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Cretaceous Volcanic Belts and the Evolution of the Black Sea Basin

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Abstract—Deposits in southwestern Crimea that contain Late Albian, Middle Senomanian, and Middle Campanian volcanic material are described and dated. Supposedly volcanic edifices are identified in the Black Sea (the Shatsky Swell) based on seismic data. The Albian, Senomanian, and Campanian volcanic belts are reconstructed for the entire Black Sea Region. The suggestion is made that the Black Sea Basin formed as a back-arc basin that started from rifting in the Albian and finished with spreading of the oceanic crust in the Senomanian–Early Santonian.

Keywords: Black Sea, volcanism, geological history, Crimea

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INTRODUCTION

Most works that deal with the origin of the Black Sea deep basin state that this structure formed as a back-arc basin of the Cretaceous Pontides volcanic arc in modern north Turkey (Zonenshain and Le Pichon, 1986; Finetti et al., 1988; Okay, Şengor, and Gorur, 1994; Robinson, Fudat, and Wiles, 1996; Nikishin et al., 2001, 2003, 2011; Afansenkov, Nikishin, and Obukhov, 2007). However, the main stages of the evolution of the Black Sea basin are unclear. One of the main methods for solving this problem is to study the history of volcanism in the framing of the Black Sea within the basin proper (Fig. 1).

In order to investigate the evolution of the Black Sea basin, we studied the Cretaceous sections of Mountainous Crimea to establish the precise datings of the stratigraphic levels that contain volcanic material. We analyzed the regional seismic profiles that cross the Black Sea basin in order to find probable Cretaceous volcanic edifices in the sedimentary stratum. On this basis, a synthesis of all of the available data was made in order to reconstruct the evolution of the Black Sea basin and the associated volcanic belts.

VOLCANIC MATERIAL IN THE CRETACEOUS SECTIONS OF THE SOUTHWESTERN CRIMEA

These sections are relatively well studied and the levels that contain volcanic material are known (*Geologicheskoe*..., 1989; Nikishin et al., 2006). We studied two sections of the Albian deposits in the area of Balaklava, the Upper Albian section in the area of the Moscow State University training base in the Bakhchysarai district, the Senomanian section on the southern slope of Sel'bukhra Mount, and the Campanian section in the area of Kudrino village, Bakhchysarai district (Fig. 2).

Characteristics of the Upper Albian Section on the Northeastern Side of the Kadykovsky Open Pit (Section 1)

The section is located 2.7 km NW of center of the town of Balaklava at 44°31′05.05″ N, 33°34′34.82″ E. The Albian stratum occurs upon Tithonian (Upper Jurassic) limestones with erosional boundaries and angular unconformities of up to 10^{-15}. The first 2–3 m are two–three detrital flows with argillaceous and sandy matrix and the fragments of Upper Jurassic limestones with different degrees of rounding that are 0.5–50 cm in size, as well as with the fragments of siltstone and sritstone lenses with pebbles of different types (mostly quartz). Above, a layered section of volcanoclastic poorly sorted rocks occurs; its visible thickness is more than 15 m. The layers are represented by alternation of different volcanoclastic sandstones and silty clays. Volcanoclastic sandstones comprise 75–89% of the mid- to coarse-grained sandy fragments and 20–25% of the carbonate-clayey mass.

The detrital part consists of plagioclase (90–65%) and hornfels (5–7%) grains, and fragments of effusive rocks (25–27%) (Fig. 3). The fragments of effusive rocks are represented by porphyry andesites and vitric tuffs of the same composition (the fragments are 0.7–0.8 mm in size). The shapes of fragments are rounded, oval, with no acute corners; the rounding is good. Glass is completely transformed into chlorite-argillaceous aggregate. Plagioclase grains are oval elongate in

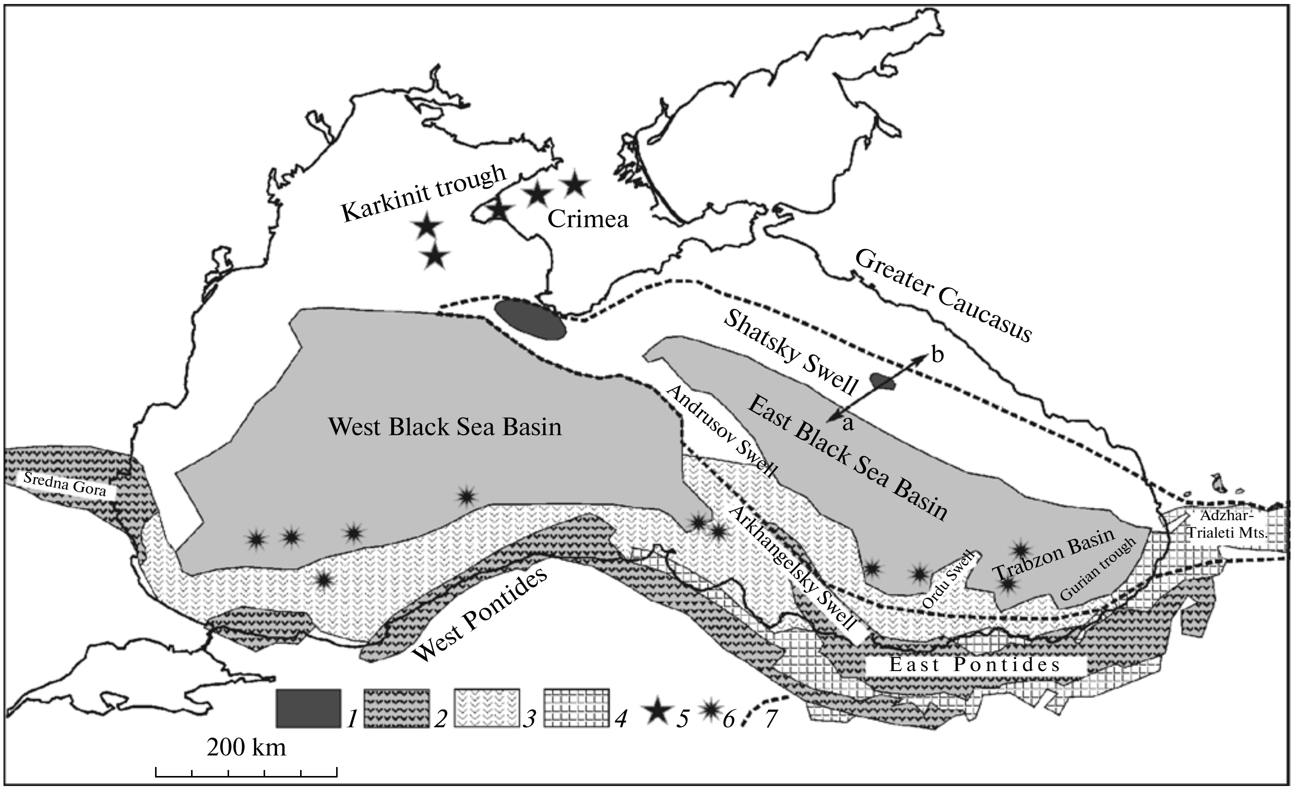

Fig. 1. A scheme that shows the structure of the Black Sea region. The Black Sea basins with oceanic crust and continental crust that are thinned by rifting are indicated in gray, after the Geology without Limits project and (Finetti et al., 1988; Starostenko et al., 2004). The areas of volcanism manifestation are shown in accord with (*Atlas*..., 1961; Okay and Sahìnturk, 1997; Tüysüz et al., 2012; Georgiev et al., 2012; Nikishin et al., 2011) and our data. (*1*) zones of Albian and Aptian–Albian volcanism; (*2*) zones of Late Cretaceous volcanism; (*3*) zones of Late Cretaceous (mainly supposed) volcanism on the continental slope and deeply sunken blocks; (*4*) zones of Middle Eocene volcanism (Late Cretaceous zones of volcanism are usually supposed beneath); (*5*) Albian volcanoes in the zone of Karkinit graben; (*6*) supposed Late Cretaceous volcanoes, detected based on seismic profiling (Geology without Limits project results, interpretation by A.M. Nikishin et al.); (*7*) contours of the zone of hypothetically Albian volcanism.

shape (rarely hexagonal), semi-rounded, up to 0.6 mm in size; rectangular cuts with no rounding can also be found. The crystals have clear zonality and drop-like melt inclusions of 0.01 mm in size. Plagioclase corresponds to labradorite in terms of composition. Hornfels grains are rectangular in shape, no more than 0.3 mm in size and with clear cleavage. Crystals are almost completely replaced by chlorite (or, to a lesser degree, carbonates). There are probably pyroxene grains (2%), which are pleochroic in greenish gray tones, but they are also almost completely replaced by chlorite.

