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Ophiolitic Association of Cape Fiolent Area, Southwestern Crimea

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Abstract—An ophiolitic association consisting of serpentinized ultramafic rocks and serpentinite, layered mafic–ultramafic complex, gabbro and gabbrodolerite, fragments of parallel dike complex, pillow lava, black bedded chert, and jasper has been identified for the first time by authors in the Cape Fiolent area. The chemistry of pillow lavas and dolerites, including REE patterns and a wide set of other microelements, indicates suprasubduction nature of the ophiolites and their belonging to a backarc basin that has reached the stage of spreading in its evolution.

Keyword: ophiolitic association, serpentinite, serpentinized peridotite, pillow lava, parallel dike complex, geodynamic setting, southwestern Crimea

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INTRODUCTION

Ophiolitic associations in folded belts represent fragments of ancient oceanic crust. They are retained in suture zones, which are traces of the closure of large basins, including oceans and backarc seas of the spreading type. In the Crimean Mountains, a Jurassic–Early Cretaceous piedmont collisional suture (Fig. 1) has been shown by Yudin [19]. In his opinion, this suture was formed as a result of the closure of the Mesotethys paleoocean. This idea is based on the discovery of serpentinized ultramafic rock in core samples from the borehole drilled 15 km to the northeast of town of Simferopol [15]. Serpentinites were also described in pebbles from the Lower–Middle Jurassic conglomerate of the Bitak Formation [20] penetrated by boreholes at the Heraclian Plateau in southwestern Crimea and dredged from the Lomonosov submarine massif at the bottom of the Black Sea, 24 miles to the southwest of Cape Fiolent [23]. At the same time, the outcrops of serpentinites remained unknown in the Crimean Mountains. Therefore, their geological position and relationships with other rock complexes were not evident. During fieldwork in 2014, we discovered outcrops of serpentinized ultramafic rocks and serpentinites at cliffs to the west of Cape Fiolent at the southern margin of the Heraclian Peninsula [2]. Fragments of parallel dike complex, which had not been described previously in this area, were also observed, along with bedded cherts. In combination with widespread pillow lavas, gabbro, peridotite, and jasper, these findings allow us to speak with confidence of an ophiolitic association [14].

Despite the fact that igneous rocks of the Crimean Peninsula were objects of thorough research by Luchitsky (1939), Kravchenko (1958), Pavlinov (1947, 1949), Lebedinsky and Makarov (1962), Lebedinsky and Solov'ev [6], Spiridonov et al. (1989, 1990), Shnyukova [17, 18], and many other workers, igneous rocks occurring in the Cape Fiolent area remain poorly studied. These rocks are exposed on almost vertical rocky cliffs along the coast of the southern Heraclian Peninsula for about 7 km (Fig. 1). In the east, these exposures are limited by the Georgievsky Fault, which separates this area from the rest of the Crimean Mountains. It is difficult to study igneous rocks in the Cape Fiolent area, because we are dealing here only with cross-sections and are not able to observe their relationships in plan view. In particular, we have failed to reliably determine strike and dip azimuths for rock sequences and fault planes. Such measurements can be implemented only at small exposed promontories, which jut out into the sea and are retained owing to small dikes, stocks, extrusions, and minor intrusions.

The magmatic activity in this district is conventionally correlated to the Karadag type [6, 7, 20, 21, 23], and the time of its manifestation is referred to the Middle Jurassic (Bajocian), as is shown in all geological maps of Crimea. Yudin [22] classifies this area as a zone of Simferopol melange composed of chaotically arranged rootless blocks of magmatic material. According to geophysical data, the lower edge of the melange sheet occurs at a depth shallower than 1–2 km, and this provides evidence for its allochthonous structural position. It has been noted that fragments of ophiolitic association are unknown in the melange [23].

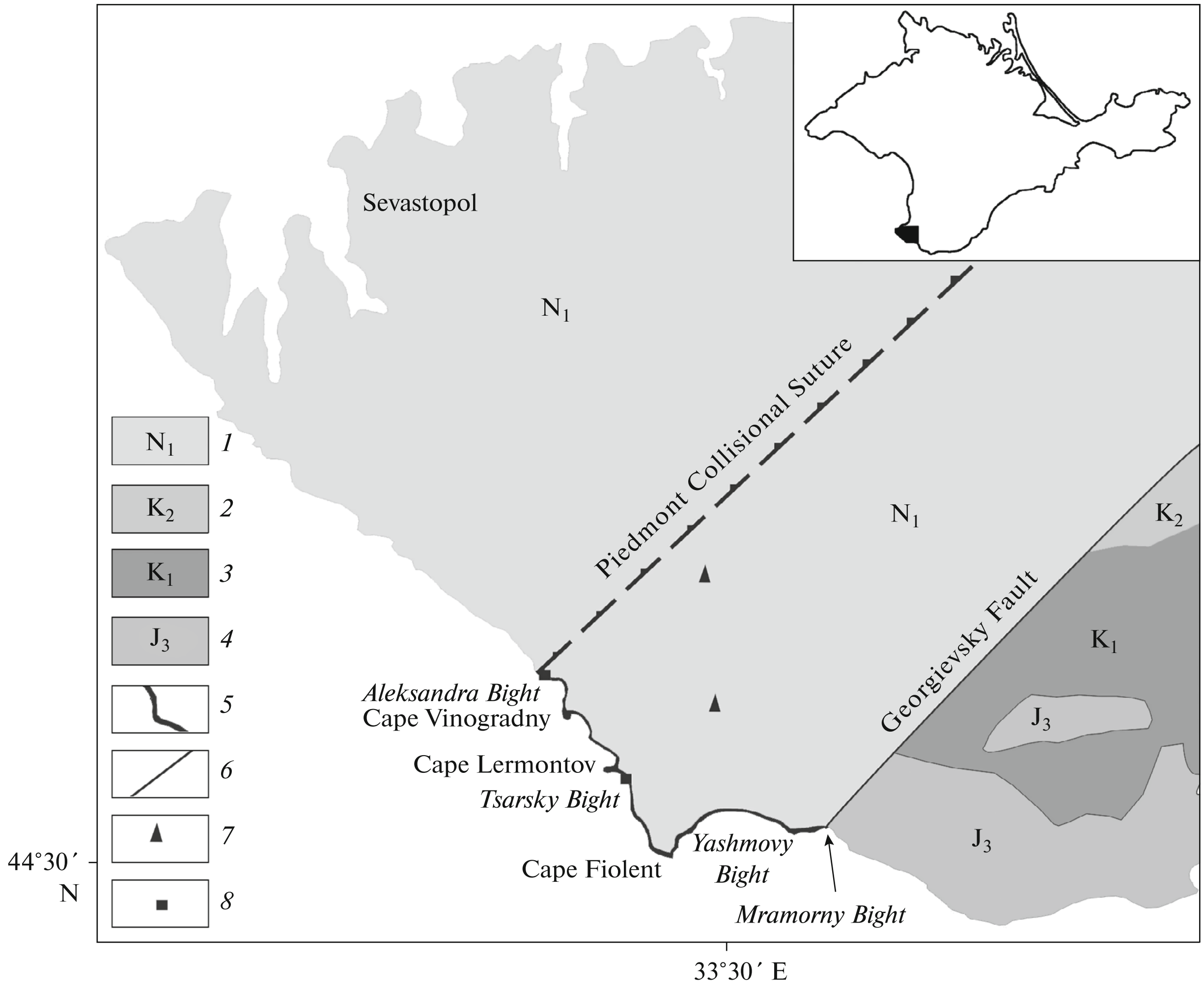

Fig. 1. Geological structure of southern Heraclean Peninsula. Compiled using modified data published by Yudin [22]. (*1*) Miocene: organogenic–detrital and clayey limestones; (*2*) Upper Cretaceous: marlstone, limestone, sandstone, and clay; (*3*) Lower Cretaceous: sandstone, conglomerate, clay, and limestone; (*4*) Upper Jurassic: reef limestone; (*5*) igneous rocks; (*6*) fault; (*7*) borehole penetrating igneous rocks; (*8*) finding of serpentinite.

The igneous rocks of Cape Fiolent are regarded as a shield volcano, the base of which is composed of Upper Triassic–Lower Jurassic sedimentary rocks related to the Taurian Series; however, such rocks have not been found in the Fiolent area either on land or at sea bottom [18]. Boreholes drilled at the Heraclian Plateau to the north of Cape Fiolent also did not penetrate the rocks of the Taurian Series. The volcanic rocks are overlain by organogenic detrital and clayey limestones pertaining to the Sarmatian Stage of the Neogene, which lie almost horizontally.

Shnyukova [17, 18] denies the existence of the Fiolent volcano as a single whole. The igneous rocks in this area are subdivided into three spots, and each is related to the self-dependent stage of magmatic activity. Gabbrodolerite and gabbronorite intrusive bodies are predominant in the western spot in association with wehrlite, less frequent lherzolite and dunite with cumulative structures. The central spot is composed of bimodal basalt–plagiogranite series. Unaltered amygdaloidal basalt, basaltic andesite, and dacite cutting through by olivine dolerite dikes are predominant in the eastern spot. Only the igneous rocks from the western spot are referred to ophiolites by E.N. Shnyukova. The pillow lavas of the central spot are not involved in ophiolites because of their geochemistry, differing, in her opinion, from the pillow lavas of the reference Kyure massif in Anatolia applied to the geodynamic reconstruction of the Black Sea region.

Sporadic determinations of isotopic age have been carried out for the Fiolent igneous rocks [17, 18]. Three analyzed (U–Pb SHRIMP) zircon grains from basaltic dike in the central spot yielded a Precambrian age (1771 ± 28 Ma). An ancient age (2091 ± 10 Ma) has been obtained for six zircon grains from wehrlite in the western spot. The K–Ar age of plagiorhyolite from the central spot is estimated at 174 Ma and corresponds to the early Middle Jurassic.

OPHIOLITIC ASSOCIATION OF CAPE FIOLENT AREA

Serpentinized ultramafic rocks and serpentinite, layered mafic–ultramafic complex, gabbro and gabbrodolerite, fragments of parallel dike complex, pillow lava, black bedded chert, and jasper are incorporated into the ophiolitic association. As will be shown hereafter, plagiorhyolites and less frequent rhyolites occur in the central part of the studied area as constituents of this association.

