaya subzone, a more complex distribution of the compression and extension axes (Fig. 6d) has been revealed. Statistical generalizations are illustrative given the small number of studied mechanisms.

For compression axes generalized for all 31 CSZ mechanisms, the predominance of subhorizontal orientation in two mutually perpendicular directions has been found: sublatitudinal and sublongitudinal (Fig. 6d). The tendency of the extension axes toward a subvertical position is typical.

This generalization of the focal mechanisms of 31 strong earthquakes during 1927–2013 demonstrated a prevalence of the reverse-fault and normal–reverse-fault deformation regimes. The orientations of the compression axes in the foci with respect to the orientation of the CSZ indicates that the current tectonic process occurs mainly in shortening and transpression settings. Mechanisms with a significant strike-slip component are confined to the western part of the CSZ.

RESULTS OF TECTONOPHYSICAL STUDY

The Crimea Mountains belong to the northern branch of the Alpine Orogen Belt, which extends along the northern margin of the Black Sea [50]. The Crimean Mountains are bent, with their western part striking NE–SW, while the eastern one stretches W–E. In their structure, the Crimean Mountains can conventionally be subdivided into western and eastern along the Alushta–Simferopol line, which is, according to the opinions of many researchers, one of the major tectonic zones of Crimea [34, 36, 61, 64].

The geological structure of the Crimean Mountains is interpreted in different ways [23, 26, 39, 52], which is largely determined by the stratigraphic scheme applied by authors [39, 52, 59, 64]. In accordance with classic concepts [2, 26], there are three structural complexes: lower (T_3–J_2), intermediate (J_3–K_1 (Berriasian)), and upper (K_1–Q). The rocks of the upper level, in turn, are divided into sedimentary cover (Cretaceous–Eocene) and the synorogenic complex (Oligocene–Quarternary).

In our study, we focus on the Cenozoic and the present-day stage of evolution of the Crimean Mountains. The problem of Cenozoic shortening and its occurrence in the geological structure of the Crimean–Black Sea region is debatable. Various researchers support extreme viewpoints to prove either the dominance or, on the contrary, lack of fold and thrust deformations during the Alpine stage of the evolution of the Crimean Mountains [2, 4, 10, 23, 26, 39, 40, 52, 58, 59, 64].

According to [52], the shortening phase in the Crimean Mountains is synchronous with the main deformation phase of Eastern Pontides and it ceased before the Middle Eocene. In the Sudak Trough, the main folding phase occurred at the Eocene–Oligocene boundary, and in the Maikop period, during the Oligocene–Early Miocene, while the main phase of the uplift of the Crimean Mountains occurred in the post-Sarmatian time.

In accordance with [39, 40], the Podgorny and Yuzhnoberezhny mélanges at the base of the cliffs of the Main Range and along the Black Sea coastline are active compression structures of Neogene–Quaternary age.

The first phase of Cenozoic shortening terminated before the Middle Eocene and the subsequent compression phase in the Oligocene–Early Miocene is related to the corresponding hiatuses of sedimentation and is recorded in deformations [28, 64].

The present-day stage of evolution of the Crimean Mountains is characterized by intense uplift and significant seismic activity in the CSZ, which points to active geodynamic processes.

In order to clarify the evolution of tectonic events in the Cenozoic–Quaternary, additional tectonophysical field work was carried out and previously published results [9, 10, 13, 18, 27, 28, 61, and references therein] have been summarized.

Reconstruction of the stress tensor was based on the principles of the kinematic method using the Win Tensor program [42]; typification of deformation regimes was carried out using orientations of the principal stress axes similar to the focal mechanisms of earthquakes. For the purposes of this study, 1128 slickensides in the western Crimean Mountains and 919 slickensides in the eastern Crimean Mountains have been measured.

The western Crimean Mountains are characterized by the dominance of strike-slip stress fields in two diagonal directions (52%) (histogram in Fig. 7c); the western terminus of the western Crimean Mountains is dominated by a field with a SW–NE strike of the compression axis. This field is comparable to the strike-slip focal mechanisms nos. 4 and 19 and with the reverse-fault mechanism of focus no. 2 (see Fig. 6), which contains a significant strike-slip component. The second position of the western Crimean Mountains take normal-fault deformation regimes, 30% (see Fig. 7c). Tectonic normal-fault slickensides are confined to the southern cliffs of the Main Ridge and boundaries of Early Cretaceous basins (Fig. 8d). The stress field with an active extension axis across the strike of the western Crimean Mountains is comparable to normal-fault mechanism no. 1.

Generalization of the deformation regimes for the eastern Crimean Mountains (see Fig. 7c), in contrast, shows the prevalence of the reverse-fault field with sublongitudinal and sublatitudinal directions of the active compression axis (45%). North–south compression slightly prevails, which occurred most intensively in the Sudak and Feodosiya regions. This reverse-fault regime may either be associated with the folding phase in the Sudak deepwater trough at the boundary of Eocene–Oligocene and during the Maikop period [52] or with the formation in the Paleocene [64] and/or reactivation in the Pliocene–Quaternary of the Sudak–Karadag thrust zone (Fig. 8a). The second in abundance in the eastern Crimean Mountains are two strike-slip fields with sublongitudinal and sublatitudinal compression axes, which together account for 34%. For the strike-slip fields, their compression axes are oriented similarly to those of reverse-fault fields, allowing them to be referred to the same compression stages.

Most on-land earthquakes in the CSZ are at depths of 0–30 km and are confined to the western part Crimean Mountains, the meridional Ayu-Dag–Chatyrdag zone, and the Demerji area (see Fig. 7).

The relationship between CSZ earthquakes and diagonal faults activated during the Quaternary was earlier discussed [5]. One of the most active faults, the following were mentioned: the Yuzhnoberezhny Fault running along the continental slope, the Demerji Fault parallel to it within the Crimean Mountains, the NW-trending segment of the West Crimean Fault bounding the Sevastopol earthquake zone from southwest, the Kuchuk–Koy Fault parallel to it within the Crimean Mountains, the Yalta Fault, etc. It seems to us that surficial foci should be considered in the context of the entire geodynamic situation in the region. For example, within the western Crimean Mountains, the earthquake distribution coincides with the maximum values of the Crimean gravity anomaly and with the hypsometrically highest segment of the Crimean Mountains, while the meridional Chatyrdag–Ayu-Dag foci zone can be traced further offshore as a dense band of epicenters; it correlates with the zone of maximum gravity anomaly gradients and reorganization of the structural plan within the Crimean Mountains (see Fig. 5).