For the section of the considered stratum, small-amplitude con-sedimentation hade-faults of up to 5–15 cm long are typical. These hade-faults are likely of a gravity origin. The layers are often wedged in their strike.

The age of the considered stratum is not dated precisely. Based on the information from the geologists from the Balaklava Mine Group (V.A. Kovalev, S.N. Boldyrev et al.), it is believed to be Late Albian. This corresponds to the data of V.I. Lysenko (2003) based on the faunal remains with no accurate referencing.

The entire Upper Albian stratum was definitely formed on the slope under a marine environment. This is indicated by the presence of detrital flows with blocks of different degrees of rounding. Volcanoclastic sandstones were also likely formed by debris flows. The transport of limestone blocks, pebbles of different compositions, and volcanic material was from the land. This land was composed of Upper Jurassic limestones and conglomerates on which the Albian volcano occurred with andesite material. The Upper Jurassic (supposedly Callovian–Oxfordian) conglomerates are commonly known in the area of Balaklava. The land was supposedly located south of the present day section, because there are no remains of the Albian volcano north of the section; this has been verified in other publications (Shnyukov, Shcherbakov, and Shnyukova, 1997; Lysenko, 2003, 2005).

The base of the Upper Albian stratum in the area of the NE part of the open pit is shifted by the fault sys-

Fig. 2. The positions of the studied sections in southwestern Crimea. The digits indicate the numbers of sections.

tem by 30–40 m. These faults were likely hade faults that formed in the Albian, coeval to sedimentation.

Characteristics of the Upper Albian Section Along the Railroad Near the Crossing with the Road to Sevastopol (Section 2)

The section is located 3.9 km NNE of the center of the town of Balaklava at 44°32′00.56″ N, 33°37′00.83″ E. Along the railroad, one can see an exposed Upper Albian volcanoclastic stratum that is more than 5 m thick. The rocks are represented by grayish green volcanoclastic mid- and coarse-grained, coarsely-stratified sandstones. The grains are unequally sorted; there is a large quantity of coarse-grained sand and fine gravel of up to 3 mm in size, as well as rounded lapilli and fragments of effusive rocks of up to 1.5 cm in size. The rock was defined as a crystalline-lithoclastic fine- to mid-fragmented redeposited andesite–dacite tuff (Fig. 3). The fragmented part (70–75%) is represented by fragments of effusive rocks (45%) and those of particular crystals of plagioclase (30%), clinopyroxene (7–10%), amphibole (12%), and magnetite (5%). Fragments of effusive rocks are irregular, elongated (rarely isometric), and angular in shape. Particles are up to 5–7 mm, mostly 0.5–2 mm; represented by porphyry andesites with large plagioclase impregnations (An_{58}) and rare smaller hornfels grains.

Plagioclase crystal sections are regular, rectangular, or rarely hexagonal, with a clear zonality; the cross sizes of the sections are 0.4–0.7 mm. Some plagioclase grains (An_{58-59} in composition) are shattered, but the fragments are situated close to each other. Clinopyroxene crystals are represented by isometric, rarely irregular but rounded grains 0.01–0.3 mm in diameter, with no pleochroism. Amphibole crystals are both isometric angular and rhombic in shape; they can be found as single grains or within effusive rock fragments and are up to 0.1–0.2 mm in size. Amphiboles are distinctly pleochroic in orange–red and brown tones, so they can be referred to kaersutite (basaltic hornfels). Additionally, there are grains (up to 0.7 mm in size) of ore nontransparent mineral (5% of the fragmented part); they are square or hexagonal, rarely rounded in shape; probably, this is magnetite. The main mass likely initially consisted of pyroclastic material; however, at the moment it has been completely replaced by carbonate and argillaceous matter.

This stratum also includes a large number of sedimentary rock fragments, rounded to different degrees.

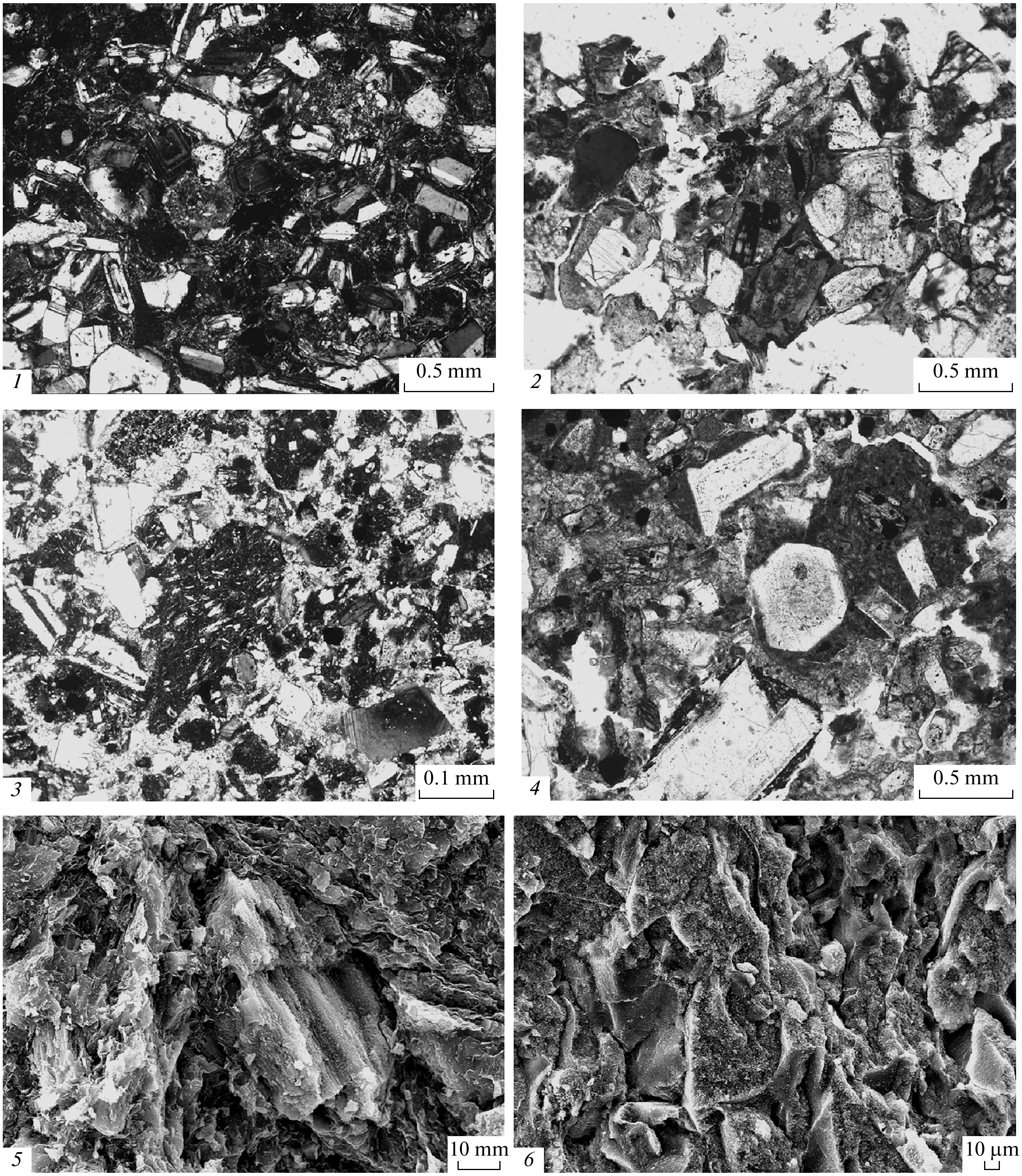

Fig. 3. Images of thin sections. (*1*), (*2*) tufogenic sandstone (Section 1), crossed nicols; (*3*) crystal-lithoclastic andesite-dacite tuff (Section 2), the fragment of porphyry andesite is marked, parallel nicols; (*4*) tufogenic sandstone (Section 3), parallel nicols; (*5*) plagioclase crystal completely replaced by montmorillonite (Section 4), LEO-450 electron microprobe; (*6*) sharply angular particles of volcanic glass, completely replaced by montmorillonite (Section 5), LEO-450 electron microprobe.