Serpentinized ultramafic rocks and serpentinites were found for the first time at the western end of the igneous rock outcrops in the Cape Fiolent area to the north of Utyug Rock, which is lenticular in shape, elongated in the northwestern direction, and composed of a fractured and altered gabbro with fragmented clinopyroxene grains, rare orthopyroxene, and tablets of calcic plagioclase saussuritized and albitized at the margins. Secondary chlorite is associated with small grains of ore mineral. The outcrops of serpentinized ultramafic rocks and serpentinites are confined to intersection of two near-vertical NE- and NW-trending fault zones that constrain cliffs of the Utyug Rock (Figs. 2a and 2b). To the west of this rock, altered and brecciated pillow lavas crop out at coastal cliffs. The pillows are separated by spaces filled with epidotized breccia and green jasper. Lavas are represented by aphyric amygdaloidal basalts with typical spilite structure. Amygdaloids are filled with epidote.

Pillow lava outcrops are limited by a fault zone in the east, along which they come in contact with serpentinized ultramafic rocks. The numerous slickensides and foliation surfaces impart them a fissile and lenticular structure. Serpentinization develops nonuniformly and is confined to parallel cleavage. Serpentinite is represented by flaked antigiorite sheets and less frequent fine fibrous chrysotile aggregates. The cleavage planes oriented perpendicular to schistosity display an augen structure expressed in occurrence of separate, rather large (up to 2 mm) fragmented clinopyroxene grains stream-lined by serpentinite, chlorite, rare talc and actinolite aggregates. The primary composition of ultramafic rocks is difficult to determine. Wehrlite and lherzolite are the most probable, because relics of altered orthopyroxene and olivine grains are identified in addition to clinoppyroxene. A dike of fine-grained dolerite with abundant ore minerals occurs at the eastern contact of serpentinized ultramafic rocks.

The zone of cataclasites and mylonites is localized farther to the east, at the Utyug Rock, where serpenitite outcrops are distinguished by rounded convex surfaces from the background of cataclastic rocks (Fig. 3a). In general, this is a serpentinite melange. Its apparent width in the northeastern direction is ~15 m and reaches 40 m in the northwestern direction. Because of its lower strength as compared with gabbro, melange is eroded more intensely and forms a depression between the rock and coastal cliff. Serpentinite characterized by coarse–flaky and lenticular jointing, a brownish dark gray color at the weathered surface and a spotted silky color with various green hues at fresh surfaces (Fig. 3b) is composed of aggregates consisting of fine serpentine (mainly chrysotile) needles oriented parallel to one another or making up sheaf-like packets. Chlorite, actinolite, tremolite, talc, carbonate, and ore minerals occur in small amounts. Relics of broken clinopyroxene grains or their separate fragments are distributed nonuniformly and in much smaller quantities than in serpentinized ultramafic rocks. This shows that similar rocks underwent serpentinization and its intensity depends on the permeability to seawater and aqueous solutions circulating through fault zones.

Serpentinites in metamorphosed breccia are observed at outcrops located to the east of the Cape Lermontov in coastal cliffs of the Tsarsky Bight and Cape L'venok (Figs. 4a and 4b). The metamorphic breccia is overlapped by pillow lavas and is cut through by a series of parallel doleritic and basaltic dikes (Fig. 5a), which are conduits of mafic magma. The dikes vary from 15 to 60 cm in thickness and have faulted diffuse contacts (Fig. 5b) with breccia in screens (20–60 cm), providing evidence for the invasion into nonlithified breccia. The breccia frequently contains fragments of dikes; the latter occasionally are fragmented into boudins, which are clearly seen at the cliffs of the Cape L'venok. Breccia is composed of angular and poorly rounded fragments of mafic and ultramafic rocks and less frequent terrigenous rocks cemented by the matrix consisting of micro- and fine-clastic material of the same rocks and light blue to green jasper. Similar jasper fills fractures in the contact zones of the dikes also containing numerous carbonate veinlets. The tabular fragments in breccia (Fig. 4b) are composed of hyaloclastites, which were formed due to cracking of lavas rapidly cooled under submarine conditions. The breccia was metamorphosed under conditions of high-temperature greenschist facies. Typical chlorite, chlorite–albite, less frequent chlorite–actinolite and chlorite–epidote schists are represented in fragments, as well as epidunitic serpentinite with looped structure. This fact implies that ultramafic rocks were exposed on the seafloor and had been intensely fragmented before basaltic eruptions. Similar breccias are widespread in ophiolites from Liguria, the Lesser Caucasus, South Tien Shan, and elsewhere [5]. Their formation is related to breaks in ophiolite formation, where the upper parts of sections are eroded down to serpentinites under settings of strongly rugged topography [1]. It should be noted that this episode in the rift zone development in oceans and spreading-type backarc seas is a tectonic or destructive stage, unlike the volcanic constructive

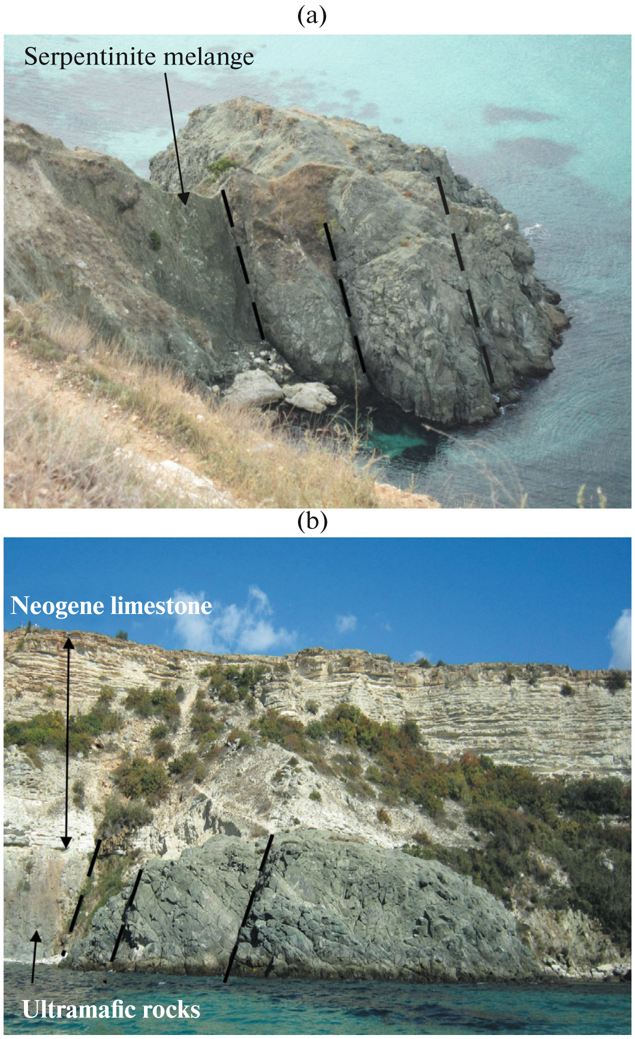

Fig. 2. Outcrops of serpentinized ultramafic rocks and serpentinites near Utyug Rock: (a) view from northwest, (b) view from southeast. Dashed lines are faults.

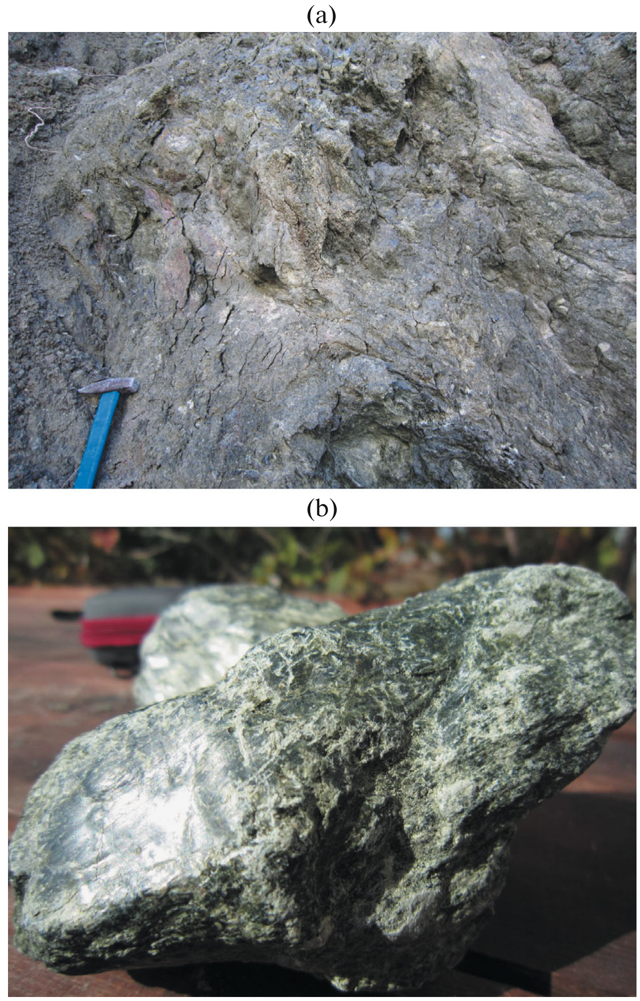

Fig. 3. Outrop (a) and hand specimen (b) of serpentinite.

stage. The cyclic character of tectonic activity is an indicator of slow-spreading ridges [4].

The layered mafic–ultramafic complex. Ultramafic rocks comprising lherzolite, wehrlite, dunite with typical cumulative structures and transitions to gabbro via gradual enrichment in plagioclase occur to the east of the Utyug Rock [18]. These rocks are referred to the layered mafic–ultramafic complex genetically related to the submarine Lomonosov massif. The geodynamic nature of the latter is a matter of debate. According to Shnyukov et al. [16], this massif consists of Cretaceous island arc fragments. Yudin [20] interprets this massif as a Late Cretaceous–Paleogene backarc spreading complex related to the opening of the West Chernomorian (Black Sea) Basin.