Deformation structures associated with the Cenozoic shortening stage are present in both the eastern (see Figs. 8a, 8b) and western Crimean Mountains. However, they are prevalent in the eastern Crimean Mountains, while in western Crimean Mountains, strike-slip slickensides are dominant (see Fig. 8a). To a greater extent, normal-fault deformations are typical in the western Crimean Mountains, related to two chronologically different processes. Synsedimentation normal-faulting in the Lower Cretaceous sediments is associated with the Lower Cretaceous stage extension phase [28], while modern normal faulting, manifested in both the landscape and earthquake mechanisms, occurred during collapse of the Crimean Orogen due to gravitational processes [27].

Surficial earthquakes are genetically relayed to foci in the Black Sea and reflect uniform geodynamic processes.

DISCUSSION

Earthquakes in the CSZ (see Fig. 2) are located within the continental slope between the continental block of the Scythian Plate with the Crimean–Caucasus orogenic belt in the south and the Black Sea Basin. The presence of the Scythian Plate and the Black Sea Microplate with discrepancies in rheological properties can be clearly seen on the gravity map (Fig. 5) showing the association of earthquake foci to the area of the sharp gradient between the Crimean gravity maximum and the negative field offshore. Therefore, it is appropriate to mention [21], in which the relationship of the CSZ seismicity to the gravity field was explained by the strain state in the tectonosphere caused by disturbance of isostatic equilibrium and possible horizontal movements in the lithosphere.

CSZ earthquakes foci (see Fig. 2, 5) are located along an arc with two main branches that differ in the pattern of their seismicity: South Crimea and Kerch–Taman, separated by an area of diffuse seismicity that can be well seen in the 3D model of the CSZ (Fig. 9). The South Crimea branch by the nature of seismicity can be subdivided into the Sevastopol, Yalta–Alushta (Yuzhnoberezhnaya), and Sudak subzones (see Fig. 2).

The Kerch–Taman branch plunges down to 90 km at an angle of 30° northward (see Fig. 3). The focal mechanism solutions in this subzone suggest the predominance of the reverse-fault-type deformations with the main compression axis oriented to the NW and SW (see Fig. 6). It should be noted that for earthquakes of the northwest Caucasus, the reverse-fault-type mechanism is also typical in combination with strike-slip displacements [7, 11], which is explained by the oblique convergence vector of the Black Sea and the Caucasus in relation to the Main Caucasus Thrust [24].

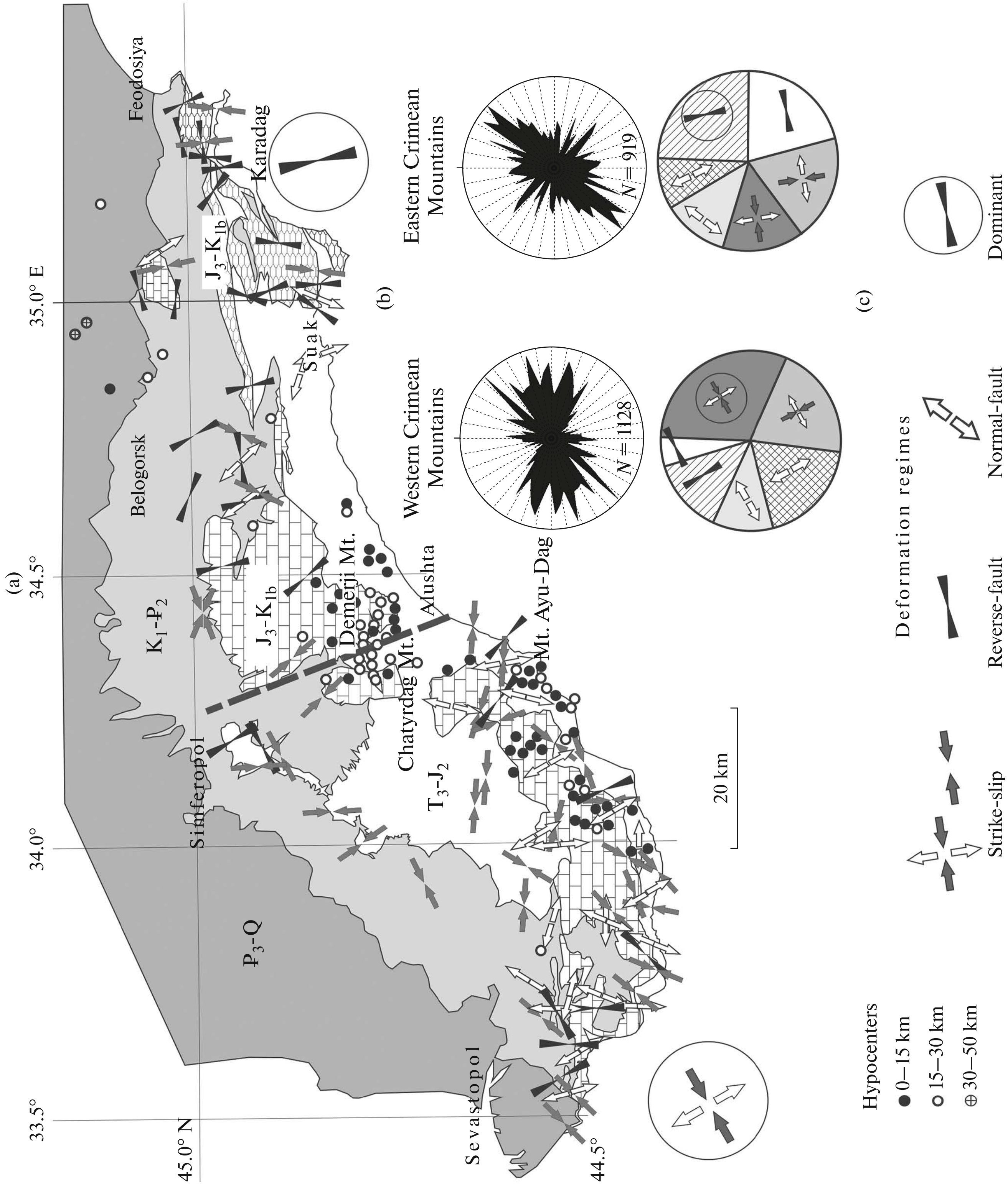

Fig. 7. Comparison of stress-deformation state of the western and eastern Crimean Mountains: (a) map of spatial distribution of deformation regimes and earthquake epicenters: compression axis of reverse–fault and strike-slip deformation regimes are shown with black and gray arrows, respectively; extension axes of normal-fault regimes are shown with white arrows. Geological background after [39] modified with highlighting of main structural complexes of the Crimean Mountains; dotted line shows conventional boundary between the western Crimean Mountains and eastern Crimean Mountains along Alushta–Simferopol line; (b) polar diagrams of strike azimuths of slickensides; (c) histogram distribution of deformation regimes.

