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Ophiolite association of Cape Fiolent (western part of the Mountainous Crimea) – the upper age constraint according to the U-Pb isotope dating of plagiorhyolites (Monakh Cliff)

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Abstract. The article presents the results of U-Pb isotope dating (SHRIMP-II, VSEGEI, Saint Petersburg) of zircon crystals extracted from plagiorhyolites of the Monakh Cliff in the area of Cape Fiolent in the western part of the Mountainous Crimea (southern suburb of Sevastopol). A concordant age estimate of 168.3±1.3 Ma was obtained from 20 zircon crystals. It exactly corresponds to the Bajocian/Bathonian boundary of the Middle Jurassic according to the International Chronostratigraphic Chart (February 2022 version). The available results of isotope dating of igneous rocks from the Mountainous Crimea, as well as their geochemical typification are synthesised. The plagiorhyolites of the Monakh Cliff in the area of Cape Fiolent are spatially, and most likely paragenetically, associated with the wallrock (Cape Vinogradny) and ore (Heraclea Plateau on the cognominal peninsula) massive sulphide formations, as well as pillow basalts, gabbroids, and serpentinized hyperbasites, combined into the ophiolite association of Cape Fiolent. The obtained dating is the upper age limit for the entire ophiolite association of Cape Fiolent.

Keywords: the Crimea; Cape Fiolent; Jurassic; ophiolites; plagiorhyolites; zircon; U-Pb isotope dating

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Introduction. The western part of the Crimean Mountains is a traditional place for educational geological practices for students of Moscow and Saint Petersburg universities, including Saint Petersburg Mining University. Since the end of the 90s of the XX century, for more than 20 years, for a number of objective reasons, there was a break in conducting these practices for SPMU students. The practices were resumed in 2015. The main practice ground is in the upper reaches of the Belbek River, in the vicinity of Kuibyshevo village (“Kuibyshevo” practice ground). Studying its geological structure, the SPMU geology students get their first experience in compiling geological maps. The sedimentary sequence dominates in this area of the Crimean Mountains. Its total stratigraphic interval covers the range from the Upper Triassic-Lower Jurassic Taurian series, represented by intensely deformed terrigenous-argillaceous flysch, to the Lower Cretaceous-Lower Paleogene argillaceous-carbonate sequence occurring in the form of a gently sloping monocline.

Students can get the ideas about the forms of occurrence, internal structure, and composition of igneous formations exemplified by the distribution area of heterogeneous rocks and igneous formations of Cape Fiolent (“Fiolent” practice ground), which is not far away (only 30-35 km to the west – southwest) from the Kuibyshevo practice ground. However, the geological community has not yet reached a consensus on the interpretation of the geodynamic nature of the igneous and associated rocks known at the Fiolent practice ground, as well as their age relationship with the other known manifestations of the Mesozoic magmatism in the Crimea. For the igneous rocks of the Fiolent practice ground, no modern reliable high-precision U-Pb isotope dating by zircon is known, and they are singular throughout the Crimea. The proposed article presents a brief description of the Fiolent practice ground, substantiating the interpretation of igneous rocks, as well as spatially and, most likely paragenetically associated rocks in this practice ground, as the ophiolite association of Cape Fiolent, as well as the results of U-Pb isotope dating of zircon crystals extracted from plagiorhyolites, which are the youngest igneous formations distributed within the Fiolent practice ground.

Mesozoic magmatism of the Mountainous Crimea. General information. A systematic study of the geological structure in the western part of the Mountainous Crimea (MC) began in the XIX century [1]. The igneous rocks developed in the MC were described and studied for the first time [2, 3]. The establishment in the MC of training grounds for geological practices of such leading geological universities in Russia as M.V.Lomonosov Moscow State University, Saint Petersburg Mining University, Saint Petersburg State University, Russian State Geological Prospecting University, Voronezh State University, etc. contributed to significant intensification of the geological study of the Crimea in the XX century in the post-war period [4-6]. Igneous rocks of Cape Fiolent on the southern coast of the Heraklea Peninsula [7, 8] are obligatory elements in the geological practice for the first-year students of the Moscow State University.

For almost two centuries of studies in the Crimea, a large amount of data obtained by traditional geological methods has been accumulated. At the beginning of the XXI century, review papers appeared, attempting to reconstruct the geological history of the Crimean Peninsula on the basis of a synthesis of all the various information [9-12]. By 2011, the international geological project "Geology Without Limits" was completed, within the framework of which 8872 km of marine deep seismic lines were worked out. The network of lines covered the entire area of the Black Sea. This enables to obtain accurate maps of the basement topography and decipher the architecture of the sedimentary filling of the Black Sea basins [13, 14], as well as to outline correlations between the tectonic structures of the Crimean, Balkan, and Anatolian peninsulas [15-17] in the context of their general geodynamic evolution in the Phanerozoic. The active development of U-Pb zircon dating methods (in the SIMS, SHRIMP, LA-ICP-MS, etc. modifications) led to the fact that in the last decade, highly accurate estimates of the isotope age of Crimean igneous rocks, as well as grain age spectra of detrital zircon from clastic rocks of the Mesozoic sequence of the MC began to appear. The first such data significantly refined the ages of magmatism in the Crimea [18, 19], as well as provided information about the source areas for the sedimentary strata developed in this region [20-22].