Gabbro and gabbrodolerite. These rocks are known mainly to the west of Cape Lermontov. The basement of this cape is composed of gabbrodolerite intrusions, which were emplaced into pillow lavas, as is clearly seen in cliffs in its eastern part. The emplacement of gabbrodolerite was accompanied by uplift of pillow lavas and faulting (Fig. 6). The fault were reactivated later, as is recorded in Neogene limestone overlying the lavas. The lavas at contact are burned, ironshot, and acquire a bright reddish brown color. The strongly tectonized gabbrodolerite intrusions are broken by numerous fractures, along which they are brecciated and ironshot. Pyroxene and plagioclase as major minerals of gabbrodolerite are fragmented and replaced with secondary chlorite, albite, and quartz. In the west, the typical isotropic gabbro and less frequent gabbronorite, which are exposed at cliffs of the Aleksandra Bight, are also appreciably tectonized, altered, and covered with Neogene limestone. Gabbro also crops out near the Cape Vinogradny, where it is cut through by felsic and mafic dikes.

Fragments of parallel dike complex. In addition to the aforementioned dikes at the Cape L'venok, this complex was recorded elsewhere in the area under

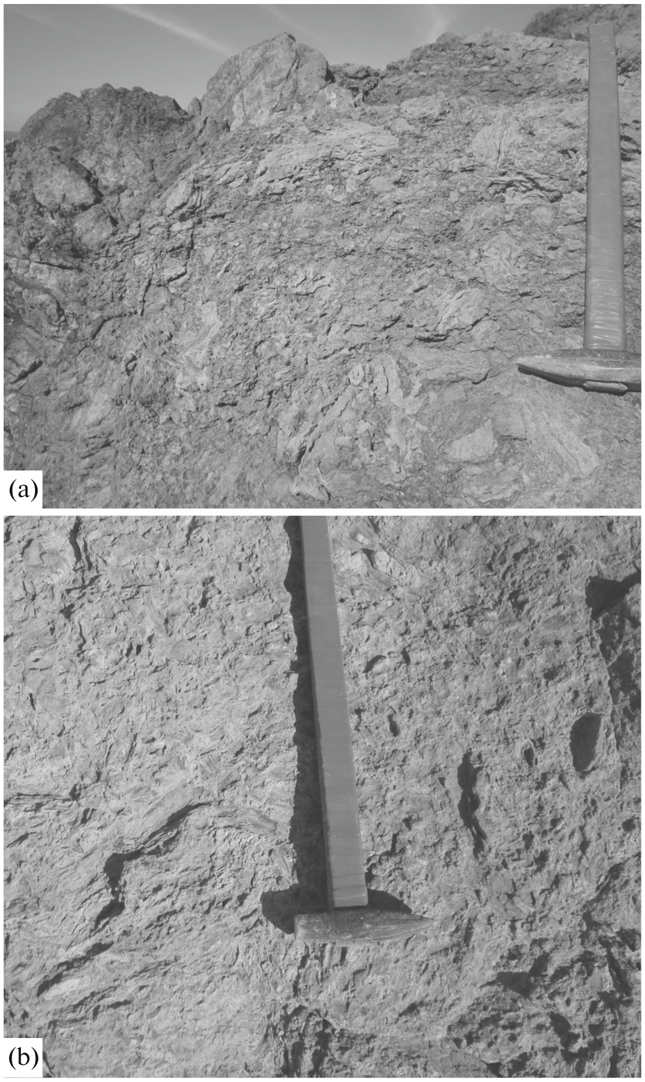

Fig. 4. Photo of metabreccia at the coastal cliffs of (a) Tsarsky Bight and (b) Cape L'venok.

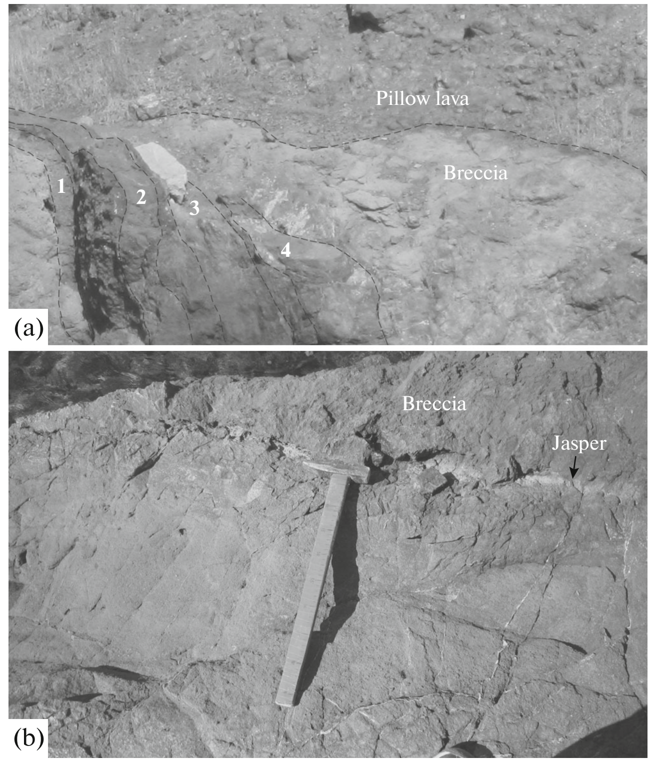

Fig. 5. (a) Parallel basaltic dikes (1–4) and (b) dikes with diffuse contacts occurring in breccia overlapped by pillow lavas. Cape L'venok.

study. At coastal exposure of the Caravel Bight (Lermontova Dacha), a fragment of this complex is represented by four dikes 20 cm to 1 m in thickness. Screens 20–50 cm thick are filled with pillow lavas, which are burned and impregnated by numerous carbonate veinlets. In the Mramorny Bight, dikes reach 85 cm to 1.5 m in thickness and are also composed of pillow lava (Fig. 7a). In both cases, contacts of dikes are diffuse and complicated by bulges, which emphasize the pillow structure of country lava. The dikes with wedge-shaped ends are also noted (Fig. 7b). The contact zones are banded owing to thin zones of hornfels and ironshot rocks. The character of contacts with country rocks shows that the dikes cut through yet incompletely solidified pillow lavas in the upper part of parallel dike complex. Screens indicate that the rate of spreading was not high.

It should be noted that younger NW-, NE-, and N–S-trending dolerite and plagiorhyolite dikes having sharp contacts with country rocks are also known in this area. Two perpendicular dikes occur at the Cape Bronevoi (Kashalot). One of these dike dips to the northwest and screens another near-vertical dike striking in the northwest direction, so that a T-shaped junction in plan view is observed (Fig. 8).

Pillow lavas are aphyric spilites and less frequent varieties with sporadic phenocrysts. These are the most abundant rocks that occupy ~70% of all outcrops in the region. They form the rocky cliffs of the Mramorny, Vinogradny, and Tsarsky bights, which extend as a continuous wall from Cape Lermontov in the west to Cape Fiolent and occupy its eastern part. The pillows are a few decimeters to 1.0–1.5 m in size and reveal zoning (Fig. 9a). The cores of the pillows are massive and better crystallized, whereas the margins are distinguished by amygdaloidal structure. The intestine-like lavas (Fig. 9b) that occur at cliffs of the Yashmovy (Jasper) Bight are similar to those exposed near Petropavlovka Settlement in the Simferopol district.

The interpillow space is filled with yellow, brown, bright red, crimson, and green jaspers. At the cliffs of the Tsarsky Bight, this space is filled with breccia of mafic and ultramafic rocks metamorphosed under conditions of high-temperature greenschist facies. The pillow lavas also overlap metamorphosed breccia (Tsarsky Bight). The pillow lava flows, which are variously oriented at coastal rocky cliffs to the west of

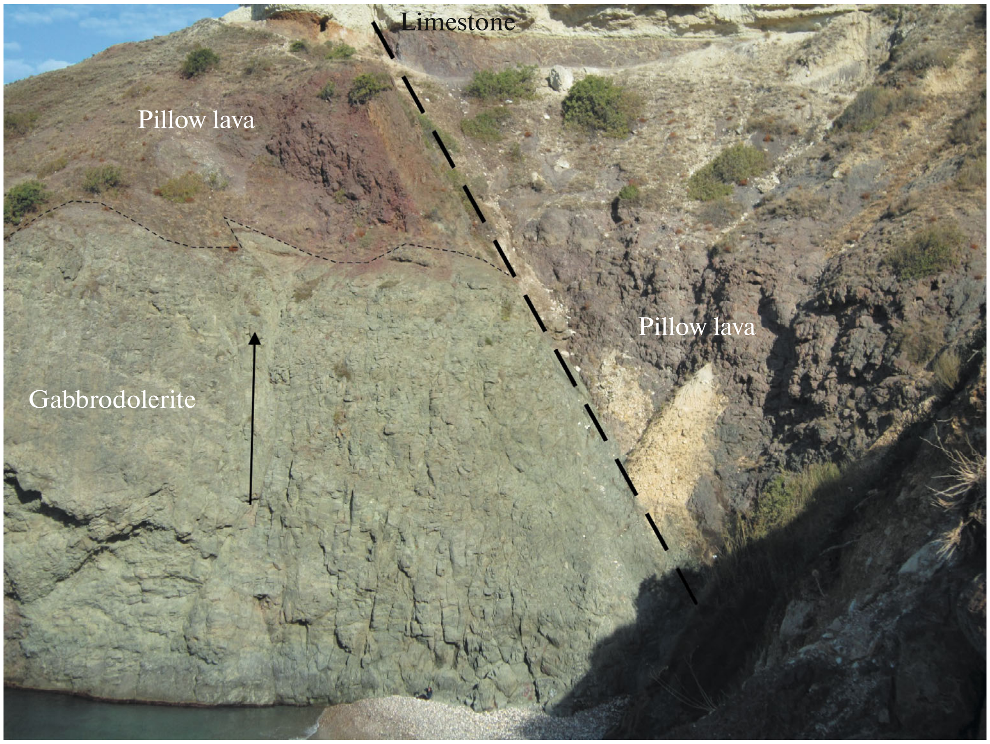

Fig. 6. Contact of gabbrodolerite with pillow lava. Arrow indicates direction of magma intruding. Cape Lermontov.

Cape Fiolent (Fig. 10), provide evidence for several eruption centers. Some particular flows differ not only in direction, but also in pillow size and the composition of the material that fills the interpillow space. Lava piles are broken by numerous and variously oriented faults, along which volcanic rocks are brecciated, fragmented, and mylonitized. Metasomatic alteration is expressed in albitization, chloritization, epidotization, less frequent carbonatization and zeolitization. Such a fault zone crops out immediately on Cape Fiolent, where a rhyolite dike is torn up and overturned (Fig. 11a); another segment of this dike is offset with a formation of a duplex structure (Fig. 11b). Yudin [22] explains similar structures in sandstones of the Taurian Series by thrusting. The deformed igneous rocks are overlain by horizontally lying Neogene limestone. A system of parallel fault zones trending in the same direction is exposed farther to the east, where the dikes underwent identical alterations. In the Mramorny Ravine, the pillow lava with calcic plagioclase phenocrysts remains unaltered, whereas calcite filling amygdaloids is intensely deformed and has a wavy extinction.