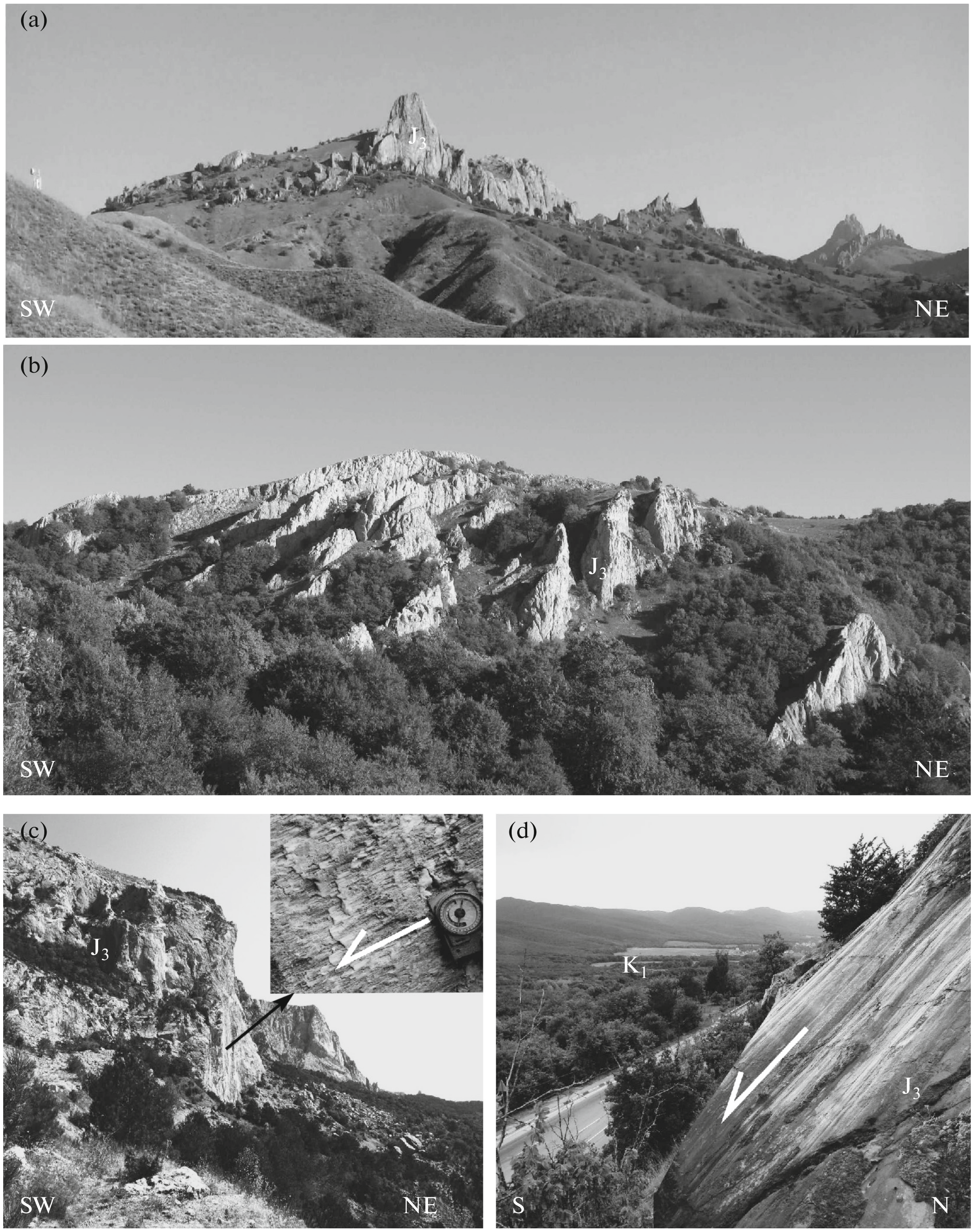

Fig. 8. Deformation of shortening and extension in the Crimean Mountains. Compression deformation: (a) thrust front marked by crests of steeply dipping Upper Jurassic limestone in flysch matrix, northwestern outskirts of village of Kurortnoye (eastern Crimean Mountains); (b) Demerji Fault (thrust) marked by steeply dipping Upper Jurassic limestone. Extension deformations: (c) normal fault limiting from northeast Varnaut Trough, filled with Lower Cretaceous clastic rocks (western Crimean Mountains); (d) strike-slip and normal-fault slickensides limiting from south cliffs of Upper Jurassic limestone of Main Range, northeast of settlement of Foros (western Crimean Mountains).

Seismic tomography and reinterpretation of the DSS results on seismic line 28–29 in the Sea of Azov and Black Sea show modern processes of underthrusting of the East Black Sea Microplate under the Scythian Plate at the Kerch Peninsula and in the North Caucasus [70, 44]. Traditionally, it was thought that this type of underthusting is typical of the entire CSZ [29, 37, 38]. In [17, 18] papers the CSZ geodynamic process has been presented as underthrusting and lateral extrusion. Our results indicate that the collision in the Yuzhnoberezhnaya subzone is characterized by a more complex character than in the Kerch–Taman subzone.