Two regions are distinguished in the Crimea: the Steppe Crimea and the MC (Fig.1). The Steppe Crimea is a fragment of the epi-Hercynian Scythian Plate, and the MC is a Cimmerian folded region involved in the Sin-Alpine orogeny. Three orographically different regions are distinctly separated within the MC, usually called the First, Second, and Third Ridges.

Two tectonic stages are distinguished in the geological structure of the MC: the lower (Cimmerian), represented by a folded complex, and the upper (Sin-Alpine), composed of a sedimentary cover. Sedimentary and volcanic-sedimentary formations of the Cimmerian structural complex compose the structures of the base of the monoclinal Sin-Alpine Cretaceous and Paleocene sequence of the MC, visible in the modern erosional truncation.

The Cimmerian structural complex, with exceedingly rare exceptions, is exposed within the First MC Ridge and forms the structural base of the monocline of the Second MC Ridge, composed of the Sin-Alpine structural complex. The Sin-Alpine structural complex consists of monoclinal Cretaceous and Cenozoic sequence. They form the upper elements of the Second MC Ridge and the Third Ridge structure.

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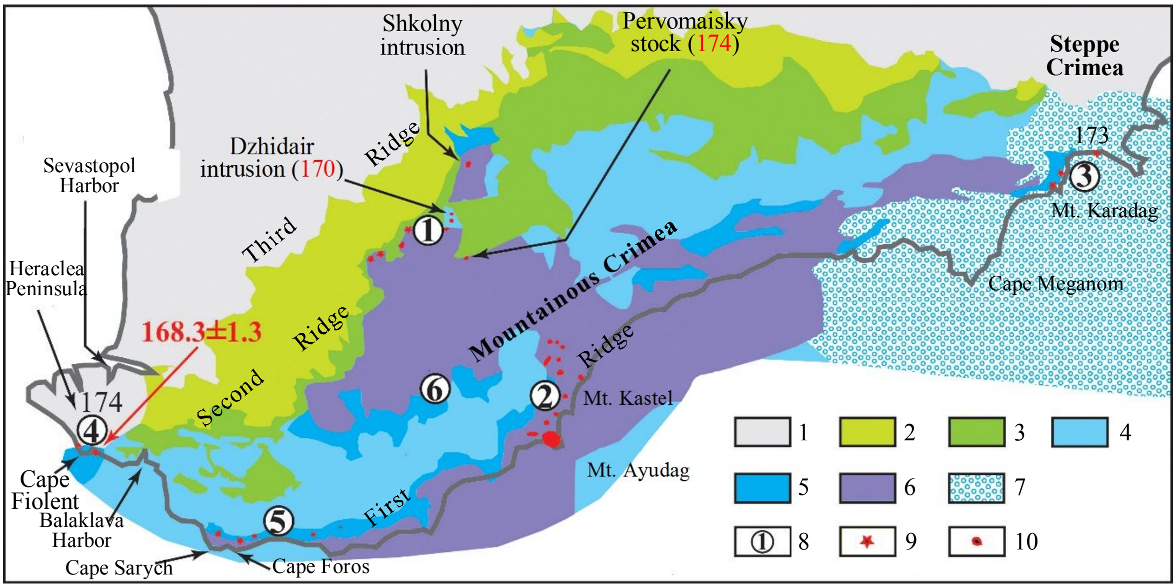

Fig.1. Geotectonic scheme of the Mountainous Crimea according to [13] with simplifications and additions