The fragments were examined in thin sections; they are represented by clays, siltstones, sandstones, limestones, and sandstones with andesite clasts. The stratum could form as a submarine debris flow (debrite) that started on land at the andesite volcanic edifice. When moving down the slope, this flow involved various fragments of rocks, on which the volcano was based.

A. M. Nikishin, A. K. Khudoley, E. V. Rubtsova, and other researchers studied detrital zircons from these deposits (personal communication). The age of the zircons was estimated at 103 ± 1 Ma, but there were peaks at 175 ± 4, 300–3015, and 570–646 Ma. These data indicate the Late Albian age of the volcanic material and that the Late Albian volcano was not the only source of sedimentary rocks in this section.

The stratum of Senomanian marls overlies the Upper Albian volcanoclastic stratum with an erosional boundary (the boundary is found in test pits). This stratum contains a rich complex of planktonic foraminifera, which clearly dominate benthic ones. The notable species are *Thalmanninella globotruncanoides* (Sigal), *T. appenninica* (Renz), *T. gandolfi* (Sigal), *T. deeckei* (Franke), and *Hedbergella simplicissima* (Magne et Sigal) (Fig. 4). This complex indicates the Early Senomanian age of the host rocks, e.g., *Thalmanninella globotruncanoides* is the index species for the lower zone of Lower Senomanian in the standard zonal stratigraphic scale and in the sections of southwestern Crimea (Gorbachik, Kopaevich, and Naidin, 2000). *T. deeckei* appears in the upperlying horizons of Lower Senomanian (Kopaevich, 2010). Coupled appearance of *Thalmanninella globotruncanoides* and *T. deeckei* suggests there are deposits of the upper part of Lower Senomanian in the section. Thus, the size of hiatus in the base of Senomanian corresponds to the deposits of the same *Thalmanninella globotruncanoides* foraminifera zone.

The Characteristics of the Upper Albian Section Along the Road from Moscow State University Training Base to Nauchnyi Settlement in the Bakhchysarai District (Section 3)

The section coordinates are 44°44′31.69″ N, 33°59′48.62″ E. It is seen as a member of sandstones with inclusions of the Upper Albian volcanic material exposed along the road. Brownish-green, quartz-glauconite sandstone with abundant inclusions of fine-gravel quartz occurs. The thickness of the member is no more than 0.5 m.

The roof of the member is the "solid bottom" surface, which is orange–brown in color. The overlying rocks start with the basal horizon of detrital material (1–10 cm) and continue with Senomanian belemnite-containing marls. In the sandstones that contain volcanic material, ammonites have been found (poor integrity cores): *Stoliczkaia notha* (Seeley), *Mariella* cf. *lewesiensis* (Spath), and *Lechites* cf. *gaudini* (Pictet et Campiche). The remains of *Inoceramus anglicus* Woods are rare. More often cores and valves of *Aucellina gryphaeoides* (Sowerby), *Gryphaeostrea canaliculata* (Sowerby) and other pelecypoda are found. As well, brachiopods and serpulidae can be found, viz., *Glomerula gordialis* (Schlotheim). The upperlying marls contain very rare cores and footprints of *Puzosia planulata* (Sowerby) and *Mantelliceras* sp. ind., which appear as early as the base of the member. The characteristic feature is presence *Neohibolites menjailenkoi* Gustomesov rostra (the first belemnite level) that form massive clusters in some places. Remains of *Inoceramus crippsi crippsi* Mantell are observed starting from the base of marl member and this is Lower Senomanian macrofossil complex (*Geologicheskoe*..., 1989). In the base of the marls, a planktonic foraminifera complex occurs as well (Gorbachik, Kopaevich, and Naidin, 2000).

Sandstone with volcanic material consists of a fragmented part (70–75% of the rock volume) and a carbonate-argillaceous cement (30–35%) (Fig. 3). The fragmented part is represented by tuffs and porphyries (20%), grains of plagioclase (40–45%), hornfels (7–10%), magnetite (5–7%), chlorite (5–7%), and quartz (15–20%). Fragments of effusive rocks are irregular, angular, isometric in shape and up to 0.7–0.9 mm in size; they are represented by fragments of porphyry andesites with completely devitrified glass and fragments of ash tuffs of the same composition, which are almost completely altered to chlorite-sericite aggregate. Plagioclase crystals are regular rectangular, hexagonal, rarely irregular angular and up to 0.8 mm in size. Many (20–25%) crystals contain melt inclusions in the form of fine drops (0.01–0.03 mm in diameter), usually with distinct zonality (60%). In terms of composition, plagioclase corresponds to labradorite (An_{54-55}). Hornfels grains are rhomboid, rarely rectangular in shape, and 0.3–0.4 mm in diameter; they also possess clear pleochroism from light to dark brown. Magnetite is represented by nontransparent grains of irregular rounded, square, or hexagonal shape and up to 0.3 mm in size. There are rounded and oval chlorite grains of up to 0.3 mm in size and with a characteristic scaly texture; their share is no more than 5–7% of the fragmented component. Large rounded quartz fragments, oval in shape and 3–5 mm in size, can also be found (about 20% of the fragmented part of rock). In cement, singular foraminifera shell fragments of up to 0.2 mm in size can be found.

Both the angular and regular shapes of fragments and strong alteration of hornfels to calcite indicate the deposition of volcanic material under marine conditions with a relatively smooth hydrodynamical regime; sediments were not redeposited. Tuff material was likely transported by air and deposited on the shallow sea bottom.

Characteristics of the Middle Senomanian Section on the Southeastern Slope of Selbukhra Mount, in the Bakhchysarai District (section 4)

The section is located at 44°44′09.59″ N, 22°59′33.97″ E. On the mount slope, the Senomanian and Turonian section is exposed. At 40 m above the base of the Senomanian, on a member with rhythmi-

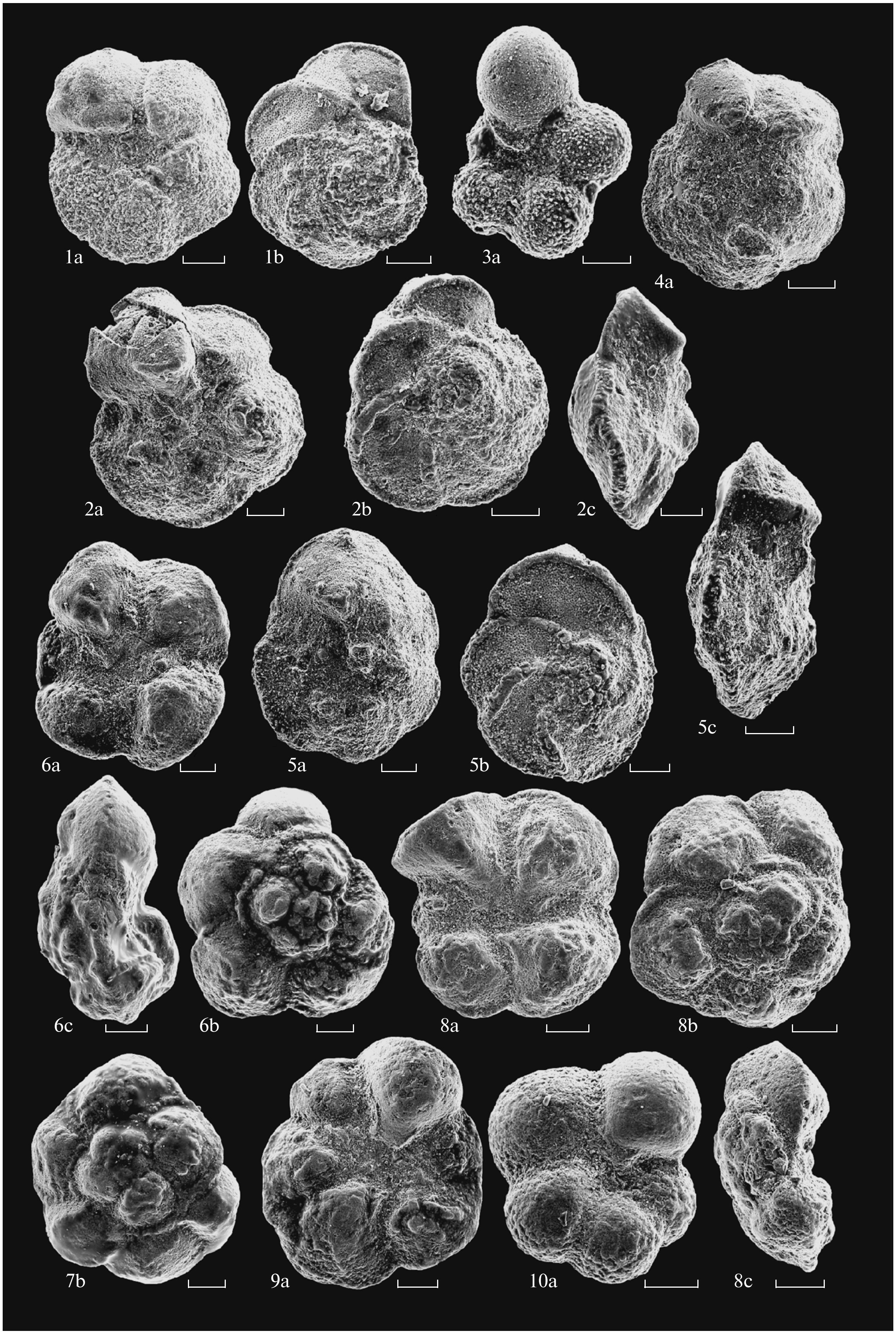
1a
1b
3a
4a
2a
2b
2c
6a
5a
5b
5c
6c
6b
8a
8b
7b
9a
10a
8c