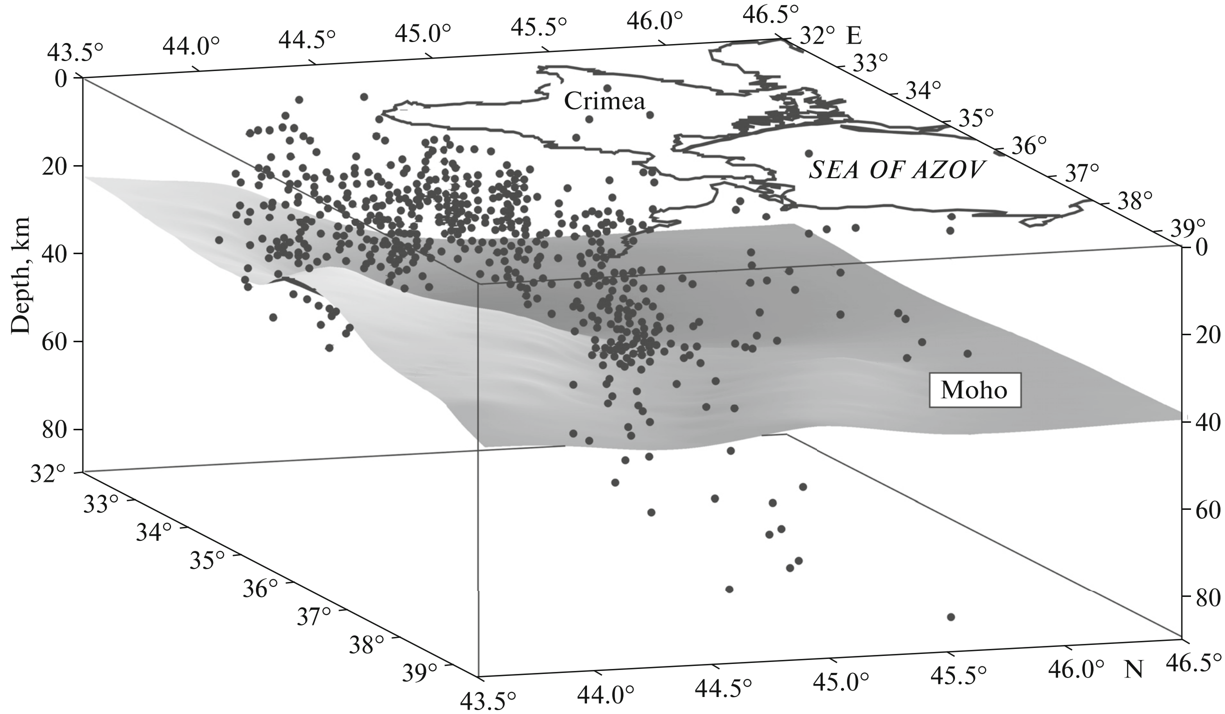

Fig. 9. Three-dimensional distribution of earthquake foci of the Crimean seismic zone.

We call the geodynamic process in the CSZ underthrusting rather than subduction, since the deepest earthquakes foci are no deeper than 90 km and the colliding Scythian Plate and Eastern Black Sea Microplate (which is a part of the Black Sea Microplate) pertain to the continental type. The lithospheric mantle under the Black Sea in its velocities, as revealed by seismic tomography and densities calculated for 3D gravity modelling, is most likely related to the continental type [41, 69]. The high-velocity crust of the Black Sea, underlain by such an upper mantle, cannot be considered oceanic one. Rather, it should be referred to as suboceanic or very thinned continental crust. This is consistent with the low values of heat flow indicating the cold lithosphere of the Black Sea [19, 25].

The earthquake distribution in the Yuzhnoberezhnaya subzone on the continental slope shows two meridional (transform) intersecting strips of foci localization at the longitude of Yalta and Alushta (see Fig. 2). The Alushta area is the zone with the densest foci clustering with hypocenters at depths down to 45 km, which coincide with the gravity field gradient (see Fig. 5); the latter separates the marine continuation of the Crimea gravity maximum from the minimum in the Sorokin Trough. On land, the Alushta meridional zone is traced by an earthquake zone in the Ayu-Dag–Chatyrdag area. Thus, on the meridian of Alushta (λ = 34.5°), a crustal separation between the western and eastern Crimean Mountains is suggested; at the surface, this zone corresponds to the Simferopol–Alushta Fault (see Fig. 8), which is considered one of the main tectonic zones of Crimea [34, 36, 61, 64]. East of the Alushta meridianal zone, the number of earthquakes is significantly reduced and their epicenters are localized sublatitudinally along the gravity field gradient (see Fig. 5).

The subdivision of the Crimean Mountains into the east and west segments is consistent with the different type of the prevailing deformation regimes according to tectonophysic studies (see Fig. 7). The western part is dominated by strike-slip and normal-fault deformation regimes. The eastern part is dominated by reverse-fault stress fields. The latter is explained as the result of a collision of the East Black Sea Microplate against the Scythian Plate, resulting in the formation of compression structures complicated by a series of asymmetric folds vergent southward in the Sorokin Trough at the foot of the continental slope of the Crimean Mountains, as can be seen in the reflection seismic survey sections [43, 51, 67]. These data may indicate underthrusting, which in the Yuzhnoberezhnaya subzone (compared to the Kerch–Taman branch) has a more complex character.

According to seismic-gravity modelling, the thickness of the crust under the Crimean Mountains reaches 50 km [69], while the maximum depth of earthquake hypocenters beneath it is 35 km. Obviously, below this level, deeper crust deformation proceeds under different rheological conditions, which leads to its horizontal delamination and triggers movements. An argument in favor of this horizontal stratification of the crust is the large number of overthrust-type focal mechanisms at a depth of 18–30 km, where one of the nodal planes has a subhorizontal orientation.

Horizontal movements in the crust of the Crimean Mountains may be associated with the indenter effect of the suboceanic crust of the East Black Sea Microplate (seismic velocities of 6.8–7.0 km/s and a density of 2.9 g/cm^3) into the continental crust of Crimea with a relatively reduced velocity and density along a tectonically weakened zone in the crust. A low-velocity zone (waveguide) in the upper–middle crust of Crimea, the northwestern shelf of the Black Sea, and the Caucasus revealed in the deep seismic sounding profiles can serve as evidence for the existence of the latter [3, 34, 56].

Wedging of the frontal part of the crust of Eastern Black Sea Microplate into the crust of the Scythian Plate in the Crimea explains the uplifting of foci in the Yuzhnoberezhnaya subzone northwards toward Crimea from a depth of 30–40 km in the south to about 5–20 km in the north (see Fig. 3). This indenter mechanism explains the formation of a the high-density body (≥3.0 g/cm^3) in the crust of the Crimean Mountains, causing the strong Crimean gravity maximum [6, 22]. If the crust of the Eastern Black Sea Microplate most likely wedges into the crust of the Scythian Plate in Crimea, then the lithospheric mantle might undergo thrusting under the Scythian Plate.