1-3 – Sin-Alpine structural complex: 1 – Upper Cenozoic sequence of sedimentary terrigenous-argillaceous-carbonate rocks that make up the Third Ridge of the Mountainous Crimea, and the upper section of the Scythian Plate regions, falling within the Steppe Crimea; 2 – Upper Cretaceous and Lower Cenozoic sequence of sedimentary argillaceous-carbonate and carbonate rocks that composes the upper section of the Second Ridge of the Mountainous Crimea; 3 – Lower Cretaceous sequence of sedimentary terrigenous rocks that composes the lower section of the Second Ridge of the Mountainous Crimea; 4-7 – Cimmerian structural complex: 4 – Upper Jurassic (Upper Jurassic-Berriasian) sequence of carbonate, carbonate-clastic, and terrigenous coarse clastic (conglomerates) rocks that composes the summit plateau-like parts of the First Ridge of the Mountainous Crimea; (5) Middle Jurassic sequences of volcanic, volcanic-sedimentary, terrigenous (conglomerates, sandstones) rocks and coal-bearing sequences that composes the slopes of the First Ridge of the Mountainous Crimea; 6 – Upper Triassic-Lower Jurassic flysch sequences – Taurian and Eskiorda series, that composes the structural basement of the First and Second ridges of the Mountainous Crimea; 7 – carbonate-argillaceous-terrigenous sequence covering the Callovian-Neogene stratigraphic interval, developed in the east of the Mountainous Crimea and on the plain on the Kerch Peninsula, as well as on the adjacent part of the Black Sea shelf; 8 – igneous areas; 9 – volcanics; 10 – intrusions. Numbers in circles are areas of (?Late Triassic-) Jurassic magmatism (numbers are modern isotopic dates, Ma, red font colour is U-Pb zircon isotope dating, black font colour is K-Ar or Ar-Ar dating)

An exception is the extreme western (southwestern) section of the Third MC Ridge. Here, in the area of Cape Fiolent (at the Fiolent practice ground), the upper parts of the Sin-Alpine complex are exposed. Its stratigraphic section begins with a gently dipping terrigenous-argillaceous-carbonate sequence of the Sarmatian (Middle Miocene) regional stage of the Peri-Thetic Region [23], corresponding to the upper parts of the Serrovalian and Tartonian stages [24]. This sequence, with a pronounced structural unconformity, overlies weathered and deeply eroded heterogeneous igneous formations, usually attributed to the Middle Jurassic [18] and combined [25-29] into the ophiolite association of Cape Fiolent.

Folded complex of the lower (Cimmerian) structural stage of the MC is represented by unevenly dislocated sequences of sedimentary, less often volcanic-sedimentary and volcanic rocks, attributed to the stratigraphic interval from the Upper Triassic to the Upper Jurassic, and possibly the lower Lower Cretaceous. This complex hosts intrusive mafic and granitoid bodies and underwent several stages of deformation, during which various folded and overthrust structures were formed.

In the MC, igneous occurrences associated with the Cimmerian folded complex are grouped in at least six areas: Bodrak-Pervomaisky, Ayudag-Kastel, Karadag, Fiolent-Heraclea, Sarych-Foros-Oliva, Upper Kacha ones (Fig.1). Until recently, the age of magmatites in the MC was substantiated mainly by field (including, in some cases, biostratigraphic) methods and very unreliable geochronological data (results of K-Ar or Ar-Ar isotope dating). [30] presents the results of $^{40}Ar/^{39}Ar$ isotope dating of 10 samples and geochemical study of 31 magmatite samples from the MC. A significant part of the studied samples was classified as rocks of low silica acidity (andesites, diorites, basalts) and high alkalinity, and the CUKR3 sample from the Pervomaisky stock (Fig.1) was classified as alkali-syenite-monzonite. The obtained dates were statistically divided into two groups. Magmatites of the Karadag area showed slightly younger ages (142-151 Ma) than those of the Bodrak-Pervomaisky area (158-172 Ma). The age (144-180 Ma) of a single sample (CUKR3) from the Pervomaisky stock (the Bodrak-Pervomaisky area) showed an exceptionally large analytical error.

In recent years, high-precision geochronological data have appeared, a brief summary of which for igneous areas is given below.

1. The Middle Jurassic sequence of volcanic-sedimentary rocks, common in the vicinity of Trudolyubovka village, and small bodies of gabbroids, diabases, gabbro-diabases, dolerites, gabbro-diorites, and micro-diorites, spatially concentrating to the fields where the rocks of this sequence are developed, including the Pervomaisky stock and the Dzhidair intrusion (the Bodrak-Pervomaisky igneous area). The age (SHRIMP-II, U-Pb zircon isotope dating) of gabbro-dolerites from the Dzhidair intrusion based on nine zircon crystals was 169.7±1.5 Ma; dolerites from the Pervomaisky stock based on 16 zircon crystals – 174.2±1.2 Ma; porphyritic leucocratic basalts from a sill-like body to the east of Trudolyubovka, according to five zircon crystals – 144.2±2.0 Ma; basaltoids for two more bodies (according to two and one zircon crystals) – 136 and 125 Ma [31].