The silicic rocks that occur close to Cape Fiolent are represented not only by jasper, but also by black bedded chert in blocks of the Yashmovy Bight and among fragments in blocks of the Tsarsky Bight.

Plagiorhyolites and their brecciated varieties mainly occur as subvolcanic dikes, extrusive domes, stocks, and, less frequently, flows. These volcanics primarily occur to the east of the Cape Fiolent, where they form rocky scarps in the Yashmovy Bight, extrusive domes of the Monakh and Georgievsky Rocks, and the Monastyrsky Stock. The Ifigenia, Orest, and Pilatus Rocks—the main sights of Cape Fiolent—are also composed of plagiorhyolite. The columnar, often fan-like jointing of plagiorhyolite corroborates its extrusive nature (Fig. 12). Three isolated eruption centers of felsic magmas have been identified at the coastal cliffs of the Yashmovy Bight. The zones of intense postmagmatic hydrothermal reworking expressed in silicification, limonitization, formation of bright yellow sulfur compounds, and intense sulfide mineralization are related to each volcanic center.

Plagiorhyolite is a rock with sporadic albitized plagioclase phenocrysts, which are incorporated into the groundmass, composed of fine albite laths, quartz grains, and altered glass. Plagiorhyolite breccias are widespread in the framework of extrusive bodies. These bodies also occur on slopes and at the foots of extrusive domes [11]. They are formed as a result of cracking of viscous magma during the dome growth. The fragments are variable in size and shape from large blocks to fine–clastic cement. All fragments are identical in composition, which is the same as the extrusion as a whole. The reddish crimson jasper between fragments is similar to the interpillow jasper in mafic lava, and this is evidence for the primary volcanic nature of breccia. Plagiorhyolites are brecciated, cataclastic, and mylonitized along numerous fault zones.

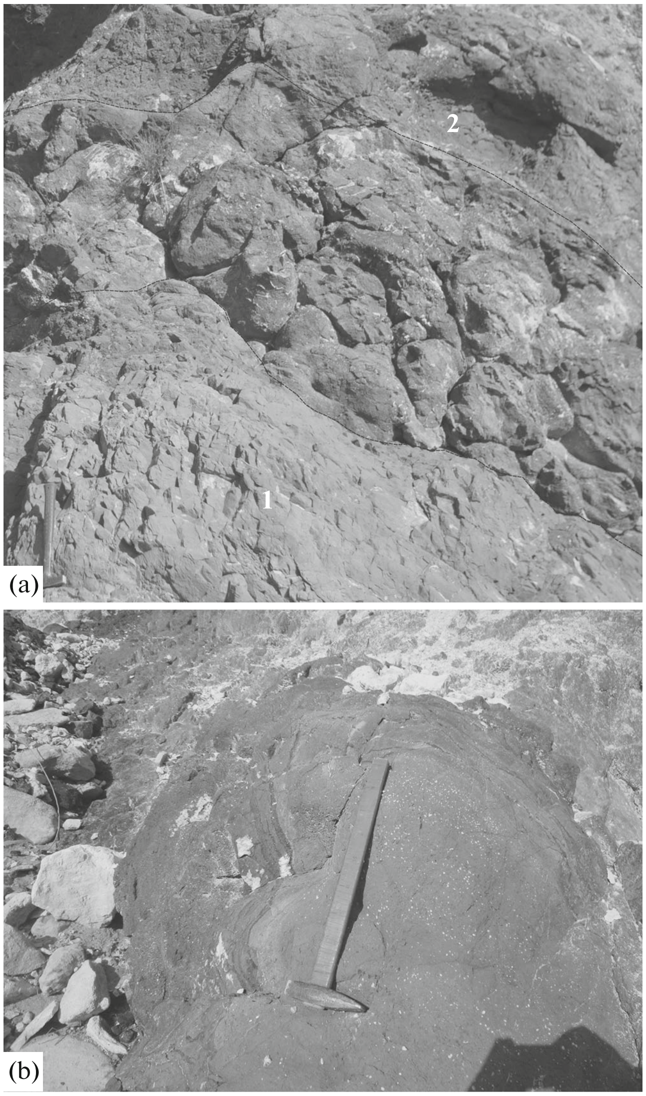

Fig. 7. (a) Parallel dikes (1, 2) and (b) wedge-shaped end of one dike at coastal cliff of Mramorny Bight.

One of the latter, up to 10–15 m in width, bisects the Monakh Dome on the eastern side (Fig. 13) and is traced at the cliff of the Yashmovy Bight up to the contact with Neogene limestone. As is clearly seen in smaller fault zones, the plagiorhyolite columns are broken (Fig. 14a) and the fragments become rounded (Fig. 14b), so that the rock resembles a conglomerate. Such tectonites are widespread in the region, especially to the east of the Monakh Dome.

Thus, all members of the ophiolitic association have been identified in the Cape Fiolent area. The section builds up from the northwest to the southeast up to the eastern end of the Yashmovy Bight. Fragments of this association also occur at coastal cliffs of the Mramorny Bight. The rocky outcrops that are most difficult of access, which are located to the east of the Monastyrsky Stock and separated by near-meridional fault zone, require additional study. Observations from the sea show the thick sequence of breccias various in composition that come into contact with volcanic–sedimentary rocks. Two sequences of relatively fresh lavas differing in structure occur farther to the east. We do not include these rocks in the ophiolitic association. Large trachyte blocks with K-feldspar phenocrysts also are not members of this association. They are related either to the stage of continental rifting, which predated the opening of the basin with ocean-type crust, or are formed in island-arc or collisional setting. It should be noted that the occurrence of igneous rocks differing in a geodynamic setting is quite allowable for suture zones.

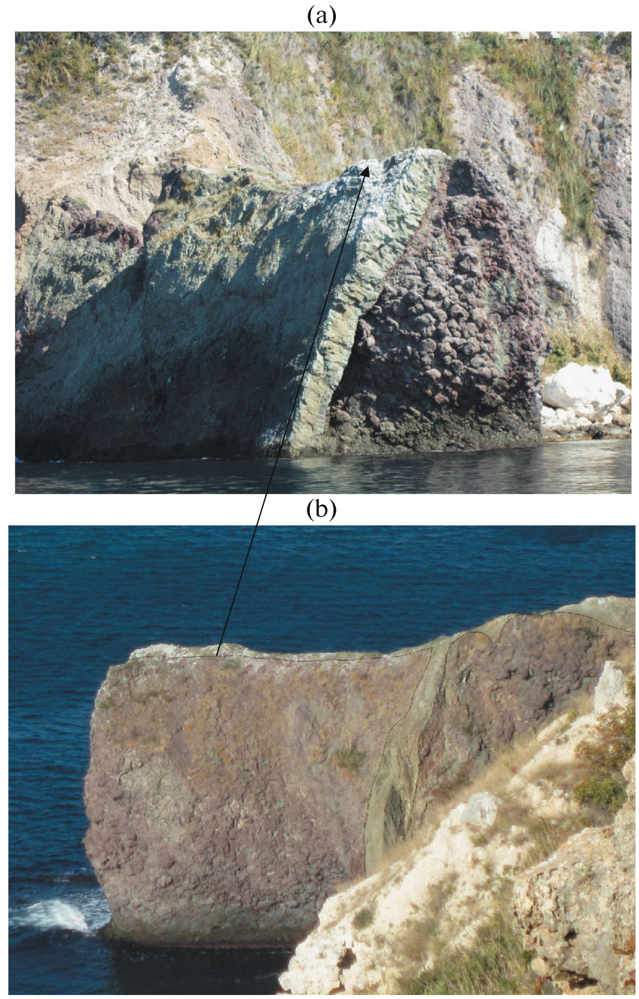

Fig. 8. Dikes arranged perpendicular to each other: (a) view from southwest and (b) view from east. Cape Bronevoi.

GEODYNAMIC SETTING OF OPHIOLITIC ASSOCIATION

To reproduce the geodynamic setting of the ophiolites, we have thoroughly studied the chemical composition of pillow lava, dolerite, plagiorhyolite, and brec-

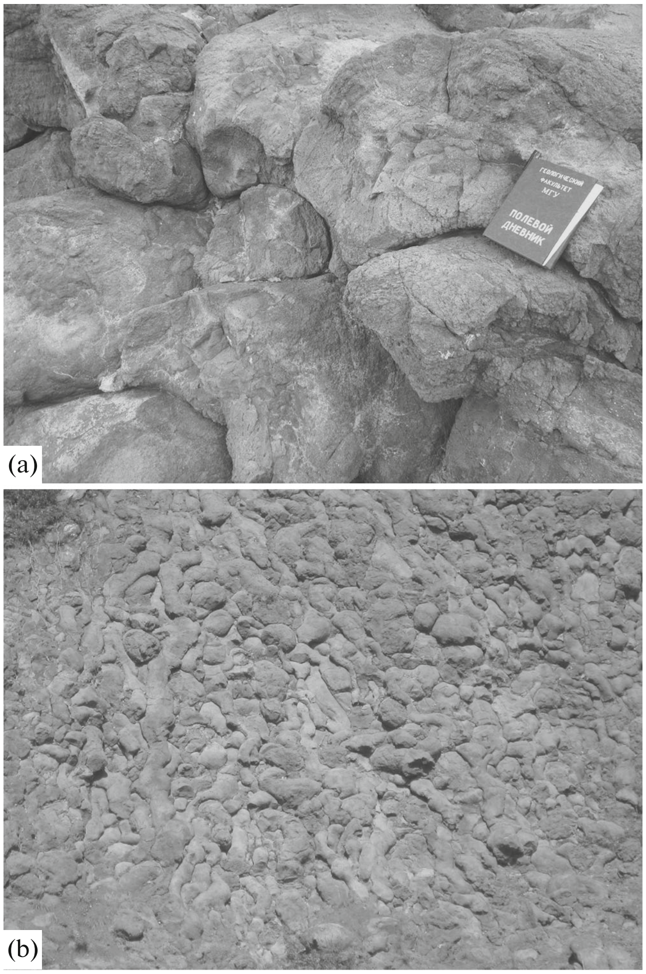

Fig. 9. Pillow lavas exposed at rocky cliffs of (a) Tsarsky and (b) Yashmovy bights.