A similar geodynamic process is responsible for the formation of the known Ivrea zone in the southwestern Alps, where the geological and tectonic settings are similar to the settings in the Crimean Mountains. The Ivrea zone's formation is suggested to be the result of the collision process with wedging of the lower crust or upper mantle of the Adriatic Microplate into the continental crust of the European Plate, which led to the formation of an anomalous zone of high density/velocity at a depth of 10–25 km, which has been recorded by deep seismic studies, local seismic tomography, and strong gravity anomaly and is seen in the Moho relief [48, 55, 62, 63].

The proposed indenter mechanism accompanied by wedging of the crust may explain the significant uplift in the Crimean mountains at present-day. Along the continental slope, the maximum gradients of vertical movements are known, with uplift of the Crimean Mountains by 4 mm/year and subsidence of the sea bed up to 10 mm/year, which led to a 4 km difference in the modern relief and almost 15 km for the entire Cenozoic time.

The Kerch–Taman branch, in which the northward underthrusting of the East Black Sea Microplate occurs, and the Yuzhnoberezhnaya subzone, which is characterized by the indenter mechanism, are separated by an area of diffuse seismicity in the region of maximum bending of the underthrusting plate (see Fig. 9).

In the Sevastopol subzone, positioned orthogonally to the Yuzhnoberezhnaya, stress relaxation occurs in response to frontal collision in the latter. V.V. Gonchar [18] explains this by an extrusion mechanism: sideways lateral extrusion of matter from the maximum compression zone along a system of strike-slip faults.

Earthquakes in the Sevastopol subzone are located within the Crimean part of the West Crimean Fault bounded from the west by fold-and-thrust dislocations of the Cenozoic cover within the offshore of the Crimean Orogen [43]. The DOBRE-5 sublatitudinal profile, which crosses the Odessa Shelf and Plane Crimea, is fairly strong evidence for the existence of the West Crimean Fault as a transition between the structures of the crust and sedimentary complexes of Crimea, which have experienced compression deformation, and the extensional environment in the Karkinit Trough of the northwestern shelf [66]. The kinematics of the West Crimean Fault is defined as a sinistral strike-slip involved in opening of the Western Black Sea Basin [45, 55, 54].

The West Black Sea Basin and the northwestern shelf are crossed by the submeridional DSS seismic profiles (25 profile) and CDP line [47, 70], which clearly demonstrate a high-amplitude normal-fault, along which the basement of the Scythian Plate abruptly (approximately down to 8 km) dips to the south, forming the base of the deepwater basin. The fault is currently active [46] and traced with a zone of earthquakes with foci located in the lower crust–upper mantle [68]. Strike-slip mechanism no. 4 in the NW shelf and no. 11 in North Dobrogea correspond to this fault zone (see Fig. 6), which is characterized by sublatitudinal orientation of the compression axis and submeridional orientation of the extension axis.

CONCLUSIONS

Analysis of the weak seismicity in the CSZ, its comparison with the gravity field, earthquake focal mechanisms, and stress-strain state of the Crimean Mountains, permit the following conclusions regarding the current geodynamic settings at the northern margin of the Black Sea Basin.

Intensive seismic activity in the region testifies to the active tectonic processes occurring in compression and transpression settings in the transition zone between the Scythian Plate and the Black Sea, which, in particular, is confirmed by the prevalence of the reverse-fault type focal mechanisms among 31 strong earthquakes.

In the CSZ, which is located along the continental slope, there are three main branches (subzones), which are characterized by different characters of the hypocenters: (1) the Kerch–Taman branch, which plunges northward to a depth of 90 km at an angle of ~30°; (2) the Yuzhnoberezhnaya branch, which tilts to the southeast at an angle of ~18° with dominant localization of earthquake foci in a layer at depths of 10–25 km; (3) the Sevastopol branch, which is orthogonal to the Yuzhnoberezhnaya and confines it from the west, characterized by diffuse seismicity down to a depth of 40 km.

The earthquake foci are located in areas of gradients separating the Crimean gravity maximum and the North Caucasus positive anomaly from the negative gravity field of the Black Sea Basin. A sublongitudinal tight band of epicenters of the Yuzhnoberezhnaya subzone coincides with the zone of maximum gravity gradients offshore; further north it is traced onshore along the conditional boundary Alushta–Simferopol, separating the western and eastern Crimean Mountains with their different features of geological structure and the stress-strain state. The eastern part is dominated by the reverse-fault regime, while the western part, by the strike-slip and normal-fault deformation modes.

The northward-plunging Kerch–Taman seismic focal subzone may represent an evidence of underthrusting of the East Black Sea Microplate with a thin suboceanic crust and cold lithospheric mantle of the continental type beneath the Scythian Plate with thick continental crust. Within the Yuzhnoberezhnaya branch, the process is complicated by pushing-in of the frontal part of the crust of the suboceanic Eastern Black Sea Microplate into the continental crust of the Scythian Plate and wedging of its edge portion, while the lithospheric mantle may likely thrust under the Scythian Plate. The Sevastopol branch of hypocenters associated with the West Crimean Fault is interpreted as a zone of strike-slip deformations, bounding from the west the area of underthrusting.

The wedging mechanism in the frontal part of the dense crust of the East Black Sea Microplate into the continental crust of the Scythian Plate explains the strong gravity anomaly of the Crimean Mountains and its present-day intense uplifting. An analog of the described wedging mechanism seems to be geodynamic processes in the Ivrea zone (southwestern Alps), characterized by similar structural features and similar strong gravity anomaly.

The area of the northwestern (Odessa) shelf and continental slope of the western Black Sea Basin, separated from Crimea by the West Crimean Fault with the observed high seismicity in the Sevastopol subzone, is characterized by dominance of extensional (rift) environments bounded by submeridional fault zones along the continental slope. At present, according to solution of earthquake focal mechanisms, this area may represent a sinistral strike-slip–normal fault zone and can be extended southeastward towards the West Crimean Fault, which is considered a sinistral strike-slip fault.