Fig. 4. Planktonic foraminifera shells from the Lower Senomanian deposits of Balaklava section (Section 2; *1–5*) and the Middle Senomanian deposits on the southern slope of the Sel'bukhra Mount (Section 4; *6–10*). Indexes a and b mean ventricular and dorsal sides, respectively; c, peripheral rim. (1a), (1b) *Thalmanninella gandolfi* (Sigal); (2a), (2b), (2c) *Thalmanninella globotruncanoides* (Sigal); (3a) *Hedbergella simplicissima* (Magne et Sigal); (4a) *Thalmanninella deeckei* (Franke); (5a), (5b), (5c) *Thalmanninella appenninica* (Renz); (6a), (6b), (6c), (7b), (8a), (8b), (8c) *Rotalipora cushmani* (Morrow); (9a) *Thalmanninella montsalvensis* (Mornod); (10a) sinistral shell of *Praeglobotruncana stephani* (Gandolfi). Scale line indicates 100 μm.

cal interbedding of light and darker marls, an argillaceous layer of 2–3 cm occurs: bentonite, grayish brown, reddish, with an admixture of carbonate matter. The interbed is superimposed by a member of grayish and white interbedding Senomanian thin-bedded and massive marls.

The clay layer is almost monomineral in composition: 97–98% of rock consists of fine flakes of montmorillonite, which are clearly discernible in scanning electron microprobe images. X-ray phase analysis allowed us to determine the mineral composition: argillaceous mineral is represented by beidellite (a variety of montmorillonite). The presence of grains with geometrically regular shapes, of up to 0.1 mm in size, which are distinct in color and possess a scaly structure suggest that montmorillonite developed on plagioclase or amphibole crystals. A small number (2–3%) of plagioclase grain relics of 0.01–0.02 mm in size occur, which are determined by the characteristic low gray interference color. Singular bright grains can be represented by relics of amphibole or pyroxene crystals.

The presence of amphibole and plagioclase pseudomorphoses was also verified by electron microprobe images: here one can clearly see a large number of grains of elongated and isometric shapes (Fig. 3). The chemical composition that was determined using the microprobe analysis indicates that the crystals are highly altered and almost Na-exhausted hornfels. The presence of relics and replaced plagioclase crystals suggests that these clays formed due to submarine erosion of tufogenic material of mafic or basic composition. This was also verified by the absence of quartz grains in the rock. Thus, the layer of benthic clays during its formation was a layer of volcanic ash that was deposited on the sea bottom.

The foraminifera that are contained in the clays of the bentonite layer, as well as in the upper lying and lower lying rocks, were studied (Fig. 4). The planktonic taxa dominate in the complex; the remarkable is *Rotalipora cushmani* (Morrow), an index species of the Middle–Upper Senomanian (excluding its terminal part). However, the coupled presence of *Rotalipora cushmani*, *Thalmanninella montsalvensis* (Mornod), and *Praeglobotruncana stephani* (Gandolfi) is typical mainly of the Middle Senomanian interval.

Characteristics of the Middle Campanian Section in an Abandoned Open Pit in the Western Margin of Kudrino Village (Section 5)

The section is located in the Bakhchysarai district (44°42′15.76″ N, 33°56′27.30″ E). In an abandoned open pit, a Campanian marl stratum is exposed. There are interbeds of grayish-green, rarely light-green clays in the stratum; clays are pure, subcalcareous, nonstratified, soapy to touch (the local name is kilovye gliny). The thickness of the interbeds in the lower part of the section is 0.2–0.4 m. Up the section, calcareousness increases, the color changes to a beige white, detrital material of the silt fraction appears, and the thickness of interbeds is reduced to 2–4 cm.

The X-ray phase analysis showed that the clay mineral is 100% montmorillonite. Examination using an electron microprobe showed that the clay contains formerly acute-angled particles of volcanic glass, which are completely replaced by montmorillonite (Fig. 3). The previous studies (Lebedinskii, Kirichenko, and Ladan, 1974) revealed the relics of volcanic glass, biotite, and sanidine, which indicated the origin of these clays from volcanic ash.

The foraminifera associations extracted from marls include benthic and planktonic taxons. Among the benthic foraminifera, the remarkable species are *Gavelinella stelligera* (Marie), *G. clementiana* (d'Orbigny), *Cibicidoides voltzianus* (d'Orbigny). In the planktonic foraminifera complex, *Globotruncana arca* (Cushman), *G. Bulloides* Vogler, *G. mariei* Banner and Blow, *Rugoglobigerina rugosa* (Plummer), *Archaeoglobigerina blowi* Pessagno, *Hedbergella holmdelensis* Olsson, *Globigerinelloides asper* (Ehrenberg), and *G. volutus* White are presented (Fig. 5). Such a foraminifera complex suggests the Middle Campanian age of rocks, based on the levels of *Cibicidoides voltzianus* (benthic foraminifera) and *Rugoglobigerina rugosa* (planktonic foraminifera) zones.

The Geochemical Characteristics of the Volcanic Material in the Cretaceous Deposits

The results of chemical analysis of rare-earth elements (Fig. 6) demonstrate that deposits in all the studied sections formed with the participation of the volcanic component.

To determine the initial composition of tuffs, the obtained values were overlain on the La–Th diagram that is given in Fig. 6. It follows from the diagram that the greatest part of the tuffs are orogenic andesites that correspond to an island arc setting. Thus, the