ciated rocks [13]. The chemical compositions of igneous rocks from central Cape Fiolent published in [18] have been used. As follows from the TAS diagram (Fig. 15a), igneous rocks make up a bimodal series. The bulk chemical compositions of pillow lavas and dolerites correspond mainly to basalt, trachybasalt, and basaltic trachyandesite; two data points are plotted in the fields of andesite and trachyandesite; chemical compositions of felsic rocks are plotted in the field of rhyolite (low- and medium-K varieties, see Fig. 15b). Most pillow lavas are also low-K; medium- and high-K varieties are much less abundant. In the AFM diagram, chemical compositions of almost all igneous rocks are clustered in the field of calc-alkaline series (Fig. 16a). In the Al_2O_3–FeO* + TiO_2–MgO plot, the overwhelming majority of pillow lavas are classified as high-Mg tholeiites; komatiitic basalt and calc-alkaline basalts are also noted (Fig. 16b). The data points of felsic rocks falls in the fields of tholeiitic and calc-alkaline rhyolite, dacite, and less frequently of andesite. Thus, uncertainty is retained in the nomenclature for the overwhelming majority of igne-

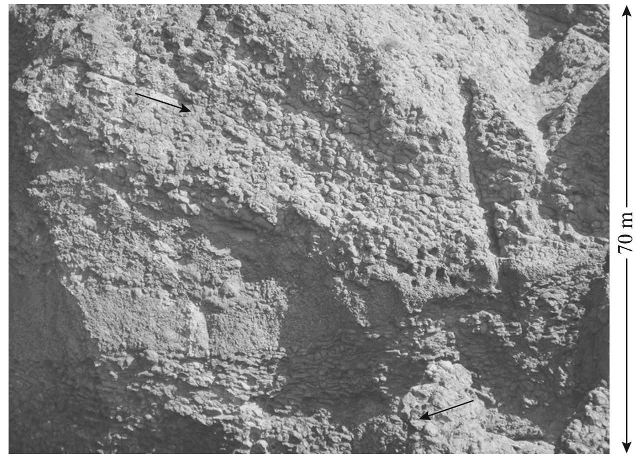

Fig. 10. Variously directed pillow lava flows. Coastal cliff west of Cape Fiolent.

ous rocks from the central Cape Fiolent. In the opinion of Mironov et al. [8], this is characteristic of within-plate continental rifting, but comes into conflict with the settled opinion on the island-arc nature of Bajocian magmatism in the Crimean Mountains, although its riftogenic character cannot be ruled out. It is well known that rifting develops at all stages of Wilson cycle, including suprasubduction setting. At the same time, magmatic activity related to continental rifting, as a rule, evolves from felsic to mafic rocks, whereas the opposite trend (from mafic to felsic) is typical of central Cape Fiolent. According to the Pearce discriminant diagrams, the data points of pillow lavas are clustered in the field of basalts from mid-ocean ridges and abyssal oceanic bottom (Figs. 17a and 17b). According to Th, Yb, and Nb proportions, the volcanic rocks fall into intermediate field between N-MORB and island-arc rocks (Fig. 17c).

All igneous rocks are distinguished by low REE contents throughout their spectrum, while the data points of basalts and dolerites are depleted in REE relative to N-MORB (Fig. 18a). The bimodal character of the magmatism, as well as the similarity of REE patterns of plagiorhyolite and its brecciated variety, is emphasized. The felsic rocks are more enriched in REE than mafic rocks throughout their spectrum; a negative Eu anomaly is typical. The latter indicates that felsic rocks are products of mafic melt fractionation. Thus, pillow basalts and plagiorhyolites pertain to the same magmatic series and the same stage of magmatic activity. The late dolerites, which cut through both pillow basalts and plagiorhyolite, are depleted in LREE, and the shape of their patterns is close to that of N-MORB (La/Lu < 1).

The distribution of microelements in basalt and dolerite, normalized to N-MORB, shows that both rocks are insignificantly enriched in LILE (Rb, Ba, Th) and depleted in HFSE from Nd to Cr; the Nb anomaly is evident (Fig. 18b). This pattern is typical of tholeiitic

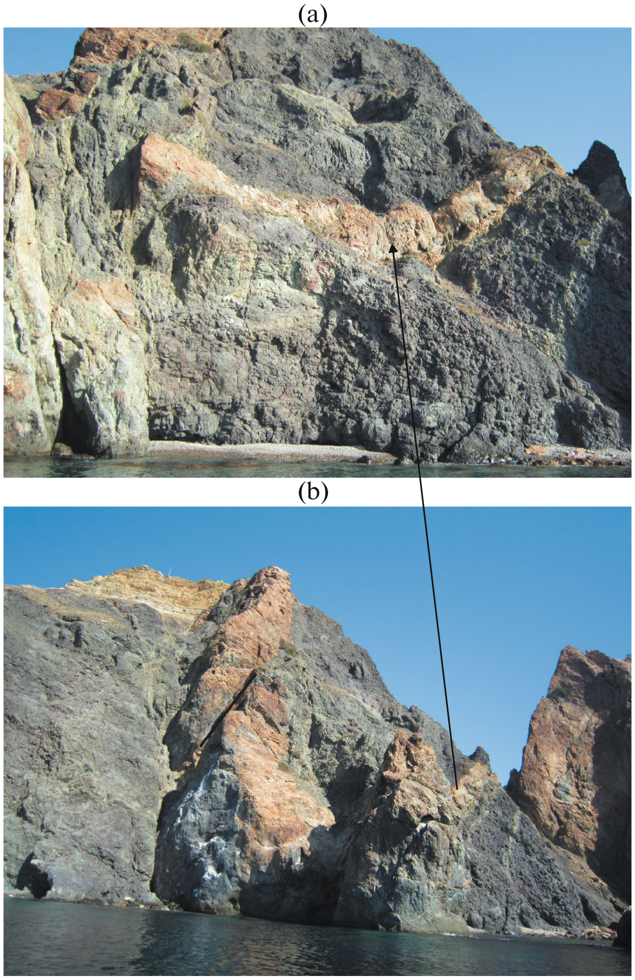

Fig. 11. Zone of brecciation, cataclasis, and mylonitization: (a) torn up and overturned segment of rhyolite dike, (b) offset dike. Cape Fiolent.

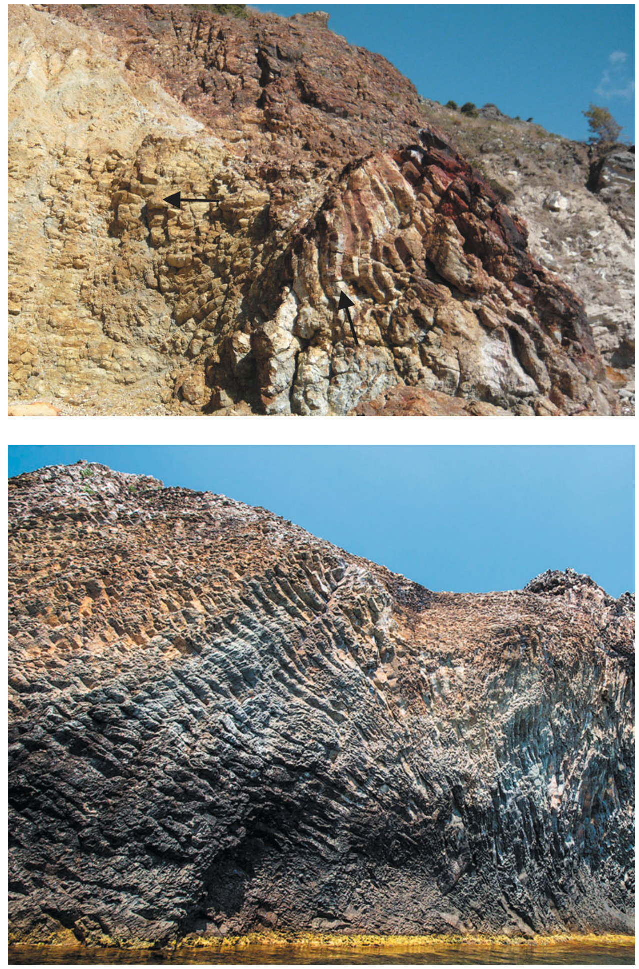

Fig. 12. Fanlike columnar jointing of extrusive domes: (a) Cape Fiolent and (b) Georgievsky Rock.

series from backarc basins [12]. The enrichment in LILE is related to the subduction-related component of the melts formed due to spreading in backarc basins with oceanic crust.

At some time after formation, the magmatic complexes of backarc basins were involved in collision or accretion, because they are conjugated with subduction, which results in the closure of large oceanic basins. Their backarc position facilitates the retention of magmatic and sedimentary complexes as compared to oceanic complexes, which are subducted almost completely. The petrology and geochemistry of ophiolitic sections and the attendant volcanic and sedimentary complexes known in various foldbelts show that most of them are relics of oceanic crust formed in backarc basins. According to Pearce et al. [12], the contribution of intermediate and felsic rocks to lavas piles and intrusions in the upper parts of sections may be the best criterion to distinguish ophiolites formed above the subduction zone from ophiolites of mid-ocean ridges. The Semail Complex in Oman, cut through by diorite–plagiogranite intrusions and containing a significant amount of andesites and rhyolites, is an example. In the Cape Fiolent area and the adjacent territory, plagiorhyolites postdate pillow lavas, and their volume is only 10% of the pillow lava volume. Thus, ocurrence of plagiorhyolite does not come into conflict with the suprasubduction nature of ophiolitic association; on the contrary, the aforementioned relationships confirm this conclusion. The subalkaline composition of some igneous rocks in the Fiolent area most likely is not a primary feature and is related to spilitization accompanied by sodic metasomatism. Subalkaline igneous rocks commonly occur in backarc basins along with calc-alkaline and tholeiitic series.