REFERENCES

1. L. M. Antonova and V. S. Gobarenko, "Inhomogeneities of the crustal structure of the Southern Crimea and adjacent areas of the Black Sea based on P and S travel times," Izv., Phys. Solid Earth **33**, 653–660 (1997).
2. A. P. Afanasenkov, A. M. Nikishin, and A. N. Obukhov, *Geologic Structure and Hydrocarbon Potential of the East Black Sea Region* (Nauchnyi mir, Moscow, 2007) [in Russian].
3. E. P. Baranova, T. P. Egorova, and V. D. Omelchenko, "Revealing of a wave guide in the north-western basement of the Black Sea Odessa shelf according to the results of DSS profiles 26 and 25 materials reinterpretation," Geofiz. Zh. **33** (6), 15–29 (2011).
4. L. S. Borisenko and L. G. Plakhotnyi, "Geodynamics of the Crimean–Black Sea region as a result of multilevel tectogenesis," in *Geodynamics of the Crimean-Black Sea Region: Proceedings of the Conference* (NPTs EKOSI-Gidrofizika, Simferopol, 1997), pp. 54–64.
5. L. S. Borisenko, E. P. Tikhonenkov, N. N. Novik, and I. I. Chabanenko, "On the structural coincidence of the epicenters of main groups of the Crimean earthquakes," Geol. Zh., No. 6, 64–69 (1983).
6. V. B. Bur'yanov and N. I. Pavlenkova, "On the crustal structure of Gorny Crimea," Sov. Geol., No. 7, 112–119 (1974).
7. A. N. Vardapetyan, Candidate's Dissertation in Geology and Mineralogy (Inst. Okeanol. im. P.P. Shirshova Akad. Nauk SSSR, 1981).
8. A. V. Vvedenskaya, *Study of Stresses and Ruptures in Earthquake Sources by Using the Dislocation Theory* (Nauka, Moscow, 1969) [in Russian].
9. Yu. M. Volfman, "On the effect of kinematic conditions on the cyclic character of geologic processes within the limits of the Crimea and Northern Pre-Black Sea area during the Alpine stage," Geofiz. Zh. **30** (5), 101–114 (2008).
10. Yu. M. Volfman, "Deformational regimes and kinematic conditions of modern tectonic faulting within the limits of the Mountain Crimea. Pt. 2," Geofiz. Zh. **37**, No. 1, 100–120 (2015).
11. I. P. Gabsatarova, E. A. Selivanova, and L. S. Malyanova, "North Caucasus," in *Zemletryaseniya Severnoi Evrazii v 2007 g.* (Geofiz. Sluzhba Ross. Akad. Nauk, Obninsk, 2013), pp. 100–115.
12. I. P. Gabsatarova, L. S. Malyanova, E. A. Selivanova, and V. N. Yakusheva, "The *Mw* 4.6 earthquake of December 10, 2012 near Anapa," in *Seismological Bulletin of Ukraine for 2012* (NPTs EKOSI-Gidrofizika, Sevastopol, 2013), pp. 35–45.
13. O. B. Gintov, *Field Tectonophysics and Its Applications in Studies of Deformations of the Earth's Crust in the Territory of Ukraine* (Feniks, Kiev, 2005) [in Russian].
14. V. S. Gobarenko, "Features of spatial distribution of *P*- and *S*-wave velocity and elastic characteristics of the crust of the Eastern Crimean peninsula," Geofiz. Zh. **22** (1), 66–76 (2000).
15. V. S. Gobarenko, "Analysis of calculation of the hypocenter coordinates in the Crimea Seismic Zone," in *Seismological Bulletin of Ukraine for 2012* (Nats. Akad. Nauk Ukr., Simferopol, 2003), pp. 110–114.
16. V. S. Gobarenko and T. B. Yanovskaya, "Velocity structure of the upper levels of the Black Sea mantle," Geofiz. Zh. **33** (3), 62–74 (2011).
17. V. V. Gonchar, "Deformation in the Crimean seimofocal zone," Dopov. Nats. Akad. Nauk Ukr., No. 6, 101–110 (2003).