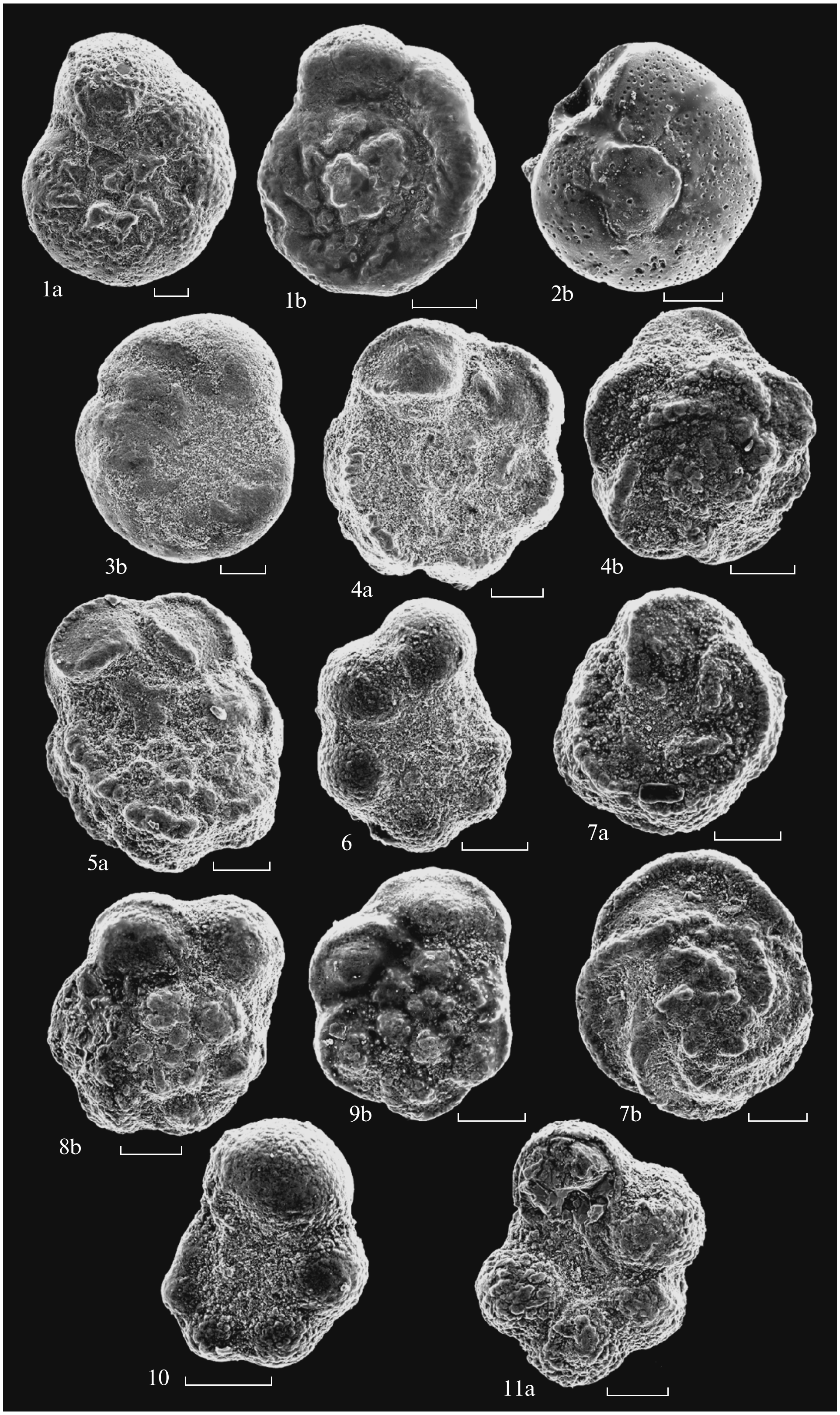

Fig. 5. Planktonic and benthic foraminifera from the Campanian deposits of the section near Kudrino village (Section 5). Indexes a and b mean ventricular and dorsal sides, respectively. (1a), (1b) *Gavelinella clementiana* (d'Orbigny); (2b) *Cibicidoides voltzianus* (d'Orbigny); (3b) *Gavelinella stelligera* (Marie); (4a), (4b), (5a) *Globotruncana arca* (Cushman); (6) *Globigerinelloides asper* (Ehrenberg); (7a), (7b) *Globotruncana mariei* Banner et Blow; (8b), (9b) *Globotruncana bulloides* (Vogler); (10) *Hedbergella holmdelensis* Olsson; (11a) *Archaeoglobigerina blowi* Pessagno. Scale line indicates 100 μm.

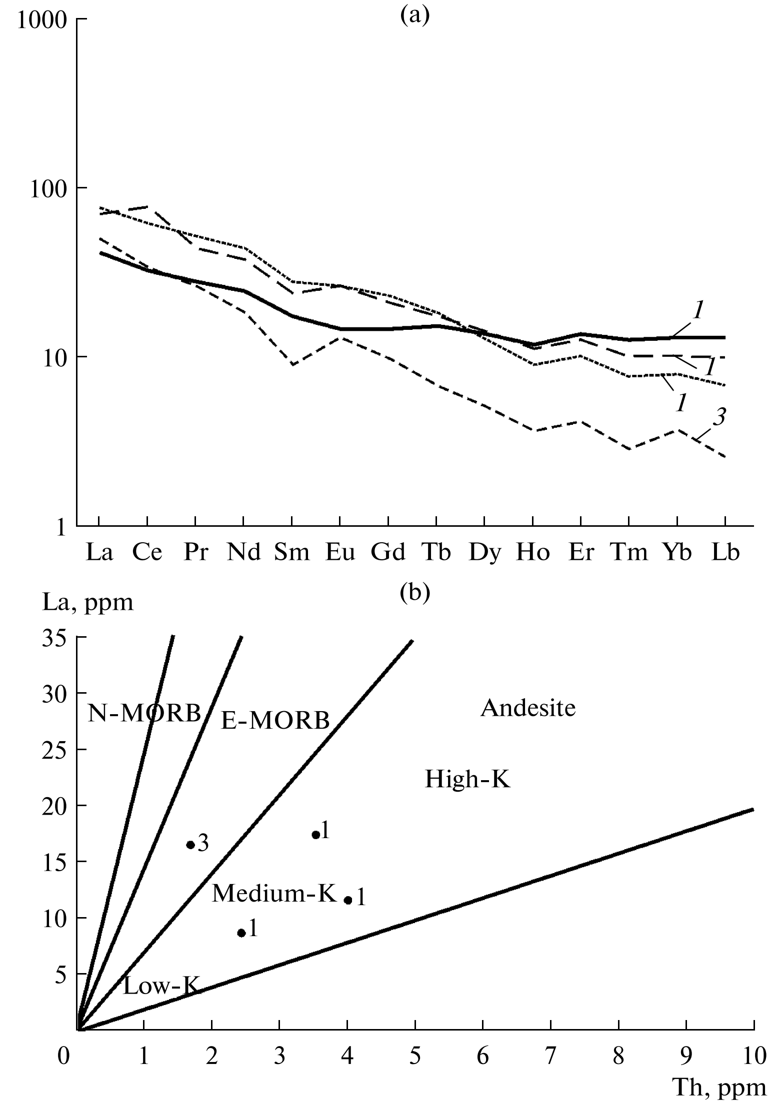

Fig. 6. The trends of rare-earth element contents in the samples from sections 1 and 3 (a). Vertical scale is logarithmic; contents are normalized to chondrite. (b) La and Th contents in the samples from Sections 1 and 3.

geochemical data verify the volcanic origin of the material that collected in the Cretaceous sections. This volcanic material most likely formed as a result of the activity of andesitic volcanoes.

CRETACEOUS VOLCANISM ON LAND IN THE BLACK SEA REGION

The large Cretaceous volcanic belt is located south of the Black Sea and comprises at least three major segments: the East Sredna Gora Zone in Bulgaria; the Pontides (West, Central, and East) in Northern Turkey; and the Transcaucasian volcanic belt in Georgia, Armenia, and Azerbaijan (Adzhar-Trialeti zone, Dziruli massif, Somkheti-Karabakh zone) (Zonenshain and Le Pichon, 1986; Finetti et al., 1988; Okay, Şengor, and Gorur, 1994; Robinson, Fudat, and Wiles, 1996; Nikishin et al., 2003, 2011; Barrier and Vrielynek, 2008; Rolland et al., 2011; Afansenkov, Nikishin, and Obukhov, 2007).

Volcanism was not strictly synchronous in the limits of the entire volcanic belt. In Bulgaria (East Sredna Gora) magmatism started about 92 Ma BP (i.e., Early Turonian). In the Turonian–Santonian, volcanism was weak. Its peak was 78–81 Ma BP (Campanian); volcanic activity then faded out (Georgiev et al., 2012).