CONCLUSIONS

Several models of the Mesozoic tectonic evolution of the Crimean Mountains have been proposed. Yudin [23] propses that the Kimmerian (Late Triassic to

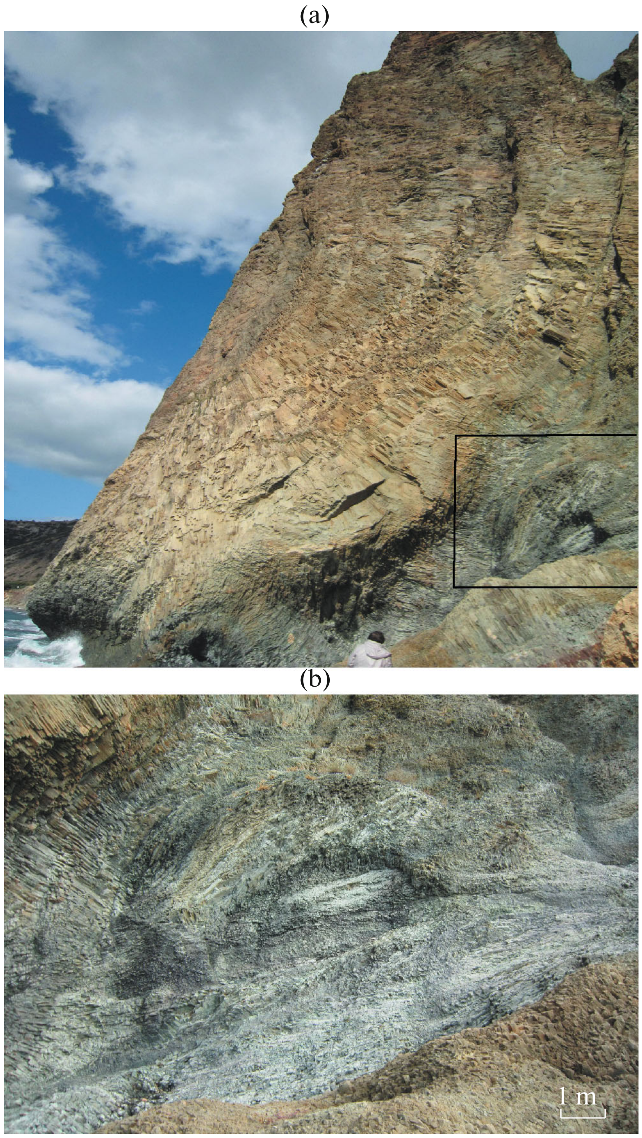

Fig. 13. Zone of brecciation, cataclasis, and mylonitization that cuts through dome of Monakh Rock: (a) general view and (b) close-up of rectangle in panel (a).

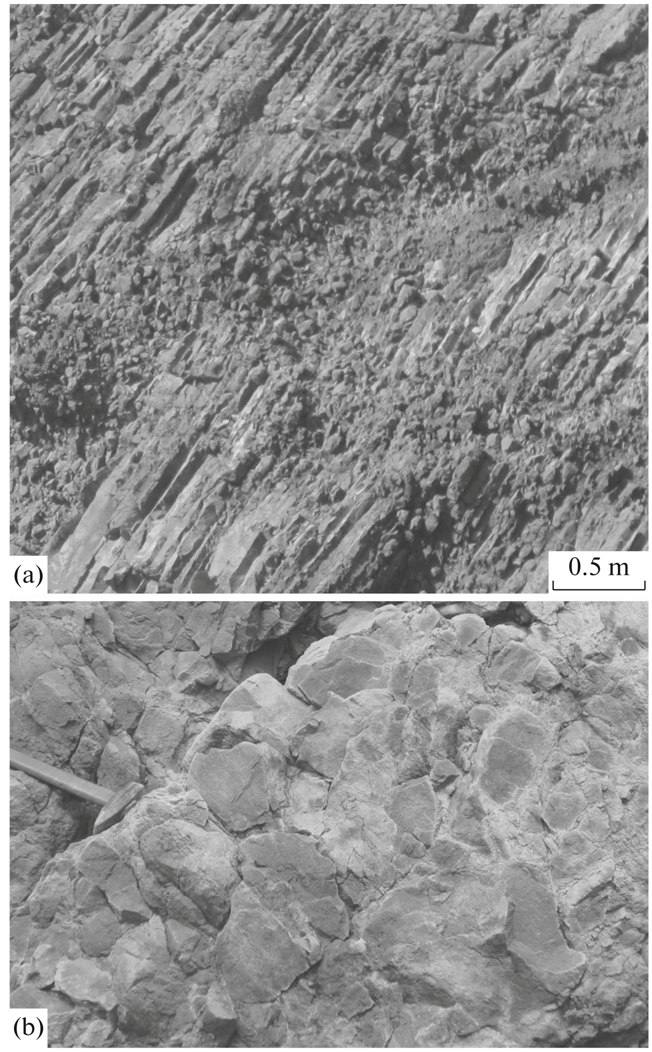

Fig. 14. Tectonic breccia in small fault zones.

Early Cretaceous) geodynamic cycle of the evolution of Crimea is related to the existence of the northern fragment of the Mesotethys paleoocean at that time. The opened Mesotethys first separated the Crimean Mountain Terrane (Crimia) from the southern margin of Laurasia. At the convergent stage, Crimia first collided with Pontia and afterward with Eurasia, i.e., a part of Laurasia, which was formed after its breakup due opening of the Atlantic Ocean. According to V.V. Yudin, the island-arc magmatism of the Crimean Mountains, including the Fiolent area, is related to the subduction zone, to which corresponds the northward dipping Izmir–Ankara Suture localized in Anatolia. The Middle Jurassic to Early Cretaceous magmatism of the Crimean Plain formed at the active margin of Laurasia is genetically related to the northward dipping Piedmont Suture [21]. Outcrops of igneous rocks on Cape Fiolent adjoin the southwestern ending of this suture (Fig. 1). Fragments of ultramafic rocks occurring as clastolites of the suture-line ophiolitic melange are dated to the Late Triassic to the Early Jurassic. Meijers et al. [28] recognize two chronological groups of igneous rocks in the Crimean Mountains: the Middle Jurassic (172–155 Ma) and the Late Jurassic to Early Cretaceous (151–142 Ma). According to them, both groups are of the suprasubduction nature and are related to opening of the Black Sea as a backarc basin. The igneous rocks in the vicinity of Simferopol and Trudolyubovka are referred to the first group, whereas volcanic rocks of the Karadag belong to the second group. In geology (pillow lavas, subvolcanic bodies with columnar jointing), the latter are quite comparable with igneous rocks in the Fiolent area.

Zonenshain et al. [3] stated that a backarc basin existed in the back zone of the Kimmerian ensimatic

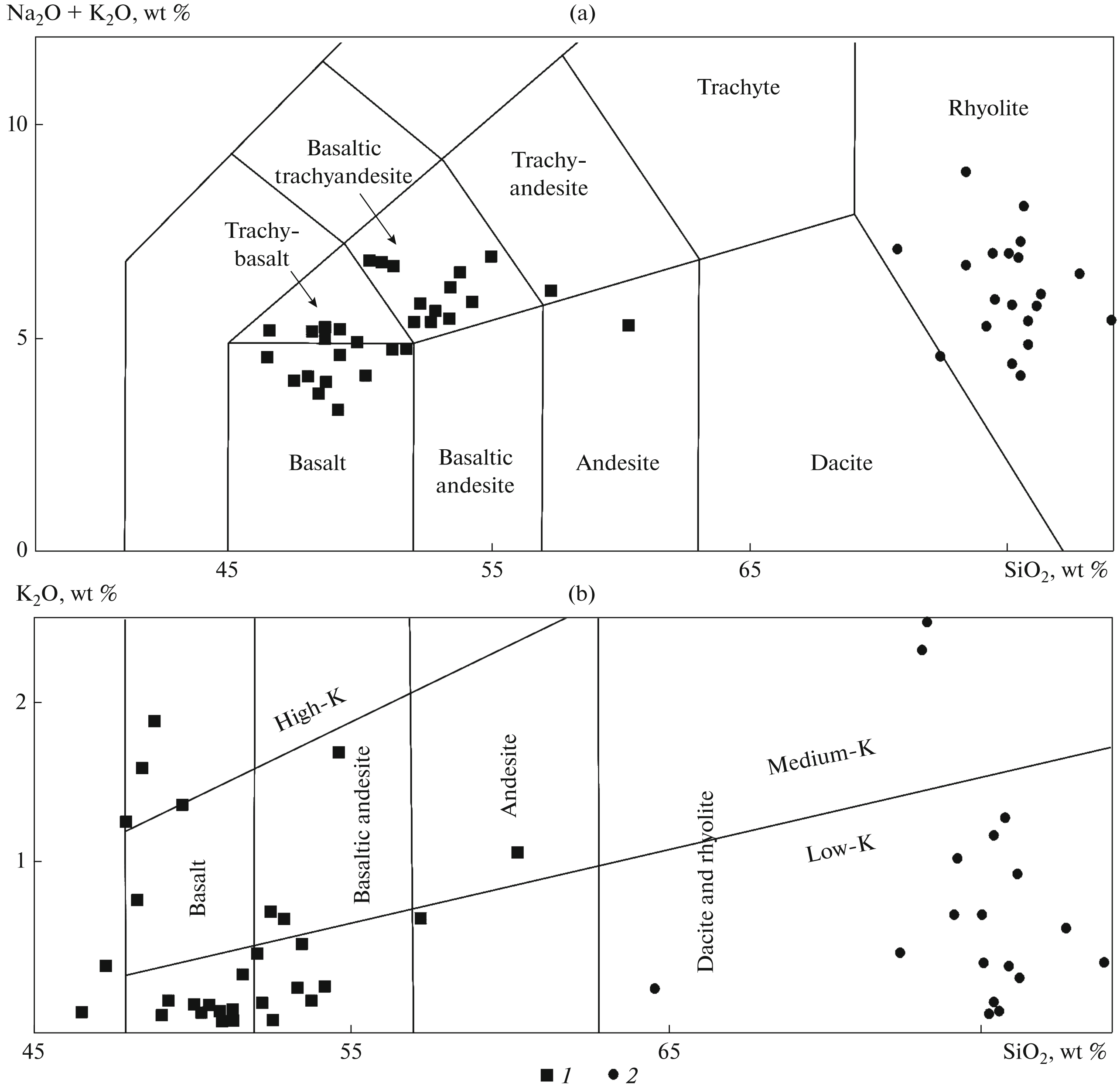

Fig. 15. Chemical compositions of volcanic rocks from central Fiolent plotted in (a) SiO_2–$Na_2O + K_2O$ and (b) SiO_2–K_2O diagrams. (*1*) mafic lavas and dikes and (*2*) plagiorhyoites. Fields in diagrams after [27]; original and published data [18] are used.

island arc. The backarc basin of the Greater Caucasus, the western part of which embraced the territory of the contemporary Crimean Mountains, has been reconstructed for the Early and Middle Jurassic by Nikishin et al [9], who did not specify the location of the area occupied by Jurassic magmatism of Crimean Mountains. The Pontian–Transcaucasus igneous belt related to subduction of the Tethys paleoocean was depicted to the south of the Greater Caucasus Basin. The magmatism of the Crimean Plain confined to the Karkinit Graben is referred by Nikishin et al. [10] to the Albian.