18. V. V. Gonchar, "On substantiation of mechanism of lateral extrusion the earth crust of the Mountain Crimea," Geofiz. Zh. **37** (4), 145–150 (2015).
19. V. V. Gordienko, I. V. Gordienko, O. V. Zavgorodnyaya, and O. V. Usenko, *Thermal Field of the Territory of Ukraine* (Znanie Ukrainy, Kiev, 2002) [in Russian].
20. O. I. Gushchenko, "Reconstruction of the field of megaregional stresses in seismoactive zones of Eurasia," in *Stress Fields and Deformations in the Lithosphere* (Nauka, Moscow, 1979), pp. 26–51.
21. M. M. Dovbnich and S. N. Demyanets, "Fields of tectonosphere stresses, caused by geoisostasy disturbances and geodynamics of the Azov-Black Sea region territory," Geofiz. Zh. **31** (2), 107–116 (2009).
22. V. A. Entin, O. B. Gintov, and S. I. Guskov, "Once more on the nature of the Crimean gravitational anomaly," Geofiz. Zh. **32** (6), 119–134 (2010).
23. Yu. V. Kazantsev, *Tectonics of Crimea* (Nauka, Moscow, 1982) [in Russian].
24. V. G. Kaz'min, L. I. Lobkovskii, and B. G. Pustovitenko, "Present-day microplate kinematics in the Black Sea–South Caspian Region," Oceanology **44**, 564–573 (2004).
25. R. I. Kutas, V. P. Kobolev, V. A. Tsvyashchenko, M. I. Bevzyuk, and O. R. Kravchuk, "Geothermal model of the Black Sea Basin," Geofiz. Zh. **19** (6), 70–83 (1997).
26. M. V. Muratov, *A Brief Overview of Geologic Structure of the Crimean Peninsula* (Gosnauchizdat, Moscow, 1960) [in Russian].
27. A. V. Murovskaya, Candidate's Dissertation in Geology and Mineralogy (Inst. Geofiz. im. Subbotina Nats. Akad. Nauk Ukr., Kiev, 2012).
28. A. Murovskaya, J.-C. Hippolite, E. Sheremet, T. Egorova, Yu. Volfman, and E. Kolesnikova, "Deformation structures and stress field of the south-western Crimea in the context of the evolution of western Black Sea Basin," Geodinamika, No. **2**, 53–68 (2014).
29. E. I. Patalakha, V. V. Gonchar, I. K. Senchenkov, and O. P. Chervinko, *Indenter Mechanism in Geodynamics of the Crimean–Black Sea Region* (Emko, Kiev, 2003) [in Russian].
30. B. G. Pustovitenko, "Focal mechanisms of tangible earthquakes in the Crimean–Black Sea region of the last 20 years," in *Seismological Bulletin of Ukraine for 2000* (NPTs EKOSI-Gidrofizika, Sevastopol, 2002), pp. 59–64.
31. B. G. Pustovitenko, E. A. Merzhei, A. A. Pustovitenko, and I. V. Kalinyuk, "Source parameters of Crimean earthquakes of 2013," in *Seismological Bulletin of Ukraine for 2013* (NPTs EKOSI-Gidrofizika, Sevastopol, 2014), pp. 12–19.
32. *Seismological Bulletins of the Western Zone of the USSR United Network for Seismological Observations (Criema–Carpathians) of 1970–1990* (Naukova dumka, Kiev, 1980–1994) [in Russian].
33. *Seismological Bulletin of Ukraine for 1991–2013* (NPTs EKOSI-Gidrofizika, Sevastopol, 1995–2014) [in Russian].
34. V. B. Sologub and N. V. Sologub, "Structure of the Earth's crust beneath the Crimean Peninsula," Sov. Geol., No. 3, 85–93 (1977).
35. D. A. Tugolesov, A. S. Gorshkov, L. B. Meisner, V. V. Solov'ev, and V. I. Khakhalev, *Tectonics of the Mesozoic–Cenozoic Deposits in the Black Sea Basin* (Nedra, Moscow, 1985) [in Russian].
36. V. E. Khain, *Regional Geotectonics. Alpine–Mediterranean Belt* (Nedra, Moscow, 1984) [in Russian].
37. A. V. Chekunov, Structure of the Earth's Crust and Tectonics of the Southern European Part of USSR (Naukova dumka, Kiev, 1972) [in Russian].
38. A. V. Chekunov, B. G. Pustovitenko, and V. E. Kul'chitskii, "Distribution of earthquake sources and energies on depth and seismicity of the Black Sea region," in *Geophysical Parameters of the Lithosphere in the Southern Sector of the Alpine Orogen*, Ed. by B. S. Vol'vovskii and V. I. Starostenko (Naukova dumka, Kiev, 1996), pp. 101–106.
39. V. V. Yudin, *Geological Map and Sections of the Gorny and Predgorny Crimea. Scale 1 : 200 000* (Soyuzkarta, Simferopol, 2009).
40. V. V. Yudin, *Geodynamics of Crimea* (Diaipi, Simferopol, 2011) [in Russian].
41. T. B. Yanovskaya, V. S. Gobarenko, and T. P. Yegorova, "Subcrustal structure of the Black Sea Basin from seismological data," Izv., Phys. Solid Earth **52**, 15–30 (2016).
42. D. Devlaux and B. Sperner, "New aspects of tectonic stress inversion with reference to the TENSOR program," in *New Insights into Structural Interpretation and Modeling*, Vol. 212 of *Geol. Soc. London., Spec. Publ.*, Ed. by D. A. Nieuwland (Geological Society Publishing House, London, 2003), pp. 75–100.
43. I. Finetti, G. Bricchi, A. Del Ben, M. Pipan, and Z. Xuan, "Geophysical study of the Black Sea," Boll. Geofis. Teor. Appl. **30** (117–118), 197–324 (1988).
44. V. Gobarenko, T. Yegorova, and R. Stephenson, "Local tomography model of the northeastern Black Sea: Intra-plate crustal underthrusting," in *Tectonic Evolution of the Eastern Black Sea and Caucasus*, Vol. 428 of *Geol. Soc. London, Spec. Publ.*, Ed. by M. Sosson, R. A. Stephenson, and S. A. Adamia (Geological Society Publishing House, London, 2015). doi 10.1144/SP428.210.1144/SP428.2
45. N. Görür and O. Tüysüz, "Petroleum geology of the southern continental margin of the Black Sea," in *Regional and Petroleum Geology of the Black Sea and Surrounding Region*, Vol. 68 of *AAPG Mem.*, Ed. by A. G. Robinson (AAPG, 1997), pp. 241–254.
46. J.-C. Hippolite, "Geodynamics of Dobrogea (Romania): New constraints on the evolution of the Tornquist-Teisseyre Line, the Black Sea and the Carpathians," Tectonophysics **357**, 33–53 (2002).
47. O. Khriachtchevskaia, S. Stovba, and R. Stephenson, "Cretaceous–Neogene tectonic evolution of the northern margin of the Black Sea from seismic reflection data and tectonic subsidence analysis," in *Sedimentary Basin Tectonics from the Black Sea and Caucasus to the Arabian Platform*, Vol. 340 of *Geol. Soc. London, Spec. Publ.*, Ed. by M. Sosson, N. Kaymakci, R. A. Stephenson, F. Bergerat, and V. Starostenko (Geological Society Publishing House, London, 2010), pp. 137–157.
48. E. Kissling, S. M. Schmid, R. Lippitsch, J. Ansorge, and B. Fügenschuh, "Lithosphere structure and tectonic evolution of the Alpine arc: New evidence from high-resolution teleseismic tomography," *European Lithosphere Dynamics*, Vol. 32 of *Geol. Soc. Mem.*, Ed. by D. G. Gee and R. A. Stephenson (Geological Society Publishing House, London, 2006), pp. 129–145.