Three volcanism epochs are known for the Pontides. Senomanian volcanism is established only for north part of East Pontides (Yilmaz et al., 2010). The Turonian volcanism is not very extensive and known for West Pontides (Tüysüz et al., 2012). The Campanian was remarkable for the extensive volcanism in the

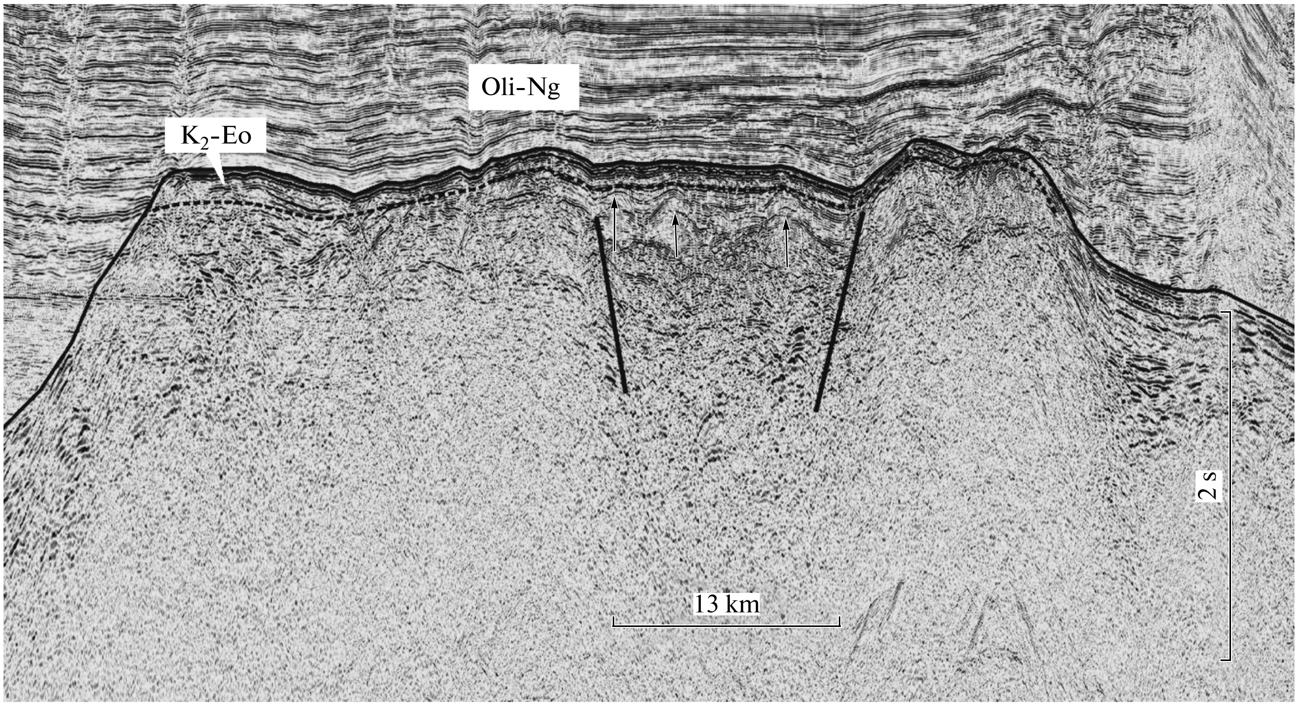

Fig. 7. A fragment of a seismic section across the Shatsky Swell, made in the framework of the Geology without Limits project. The position of the section is shown with the a–b line in Fig. 1; $K_2–E_O$, Upper Cretaceous–Eocene; Oli–Ng, Oligocene–Neogene. Three arrows indicate the positions of probable Albian volcanic edifices. Subvertical black lines denote probable Early Cretaceous hade-faults.

entire Pontides belt (Okay, Şengor, and Gorur, 1994; Okay and Sahinturk, 1997; Tüysüz et al., 2012).

In the Transcaucasian volcanic belt, Cretaceous volcanic activity took place mainly in the Adzhar-Trialeti zone from the Aptian to Turonian (*Atlas*..., 1961; Nikishin et al., 2001). Small and local phases of volcanism were also noted in the Transcaucasian belt during the Coniacian–Campanian (Nikishin et al., 2001).

On the southern slope of the Greater Caucasus, in the Adler-Abkhaz Zone, which is a continuation of the Shatsky Swell in the Black Sea, volcanoclastic sandstones were found in the Senomanian deposits (Lavrishchev et al., 2000; Gabdullin et al., 2012). In the Taman Zone of the Greater Caucasus, drilling revealed Albian and Senomanian volcanoclastic sandstones. In the Fore-Caucasian Region, near Armavir, drilling revealed the basalts and rhyolites of conditionally Aptian age (according to Kavkazgeols'emka, Yessentuki (Lavrishchev et al., 2000)).

CRETACEOUS VOLCANISM ON THE ODESSA SHELF OF THE BLACK SEA AND AT THE SHATSKY SWELL

On the Odessa shelf, the Karkinit graben of Early Cretaceous is known (Gozhik et al., 2006; Afansenkov, Nikishin, and Obukhov, 2007; Khriachtchevskaia, Strobova, and Stephenson, 2010; Gnidets' et al., 2010). It formed in the Late Barremian–Albian, but the main phase of rifting also took place in the Albian; rifting was accompanied by the formation of a large number of volcanoes, mainly in the Late Albian (Gozhik et al., 2006). These volcanoes have been well studied by seismic exploration and drilling works. The zone of rifting and volcanism is traced by drilling in Crimea as well, in the areas of Sivash Bay and the Tarkhan-Kut Peninsula (Gnidets' et al., 2010). The composition of volcanic rocks was reported in (Gnidets' et al., 2010): the boreholes opened the andesitic lavas and tuffs, but the geochemical study data are not given. Therefore, rifting and volcanism occurred at the above-subduction setting.

The Shatsky Swell has been relatively well studied by seismic exploration work. Its detailed description was given in (Afansenkov, Nikishin, and Obukhov, 2007); in particular, on the basis of the analyzed magnetic and gravity anomalies, the presence of Cretaceous (Albian) volcanic rocks was suggested along the southwestern rim of the swell. In 2011, in the framework of the Geology without Limits project, a new network of regional seismic profiles was worked out in the Black Sea and these profiles covered the Shatsky Swell in particular.

Figure 7 shows a fragment of the BS-200 regional seismic profile for the Shatsky Swell. Several cone-shaped structures that are 100–200 m high and 3–5 km width can be clearly identified in the section. We can interpret these seismic facies of conic sections as volcanoes buried beneath the sediments. In accordance with our scheme of the ages of the seismic facies of the Shatsky Swell (Afansenkov, Nikishin, and Obukhov, 2007), these volcanoes are approximately Albian in age. Note that no boreholes have been drilled at the Shatsky Swell; thus, all the datings are given on the basis of regional correlations. We can suggest that the volcanism took place on the Shatsky Swell approximately in the Albian, as we previously believed (Nikishin et al., 2003, 2011).

RECONSTRUCTION OF THE FORMATION HISTORY OF THE BLACK SEA BASIN AND THE CRETACEOUS VOLCANIC BELTS

In the evolution of the Sredna Gora–Pontides–Transcaucasian volcanic belt, we can distinguish several stages, but it should be noted that the ages of volcanic rocks are not clearly founded for all locations as yet. Aptian–Albian volcanism is known in the Transcaucasian belt (mainly in the Adzhar-Trialeti Zone), in the area of Balaklava and Karkinit graben. We believe that volcanism of this age occurred for the area along the Shatsky Swell and probably along the Andrusov Rise (the probable Albian level looks similar in the seismic profiles of these structures. Volcanism of this age is unknown in the Pontides and Sredna Gora. Therefore we believe that the Aptian–Albian (or Albian) volcanic belt ran from the Transcaucasian belt (Adzhar-Trialeti Zone) through the Shatsky and Andrusov swells and reached the area of Balaklava. We suggest calling this volcanic belt Balaklava–Trialeti. In the Senomanian, the reconstruction of this belt occurred and it continued from the Adzhar-Trialeti Zone to the Eastern Pontides. Since the Turonian, volcanic activity has been recorded along the entire Sredna Gora–Pontides–Transcaucasian belt. The most extensive volcanism in this belt was in the Campanian; the volcanic belt then became extinct.

Models of the formation of the Black Sea basins have been suggested by many researchers (Zonenshain and Le Pichon, 1986; Finetti et al., 1988; Okay, Şengor, and Gorur, 1994; Robinson, Fudat, and Wiles, 1996; Nikishin et al., 2003, 2011; Barrier and Vrielynck, 2008; Afansenkov, Nikishin, and Obukhov, 2007). The main problem is related to the time that the basins opened and the question of whether the West and East Black Sea basins opened synchronously or by in turns. Here, we will develop the model of the opening the Black Sea that was suggested by A.M. Nikishin (Nikishin et al., 2003, 2011; Afansenkov, Nikishin, and Obukhov, 2007) but with the modifications on the basis of new data on volcanism.