According to Mileev et al. [7], a deepwater riftogenic Taurian Basin existed in the Late Triassic to Early Jurassic at the location of the present-day Crimean Mountains. This basin separated the Scythian (contemporary Crimean steppe) and the Euxinian (contemporary Black Sea) terranes. Their convergence took place at the end of the Early Jurassic or the onset of the Middle Jurassic, when the crust of the Taurian Basin was subducted northward beneath Scythia. The island arc arose in the late Bajocian. The intrusions of the Pervomaisky–Ayudag Complex were emplaced at that time, along with the formation of the

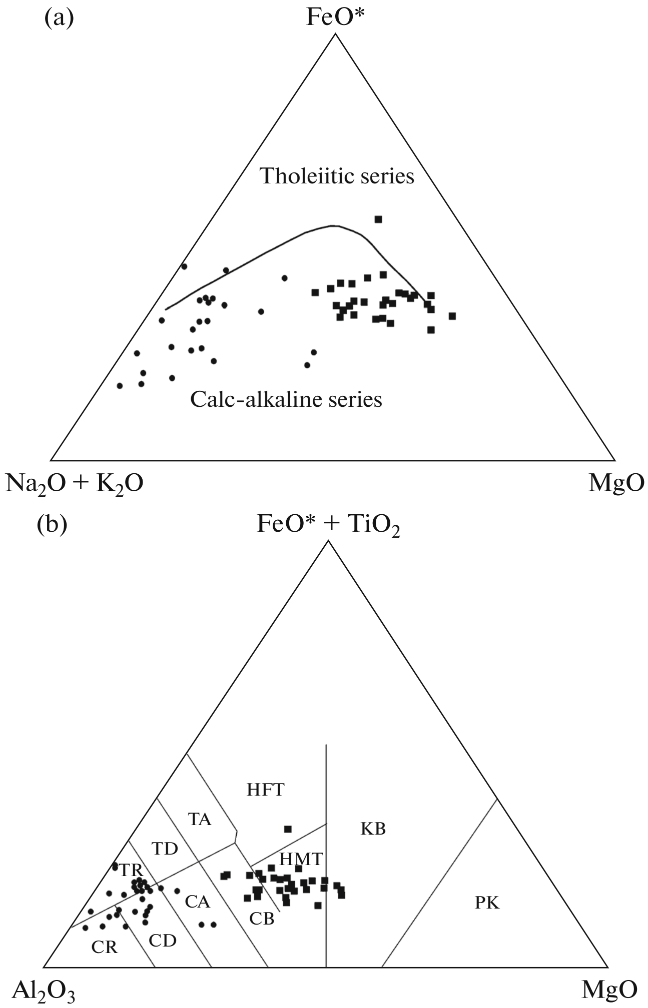

Fig. 16. Chemical compositions of volcanic rocks from central Fiolent area plotted in (a) AFM and (b) Al_2O_3–FeO^*+TiO_2–MgO diagrams. Fields in diagrams: (a) after [24], (b) after [26]. Abbreviations in panel (b): TR, rhyolite; TD, dacite, and TA, andesite of tholeiitic series; CR, rhyolite; CD, dacite; CA, andesite, and CB, basalt of calc-alkaline series; HFT, high-Fe tholeiite; HMT, high-Mg tholeiite; KB, komatiitic basalt; PK, peridotitic komatiite. Original and published data [18] are used. See Fig. 15 for legend.

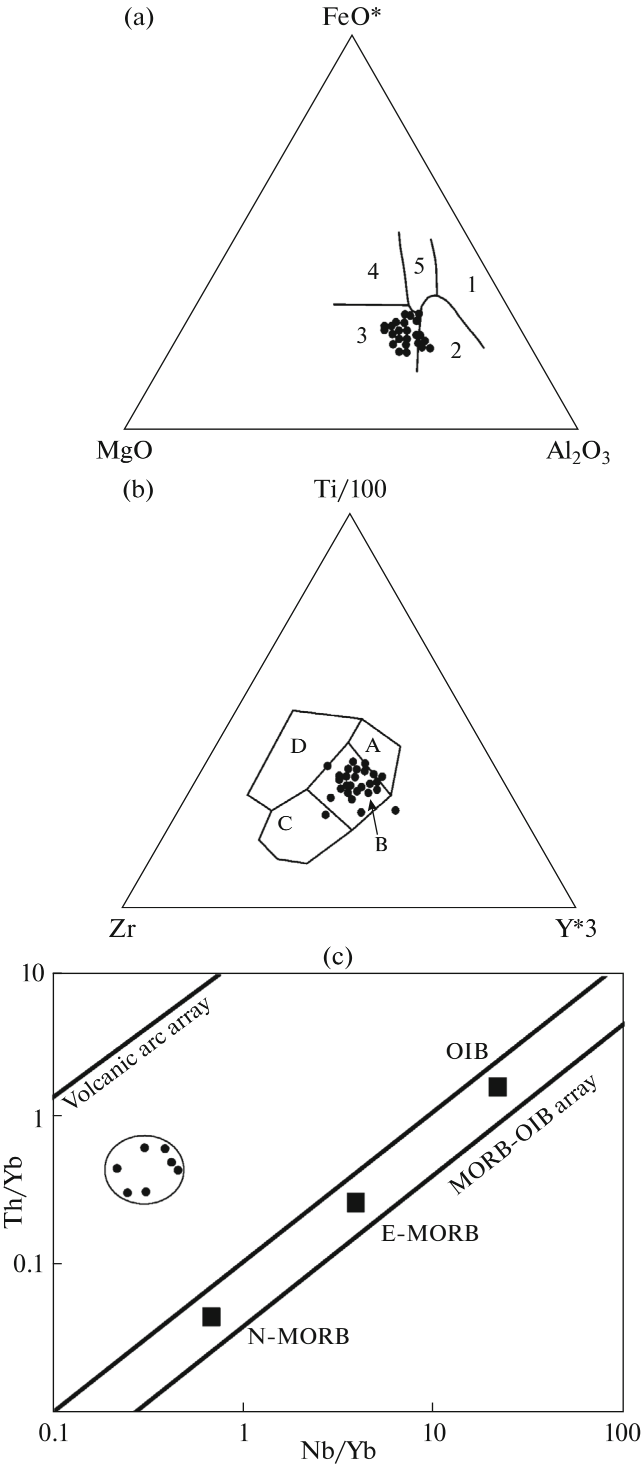

Fig. 17. Chemical compositions of pillow lavas and dolerites from Fiolent area plotted in discriminant diagrams: (a) after [31], (b) after [30], and (c), after [29]. Panel (a). Basalt and basaltic andesite: 1, spreading centers of islands; 2, orogenic regions; 3, mid-ocean ridges and oceanic bottom; 4, oceanic islands; 5, continents. Panel (b). Basalts: A, B, low-K tholeiite; B, oceanic bottom; B, C, calc-alkaline; D, within-plate. In panel (b): oceanic (MORB-OIB array) and island arc (volcanic arc array) igneous rocks. Original and published data [18] are used in panels (a, b) and published data [13] in panel (c).

volcanic Bodrak–Karadag Series. Most researchers refer the igneous rocks of the Fiolet area to this series. The complete closure of the Taurian Basin and the collision between Euxinia and Scythia took place at the end of the Middle Jurassic. As a result, the Lozovsky Shear Zone arose. Note that Yudin [22] refers formation of the Lozovsky Zone and the Cape Fiolent area to the Simferopol melange.

Thus, the currently discussed concepts concerning the Mesozoic tectonic evolution of Crimea are controversial. In our view, this is caused (besides other factors) by the insufficiently studied chemical compositions of the igneous rocks. This does not allow the