49. Y. P. Neprochnov, I. P. Kosminskaya, and Ya. P. Malovitsky, “Structure of the crust and upper mantle of the Black and Caspian seas,” Tectonophysics **10**, 517–538 (1970).
50. A. M. Nikishin, P. A. Ziegler, D. I. Panov, B. P. Nazarevich, M.-F. Brunet, R. A. Stephenson, S. N. Bolotov, M. V. Korotaev, and P. L. Tikhomirov, “Mesozoic and Ceinozoic evolution of the Scythian Platform—Black Sea—Caucasus domain,” in *Peri-Tethys Memoir 6: Peri-Tethyan Rift/Wrench Basins and Passive Margins*, Ed. by P. A. Ziegler, W. Cavazza, A. H. F. Robertson, S. Crasquin-Soleau (Museum National d’Histoire Naturelle, Paris, 2001), pp. 295–346.
51. A. M. Nikishin, A. I. Okay, O. Tüysüz, A. Demirer, N. Amelin, and E. Petrov, “The Black Sea basins structure and history: New model based on new deep penetration regional seismic data. Part 1: Basins structure and fill,” Mar. Pet. Geol. **59**, 638–655 (2015).
52. A. M. Nikishin, M. Wannier, A. S. Alekseev, O. A. Almendinger, P. A. Fokin, R. R. Gandullin, A. K. Khudoley, L. F. Kopaevich, A. V. Mityukov, E. I. Petrov, and E. V. Rubtsova, “Mesozoic to recent geological history of southern Crimea and the Eastern Black Sea region,” in *Tectonic Evolution of the Eastern Black Sea and Caucasus*, Vol. 428 of *Geol. Soc. London, Spec. Publ.*, Ed. by M. Sosson, R. A. Stephenson, and S. A. Adamia (Geological Society Publishing House, London, 2015). doi 10.1144/SP428.110.1144/SP428.1
53. A. I. Okay and O. Tüysüz, “Tethyan sutures of northern Turkey,” in *The Mediterranean Basins: Tertiary Extension within the Alpine Orogen*, Vol. 156 of *Geol. Soc. London, Spec. Publ.*, Ed. by B. Durand, L. Jolivet, F. Horváth, M. Séranne (Geological Society Publishing House, London, 1999), pp. 475–515.
54. A. I. Okay, A. M. C. Şengör, and N. Görür, “Kinematic history of the opening of the Black Sea and its effect on the surrounding regions,” Geology **22**, 267–270 (1994).
55. A. Paul, M. Cattaneo, F. Thouvenot, D. Spallarossa, N. Béthoux, and J. Fréchet, “A three-dimensional crustal velocity model of the southwestern Alps from local earthquake tomography,” J. Geophys. Res. **106**, 19367–19387 (2001).
56. N. I. Pavlenkova, “Crust and upper mantle structure in Northern Eurasia from seismic data,” Adv. Geophys. **37**, 3–133 (1996).
57. N. K. Pavlis, S. A. Holmes, S. C. Kenyon, and J. F. Factor, “The development and evaluation of the Earth Gravitational Model 2008 (EGM2008),” J. Geophys. Res.: Solid Earth **117**, B04406 (2012). doi 10.1029/2011JB008916
58. I. V. Popadyuk, O. Khriachtchevskaia, and S. Stovba, “Geology of the Crimean Mountains in the context of petroleum exploration in the Black Sea,” in *AAPG European Region Conference and Exhibition 2010, Kyiv, Ukraine. Guidebook to Field Trip No. 1* (2010).
59. I. V. Popadyuk, S. M. Stovba, and O. I. Khriachtchevskaia, “The new geological map of the Crimea Mountains by SPK-Geoservice as a new approach to understanding the Black Sea Region,” in *DARIUS Programme, Eastern Black Sea—Caucasus Workshop, Tbilisi, Georgia, 2013* (2013), pp. 48–50.
60. A. G. Robinson, J. H. Rudat, C. J. Banks, and R. L. F. Wiles, “Petroleum geology of the Black Sea,” Mar. Pet. Geol. **12**, 821–835 (1995).
61. A. Saintot, J. Angelier, and J. Chorowicz, “Mechanical significance of structural patterns identified by remote sensing studies: A multiscale analysis of tectonic structures in Crimea,” Tectonophysics **313**, 187–218 (1999).
62. D. Scafidi, S. Solarino, and C. Eva, “Structure and properties of the Ivrea body and of the Alps-Apennines system as revealed by local earthquake tomography,” Boll. Geofis. Teor. Appl. **47**, 497–514 (2006).
63. D. Schreiber, J.-M. Lardeaux, G. Martelet, G. Courrioux, and A. Guillen, “3-D modelling of the Alpine Mohos in Southwestern Alps,” Geophys. J. Int. **180**, 961–975 (2010).
64. Y. Sheremet (Korniyenko), M. Sosson, C. Muller, O. Gintov, A. Murovskaya, and T. Yegorova, “Key problems of stratigraphy in the Crimea Peninsula, some insights from new dating and structural data,” in *Tectonic Evolution of the Eastern Black Sea and Caucasus*, Vol. 428 of *Geol. Soc. London, Spec. Publ.*, Ed. by M. Sosson, R. A. Stephenson, and S. A. Adamia (Geological Society Publishing House, London, 2015). doi 10.1144/SP428.1410.1144/SP428.14
65. V. Starostenko, V. Buryanov, I. Makarenko, O. Rusakov, R. Stephenson, A. Nikishin, G. Georgiev, M. Gerasimov, R. Dimitriu, O. Legostaeva, V. Pchelarov, and C. Sava, “Topography of the crust—mantle boundary beneath the Black Sea, ” Tectonophysics **381**, 211–233 (2004).
66. V. Starostenko, T. Janik, T. Yegorova, L. Farfuliak, W. Czuba, P. Środa, H. Thybo, I. Artemieva, M. Sosson, Y. Volfman, K. Kolomiyets, D. Lysynchuk, V. Omelchenko, D. Gryn, A. Guterch, et al., “Seismic model of the crust and upper mantle in the Scythian Platform: The DOBRE-5 profile across the north western Black Sea and the Crimean Peninsula,” Geophys. J. Int. **201**, 406–428 (2015).
67. S. M. Stovba, O. I. Khriachtchevskia, and I. V. Popadyuk, “Crimea and Ukrainian Eastern Black Sea as an inverted Early Cretaceous rift system,” in *Geoservice as a New Approach to Understanding the Black Sea Region. Abstracts of DARIUS Programme, Eastern Black Sea—Caucasus Workshop, Tbilisi, Georgia, 2013* (2013), pp. 65–67.
68. T. Yegorova and V. Gobarenko, “Structure of the Earth’s crust and upper mantle of West- and East Black Sea Basins revealed from geophysical data and their tectonic implications,” in *Sedimentary Basin Tectonics from the Black Sea and Caucasus to the Arabian Platform*, Vol. 340 of *Geol. Soc. London, Spec. Publ.*, Ed. by M. Sosson, N. Kaymakci, R. A. Stephenson, F. Bergerat, and V. Starostenko (Geological Society Publishing House, London, 2010), pp. 23–42.
69. T. Yegorova, V. Gobarenko, and T. Yanovskaya, “Lithosphere structure of the Black Sea from 3-D gravity analysis and seismic tomography,” Geophys. J. Int. **193**, 287–303 (2013).
70. T. P. Yegorova, E. P. Baranova, and V. D. Omelchenko, “The crustal structure of the Black Sea from reinterpretation of Deep Seismic Sounding data acquired in the 1960s,” in *Sedimentary Basin Tectonics from the Black Sea and Caucasus to the Arabian Platform*, Vol. 340 of *Geol. Soc. London, Spec. Publ.*, Ed. by M. Sosson, N. Kaymakci, R. A. Stephenson, F. Bergerat, and V. Starostenko (Geological Society Publishing House, London, 2010), pp. 43–56.

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