If the Balaklava–Trialeti volcanic belt truly runs through the Shatsky and Andrusov swells, then the Eastern Black Sea basin appeared during rifting along the Albian volcanic arc. If the Senomanian volcanic belt actually stretched from the Transcaucasian Region to the Eastern Pontides, there was a reconstruction of tectonic regime in the period between the Albian and the Senomanian. Most likely, at least local back-arc spreading of the oceanic crust had started in the Eastern Black Sea basin since the Senomanian. There is an uncertainty in the history of the Senomanian volcanic belt. We cannot exclude the possibility that at least the eastern part of the Western Black Sea basin appeared as a result of rifting along the Senomanian volcanic arc. In the Turonian, the Western and Eastern Black Sea basins obviously were opening and the volcanic belt stretched from Bulgaria to Azerbaijan to the south of them.

The suggested scheme of the development of the volcanic belts allows us to compile new reconstruction of the evolution of the Black Sea in the Cretaceous (Fig. 8). Many problems of the formation of the Black Sea basin were reported in (Nikishin et al., 2003, 2011; Afansenkov, Nikishin, and Obukhov, 2007). We believe that opening of the Black Sea basins had finished in the mid-Santonian. Hence, the Campanian volcanic arc was active after the rifting and spreading of the oceanic crust had finished. Thus, important consequence can be inferred. Back-arc tension and spreading of the oceanic crust were accompanied by relatively non-intensive volcanism in the arc above the subduction zone, but when the back-arc tension ceased, arc volcanism became more intensive.

For the geology of the southwestern Crimea, we can suggest the following origins of the volcanic material: (1) Late Albian volcanic material in the area of Balaklava transported upon the sea bottom directly from the volcanic arc; (2) Late Albian volcanic material in the Bakhchysarai district was transported by air from either the Balaklava volcanic arc or a volcanic region in the Karkinit graben; (3) Senomanian volcanic material was transported by air from the region of the East Pontides–Transcaucasian volcanic arc; (4) Campanian volcanic material was supplied from the region of the Pontides volcanic arc.

CONCLUSIONS

(1) In the Albian, a volcanic arc stretched from the area of Balaklava to the Adzhar-Trialeti Zone and Albian volcanic rocks were deposited on the Shatsky and probably the Andrusov swells.

(2) Since the Senomanian–Turonian, a volcanic arc evolved to the south of the modern Black Sea in the Sredna Gora–Pontides–Transcaucasian zone.

(3) The Campanian is notable for the maximal extent of volcanism, along the entire Sredna Gora–Pontides–Transcaucasian belt, but after the Campanian volcanism stopped.

(4) The Eastern Black Sea basin appeared during rifting in the Senomanian–Early Santonian and spreading along the Albian volcanic arc.

(5) The West Black Sea basin formed during Senomanian–Early Santonian rifting and back-arc

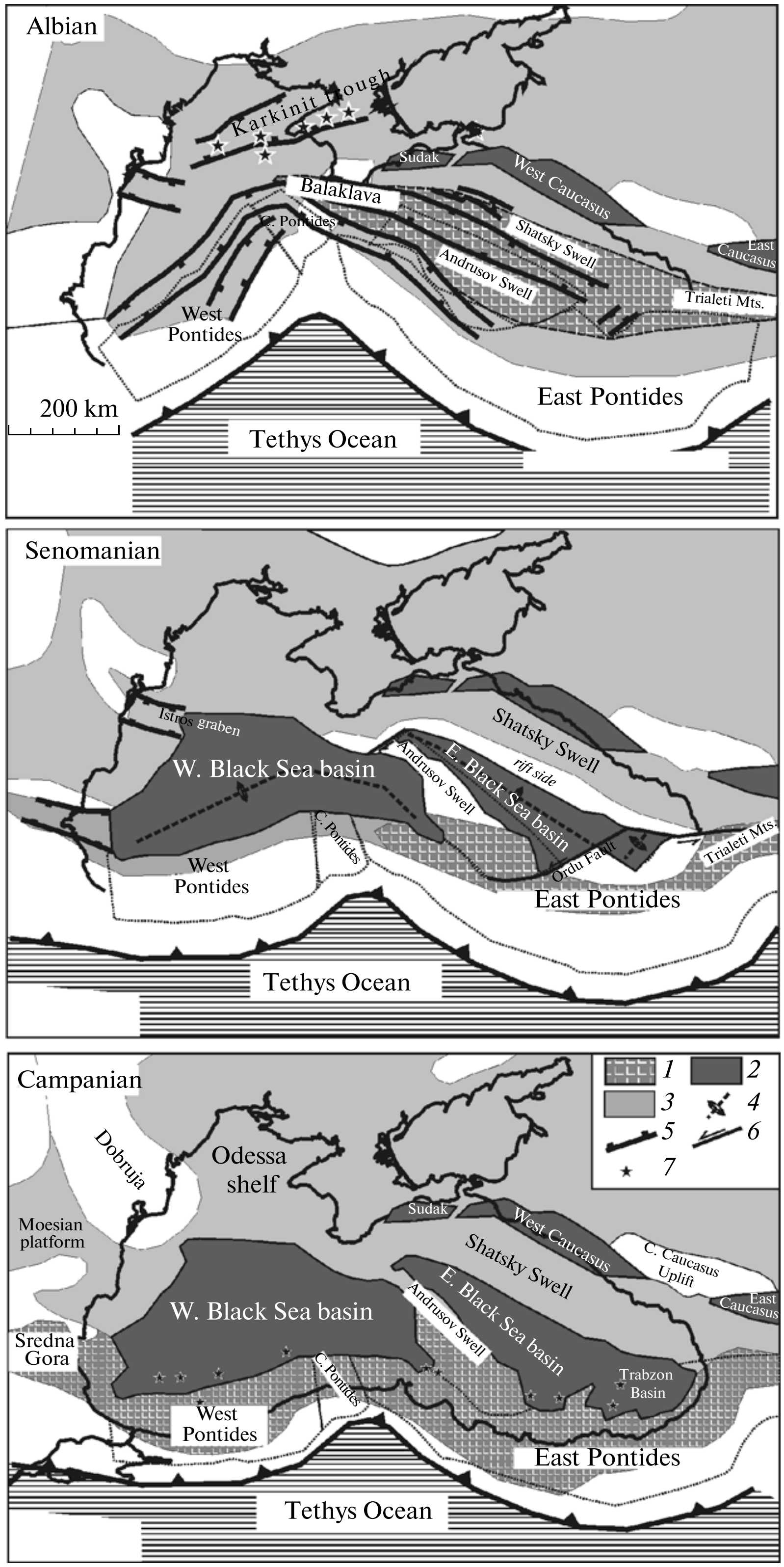

Fig. 8. A cartoon of the formation of the Black Sea basin and the evolution of the Cretaceous volcanic belts. Reconstructions of the Albian, Senomanian, and Campanian are presented. (*1*) volcanic belts; (*2*) deep basins with oceanic or continental (highly thinned by rifting) crust; (*3*) sedimentary basins; (*4*) axes of the oceanic crust's rifting or spreading; (*5*) normal faults; (*6*) strike–slips; (*7*) individual volcanoes. In the map for the Albian, the Sudak, West Caucasian and East Caucasian deep troughs, which formed in the Callovian–Late Jurassic, are shown.

spreading, but probably with rifting along the Albian-Senomanian volcanic arc in its eastern part.

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REFERENCES

Afanasenkov, A.P., Nikishin, A.M., and Obukhov, A.N., *Geologicheskoe stroenie i uglevodorodnyi potentsial Vostochno-Chernomorskogo regiona* (Geological structure and hydrocarbon potential of the Eastern Black Sea Region), Moscow: Nauchnyi mir, 2007.

Atlas litologo-paleogeograficheskikh kart Russkoi platformy i ee geosinklinal'nogo obramleniya. Ch. 2. Mezozoi i kainozoi. Masshtab 1 : 5000000 (Atlas of lithologic-paleogeographic maps of the East European Craton and its geosyncline framing, Pt. 2: Mesozoic and Cenozoic, 1 : 5000000), Vinogradov, A.P., Ed., Moscow: Gos. nauch.-tekh. izd. liter. geol. okhran. nedr, 1961.

Barreir, E. and Vrielynck, B., *Paleotectonic maps of the Middle East: tectono-sedimentary-palinspastic maps from Late Norian to Piacenzian*, Commission for the Geological Map of the World/UNESCO, 2008.

Finetti, I., Bricchi, G., Del Ben, A., Papin, M., and Xuan, Z., Geophysical study of the Black Sea area, *Boll. Geofis. Teor. Appl.*, 1988, vol. 30, nos. 117–118, pp. 197–234.