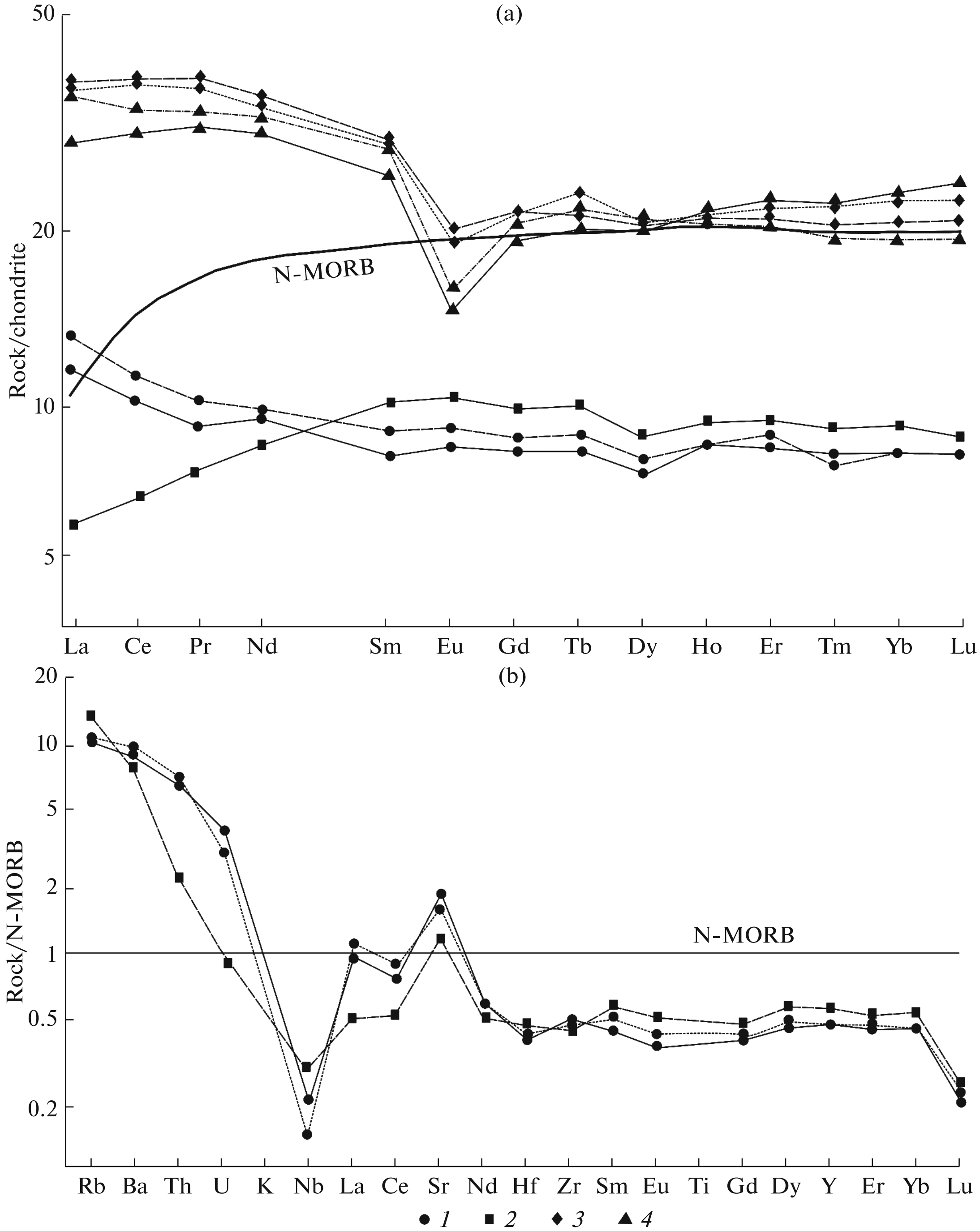

Fig. 18. REE patterns (a) and spidergrams of microelements (b) for igneous rocks of central Fiolent area. (*1*) basalt, (*2*) dolerite, (*3*) plagiorhyolite, (*4*) brecciated plagiorhyolite. Compositions of chondrite and N-MORB are from [32] and [13], respectively. Data from [13] are used.

use of magmatic complex indicators of geodynamic settings in full measure, so that the reliable correlation of igneous rocks occurring in various places of the peninsula becomes impossible.

As a result of investigations carried out in the Cape Fiolent area, the ophiolitic association has been established for the first time as a combination of serpentinized ultramafic rocks and serpentinite, layered mafic–ultramafic complex, gabbro and gabbrodolerite, fragments of parallel dike complex, pillow lavas, bedded black cherts, and jasper. The chemistry of pillow lavas and dolerites from ophiolites of Cape Fiolent area, including REE patterns and a wide set of other microelements, indicates their suprasubduction nature and belonging to the backarc basin, which has reached the stage of spreading in its evolution.

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REFERENCES

1. L. N. Abakumova, O. S. Berezner, G. S. Gusev, I. I. Abramovich, A. S. Kireev, A. G. Konyukhov, A. F. Morozov, L. M. Natapov, V. M. Nenakhov, and A. P. Stavskii, Studies of Ophiolotic Complexes when Geological Mapping (Roskomnedra, Moscow, 1994) [in Russian].
2. L. I. Demina, M. Yu. Promyslova, and V. V. Tsarev, "The first finding of serpentinite outcrop in the Gorny Crimea and its implication for paleogeodynamics of this region," in *Novye idei v naukakh o Zemle. Doklady XII Mezhdunarodnoi nauchno-prakticheskoi konferentsii* (MGRI-RGGRU, Moscow, 2015), Vol. 1, pp. 48–49.
3. L. P. Zonenshain, M. I. Kuz'min, and L. M. Natapov, *Plate Tectonics of the USSR*, 2 Vols. (Nedra, Moscow, 1990) [in Russian].
4. L. P. Zonenshain and M. I. Kuz'min, *Palegeodynamics* (Nauka, Moscow, 1993) [in Russian].
5. A. L. Knipper, "Ophiocalcites and some other breccia types accompanying the pre-orogenic formation of ophiolitic complexes," Geotektonika, No. **2**, 50–65 (1978).
6. V. I. Lebedinskii and I. V. Solov'ev, "Bajocian volcanic structures of the Gorny Crimea," Geol. Zh., No. 4, 85–93 (1988).
7. V. S. Milev, S. B. Rozanov, E. Yu. Baraboshkin, and I. V. Shalimov, "Tectonic structure and evolution of the Gorny Crimea," in *Ocherki geologii Kryma* (Mosk. Gos. Univ., Moscow, 1997), pp. 189–206.
8. Yu. A. Mironov, E. A. El'yanova, Yu. G. Zorina, and E. G. Mirlin, *Volcanism and Formation of Pyrites in Ocean* (Nauchn. mir, Moscow, 1999) [in Russian].
9. A. M. Nikishin, S. N. Bolotov, E. Yu. Baraboshkin, A. V. Ershov, L. F. Kopaevich, B. P. Nazarevich, and D. I. Panov, "Geological history of the Scythian–Black Sea Region," in *Ocherki geologii Kryma* (Mosk. Gos. Univ., Moscow, 1997), pp. 207–227.
10. A. M. Nikishin, A. O. Khotylev, A. Yu. Bychkov, L. F. Kopaevich, E. I. Petrov, and V. O. Yapaskurt, "Cretaceous volcanic Belts and the evolution of the Black Sea basin," Moscow Univ. Geol. Bull. **68**, 141–154 (2013).
11. *Petrography*, Ed. by. A. A. Marakushev (Mosk. Gos. Univ., Moscow, 1981), Vol. 2 [in Russian].
12. J. A. Pearce, S. J. Lippard, and S. Roberts, "Characteristics and tectonic significance of supra–subduction zone ophiolites," in *Marginal Basin Geology*, Vol. 16 of *Geol. Soc. London, Spec. Publ.* (London, 1984), pp. 77–89.
13. M. Yu. Promyslova, L. I. Demina, A. Yu. Bychkov, A. I. Gushchin, and V. V. Tsarev, "The nature of magmatism in the Fiolent Cape area, southwestern Crimea," Moscow Univ. Geol. Bull. **69**, 390–398 (2014).
14. M. Yu. Promyslova, L. I. Demina, A. Yu. Bychkov, V. V. Tsarev, A. I. Gushchin, "Geodynamical formation setting of the ophiolitic association from the Cape Fiolent area, southwestern Crimea," in *Tektonika i geodinamika kontinental'noi i okeanicheskoi litosfery. Materialy XLVII Tektonicheskogo soveshchaniya* (GEOS, Moscow, 2015), pp. 65–70.
15. E. F. Shnyukov, V. A. Ryabenko, and O. G. Sidenko, "The first finding of ultramafites in Crimea," Dokl. Akad. Nauk Ukr. SSR, Ser. B., No. **1**, 18–20 (1979).
16. A. F. Shnyukov, I. B. Shcherbakov, and E. E. Shnyukova, *Paleoarc in the Northern Black Sea* (Nats. Akad. Nauk Ukr., Kiev, 1997) [in Russian].
17. E. E. Shnyukova, "Igneous rocks of Cape Fiolent," in *Petrografiya XXI veka. Materialy X Vserossiiskogo petrograficheskogo soveshchaniya* (KNTs, Apatity, 2005), pp. 289–291.
18. E. E. Shnyukova, Extended Abstract of Doctoral Dissertation in Geology and Mineralogy (Kiev, 2013).
19. V. V. Yudin, "Predgornaya suture of Crimea," Geol. Zh., Nos. **3–4**, 56–61 (1995).
20. V. V. Yudin, "Magmatism of the Crimean–Black Sea Region from the viewpoint of actualistic geodynamics," Miner. Resur. Ukr., No. 3, 18–21 (2003).
21. V. V. Yudin, *Geodynamics of the Black Sea–Caspian Region* (UkrGGRI, Kiev, 2008) [in Russian].
22. V. V. Yudin, *Geological Map and Cross Sections of the Gorny and Predgorny Crimea* (NPTs Soyuzkarta, Simferopol, 2009).
23. V. V. Yudin, *Geodynamics of Crimea* (DIAIPI, Simferopol, 2011).
24. T. N. Irvine and W. R. A. Barager, "A guide to the chemical classification of the common volcanic rocks," Can. J. Earth Sci. **8**, 523–548 (1971).
25. G. A. Jenner, *The Standard of MORB* (St John's, Mem. Univ. Newfoundland, 1990).
26. L. S. Jensen, *A New Cation Plot for Classification of the Common Volcanic Rocks (Miscellaneous Paper 66)* (Ontario Dept. Mines, 1976).
27. R. W. Le Maitre, P. Bateman, A. Dudek, J. Keller, J. Lameyre, M. J. Le Bas, P. A. Sabine, and B. Zanettin, *A Classification of Igneous Rocks and Glossary of Terms* (Blackwell, Oxford, 1989).
28. M. J. M. Meijers, B. Vrouwe, D. J. J. Hinsbergen, K. F. Kuiper, J. Wijbrans, G. R. Davies, R. A. Stephenson, N. Kaymakci, L. Matenco, and A. Saintot, "Jurassic arc volcanism on Crimea (Ukraine): Implications for the paleo-subduction zone configuration of the Black Sea region," Lithos **119**, 412–426 (2010).
29. J. A. Pearce, "Geochemical fingerprinting of oceanic basalts with applications to ophiolite classification and the search for Archean oceanic crust," Lithos **100**, 14–48 (2008).
30. J. A. Pearce and J. R. Cann, "Tectonic setting of basaltic volcanic rocks determined using trace element analysis," Earth Planet. Sci. Lett. **19**, 290–300 (1973).
31. T. H. Pearce, B. E. Gorman, and T. C. Birkett, "The relationships between major element chemistry and tectonic environment of basalt and intermediate volcanic rocks," Earth Planet. Sci. Lett. **36**, 121–132 (1977).
32. S. S. Sun, "Chemical composition and origin of the Earth's primitive mantle," Geochim. Cosmochim. Acta **46**, 179–192 (1982).

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