Gabdullin, R.R., Kopaevich, L.F., Shcherbinina, E.A., Zerkal', O.V., Samarin, E.N., Yakovishina, E.V., Akuba, A.M., Zagrachev, N.T., and Kozlova., G.K., Lithological–Stratigraphic Characteristics of the Aptian–Cenomanian Sediments of the Abkhazian Zone of the Western Caucasus, *Moscow Univ. Geol. Bull.*, 2012, vol. 67, no. 4, pp. 218–232.

Geologicheskoe stroenie Kachinskogo podnyatiya Gornogo Kryma. Stratigrafiya mezozoya (Geological structure of the Kacha Uplift, Mountain Crimea: stratigraphy of Mesozoic) Mazarovich, O.A. and Mileev, V.S., Eds., Moscow: Mosk. Gos. Univ., 1989.

Georgiev, S., von Quadt, A., Heinrich, C.A., Peytcheva, I., and Marchev, P., Time evolution of a rifted continental arc: integrated ID-TIMS and LA-ICPMS study of magmatic zircons from the Eastern Srednogorie, Bulgaria, *Lithos*, 2012, vol. 154, pp. 53–67.

Gnidets, V.P., Grigorchuk, K.G., Zakharchuk, S.M., et al., *Geologiya nizhn'oi kreidi Prichornomors'ko-Krims'koi naftogazonosnoi oblasti (geologo-strukturni umovi, sedimento-litogenez, porodi-kollektori, permpektivi naftogazonosnosti)* (Geology of the lower part of the Near-Black-Sea–Crimean petroleum basin: geological-structural conditions, collector rocks, and perspectives of oil and gas bearing potential), L'viv: Inst. geol. geokhim. goryuchikh kopalin NAN Ukraini, 2010.

Gorbachik, T.N., Kopaevich, L.F., and Naidin, D.P., The Albian–Cenomanian boundary in the Southwestern Crimea, *Stratigr. Geol. Correl.*, 2000, vol. 8, no. 5, pp. 470–481.

Gozhik, P.F., Maslun, N.V., Plotnikova, L.F., et al., *Stratigrafiya Mezokainozois'kikh vidkladiv pivnichno-zakhidnogo shel'fu Chornogo morya* (Stratigraphy of Mesozoic–Cenozoic deposits in the Northwestern Black Sea shelf), Kiiv, Inst. geol. nauk NAN Ukraini, 2006.

Khriachtchevskaia, O., Stovba, S., and Stephenson, R., Cretaceous–Neogene tectonic evolution of the northern margin of the Black Sea from seismic reflection data and tectonic evolution of the northern margin of the Black Sea from seismic reflection data and tectonic subsidence analysis, *Geol. Soc. London, Spec. Publ.*, 2010, vol. 310, no. 1, pp. 137–157.

Kopaevich, L.F., Zonal scheme for the Upper Cretaceous deposits of the Crimean-Caucasian Region based on Globotrunñana (planktonic foraminifera), *Byull. Mosk. O–va Ispyt. Prir., Otd. Geol.*, 2010, vol. 85, no. 5, pp. 40–52.

Lavrishchev, V.A., Semenukha, I.N., Andreev, V.M., and Gorshkov, A.S., *Gosudarstvennaya geologicheskaya karta Rossiiskoi Federatsii masshtaba 1 : 200000. Kavkazskaya seriya. K-37-VI (Sochi)* (State geological map of Russian Federation, 1 : 200000, Caucasian series, sheet K-37-VI (Sochi)), St. Petersburg: S.-Peterb. kartograficheskaya fabrika VSEGEI, 2000, 2nd ed.

Lebedinskii, V.I., Kirichenko, L.N., and Ladan, A.N., New data on bentonite clays of Mountain Crimea, *Dokl. Akad. Nauk SSSR*, 1974, vol. 218, no. 6, pp. 1442–1445.

Lysenko, V.I., Paleobiostratigraphic substantiation of the Albian olistostromes in the vicinity of Balaklava, in *Teoretichni ta prikladni aspekti suchasnoi biostratigrafi fanerozoyu Ukraini* (Theoretical and applied aspects of modern biostratigraphic studies of Phanerozoic deposits in Ukraine), Kiiv, 2003, pp. 128–129.

Lysenko, V.I., New data on the composition of allothigenic material of the Albian tuffs from Balaklava depression, Southwestern Crimea, *Geol. Zhurn.*, 2005, no. 4, pp. 22–27.

Nikishin, A.M., Ziegler, P.A., Panov, D.I., Nazarevich, B.P., Brunet, M.F., Stephenson, R.A., Bolotov, S.N., Korotaev, M.V., and Tikhomirov, P.L., Mesozoic and Cenozoic evolution of the Scythian platform–Black Sea–Caucasus domain, *Mem. Mus. Natl. Hist. Nat., Ser. C (Paris)*, 2001, vol. 186, pp. 296–346.

Nikishin, A.M., Korotaev, M.V., Ershov, A.V., and Brunet, M.F., The Black Sea basin tectonic history and Neogene–Quaternary rapid subsidence modeling, *Sediment. Geol.*, 2003, vol. 156, nos. 1–4, pp. 149–168.

Nikishin, A.M., Alekseev, A.S., Baraboshkin, E.Yu., Bolotov, S.N., Kopaevich, L.F., Nikitin, M.Yu., Panov, D.I., Fokin, P.A., Gabdullin, R.R., and Gavrilov, Yu.O., *Geologicheskaya istoriya Bakhchisaraiskogo raiona Kryma. Ucheb. posobie po Krymskoi praktike* (Geological evolution of the Bakhchisaray district, Crimea: textbook), Moscow: Mosk. Gos. Univ., 2006.

Nikishin, A.M., Ziegler, P.A., Bolotov, S.N., and Fokin, P.A., Late Palaeozoic to Cenozoic evolution of the Black Sea–Southern Eastern Europe region: a view from the Russian platform, *Turk. J. Earth. Sci.*, 2011, vol. 20, pp. 571–634.

Okay, A.I., Şengor, A.M.C., and Gorur, N., Kinematic history of the opening of the Black Sea and its effect on the surrounding regions, *Geology*, 1994, vol. 22, no. 3, pp. 267–270.

Okay, A.I. and Sahınturk, O., Geology of the Eastern Pontides, *AAPG Mem.*, Tulsa, Oklahoma: AAPG, 1997, vol. 68, pp. 291–312.

Robinson, A.G., Fudat, J.H., and Wiles, R.L.F., Petroleum geology of the Black Sea, *Mar. Petr. Geol*, 1996, vol. 13, no. 2, pp. 195–223.

Rolland, Y., Sosson, M., Adamia, Sh., and Sadradze, N., Prolonged Variscan to Alpine history of an active Eurasian margin (Georgia, Armenia) revealed by $^{40}Ar/^{39}Ar$ dating, *Gondwana Res.,* 2010, vol. 20, pp. 798–815.

Shnyukov, E.F., Shcherbakov, I.B., and Shnyukova, E.E., *Paleoostrovnaya duga severa Chernogo Morya* (Ancient island arc in the northern Black Sea), Kiev: NANU, 1997.

Starostenko, V., Buryanov, V., Makarenko, I., Rusakov, O., Stephenson, R., Nikishin, A., Georgiev, G., Gerasimov, M., Dimitriu, R., Legostaeva, O., Pchelarov, V., and Sava, C., Topography of the crust-mantle boundary beneath the Black Sea Basin, *Tectonophysics*, 2004, vol. 381, nos. 1–4, pp. 211–233.S

Tüysüz, O., Yilmaz, I.O., Švábenická, L., and Kirici, S., The Unaz formation: a key unit in the western Black Sea region, N. Turkey, *Turk. J. Earth. Sci*, 2012, vol. 21, pp. 1009–1028.

Yilmaz, I.O., Altiner, D., Tekin, U.K., Tüysüz, O., Ocakoglu, F., and Acikalin, S., Cenomanian–Turonian oceanic anoxic event (OAE2) in the Sakarya Zone, northwestern Turkey: sedimentological, cyclostratigraphic, and geochemical records, *Cretaceous Res.*, 2010, vol. 31, pp. 207–226.

Zonenshain, L.P., Pichon, X., Deep basins of the Black Sea and Caspian sea as remnants of Mesozoic back-arc basins, *Tectonophysics*, 1986, vol. 123, nos. 1–4, pp. 181–211.

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