2. The massifs of gabbroids and granitoids that composes the Ayudag and Kastel mountains, and the smaller intrusive bodies associated with them (the Ayudag-Kastel igneous area), according to regional geological data, are usually considered to be Bathonian-Bajocian [6, etc.]. Geochronological age estimates of igneous rocks from this area are still constrained only by indirect data, i.e., the study of single zircon grains isolated from conglomerates of the lower sequence of the Upper Jurassic Demerdzhi Fm. of Mt. South Demerdzhi using the fission track method (ZrFT) [32]. According to the authors of this work, the studied zircon grains originated from the granitoids of Mt. Kastel, and the age of magmatism in the Ayudag-Kastel area is not younger than 150 Ma.

3. Basalts, andesites, and dacites composing a part of the Karadag mountain range are the volcanic structures of Khoba-Tepe and Svyataya Gora (Karadag igneous area). The Ar-Ar isotopic age of 172.8±4.5 Ma was recently obtained for the Karadag volcanic rocks [33].

4. Apoperidotite serpentinites, gabbroids, basalts, dolerites, and plagiorhyolites exposed in coastal rocks in the area of Cape Fiolent [25-29] and, moreover, penetrated by boreholes on the Heraclea Plateau [18] (Fiolent-Heraclea igneous area). Attempts to obtain the U-Pb isotopic age from three zircon crystals from a dolerite dike in the centre of the exposed part of the Fiolent-Heraclea area using SHRIMP-II gave estimates of 1771±28 Ma [18]. This value was interpreted either as the age of the mantle substrate from which basic magmas were melted, or as the age of zircon from the Precambrian rocks captured during the magma movement to the surface. The age of plagiorhyolite was determined by the K-Ar method at 174 Ma.

5. Dolerites, andesibasaltic porphyrites, and dacites, which compose subvolcanic bodies, hypabyssal stocks and sills, spatially and, apparently, paragenetically associated with the Middle Jurassic tuff-sedimentary sequence, common in the western part of the southern coast of Crimea, in the band from Tesseli's dacha in the west, through the Foros area to Oliva village (former Mukhalatka), in the east, Sarych-Foros-Oliva igneous area. Evidently, the igneous formations found at the Black Sea bottom 44 km south of Balaklava Bay (Foros uplift) should also be attributed to this area (an off-shore part). During the expeditions of the PV "Professor Vodyanitsky" and "Vladimir Parshin" scientific ships, dacites were dredged from the Foros uplift from depths of 1240, 1606, and 1757 m, for which the K-Ar isotopic age of ~197 Ma was obtained [18]. There are no direct geochronological estimates of the age of igneous rocks within the onshore Sarych-Foros-Oliva area. Igneous formations in the western part of the southern coast of Crimea, including igneous rock bodies in the western part of the southern slope of the First MC Ridge in the areas of the villages of Oliva, Mellas, Foros, were described as early as the second half of the XIX century [1-3, etc.]. In fact, it is generally accepted to consider them as Middle Jurassic in age [4, 5]. However, in recent years, information has appeared requiring serious verification about the discovery of paleontological remains in the rocks hosting

these bodies in the Tesseli dacha area, indicating that the igneous rocks of the Tesseli complex cannot be younger than the Late Triassic [34, 35].

6. Igneous rocks occurring among sedimentary rocks classified as the Taurian series, penetrated by drilling at several intervals with a vertical thickness of 50 to 150 m in the central part of the Kacha uplift, the Upper Kacha igneous area. General information about these igneous rocks with references to the results of large-scale geological surveys by V.I.Ivanov and B.I.Tchaikovsky is given in [34, 35]. In the same papers, an assumption was made about the Late Triassic age of these igneous formations.

Thus, by the time this article was written, reliable U-Pb dates based on syngenetic accessory zircon were known only for two MC sites, the Pervomaisky stock and the Dzhidair intrusion.

Fiolent-Heraclea igneous area. Igneous formations of the Fiolent-Heraclea area are known in the literature as: 1) heterogeneous and diverse (from rhyolites to mafic rocks) igneous formations that compose the so-called Heraclean volcano-tectonic structure [36]; 2) ophiolite association of Cape Fiolent or ophiolites of the Heraclea Peninsula [25-29]. These formations are exposed in steep (reaching a height of 200 m to the east of Cape Fiolent) coastal cliffs of the southern part of the Heraclea Peninsula (Fig.2), as well as penetrated by boreholes drilled on the Heraclea Plateau on the cognominal peninsula [36]. The igneous rocks of this area with a structural unconformity at the base are stratigraphically overlain by the Sarmatian regional stage (Fig.3).

The field of igneous rocks distribution in this area is limited in the east by the Georgievsky fault. The northern and western boundaries of the area are hidden under the gently sloping sequence of the Sarmatian regional stage, which armours the Heraclea Plateau. Igneous formations of the Fiolent-Heraclea area, together with the edaphogenic breccias and jasperoids occurring among them, are combined into an ophiolite association. The rocks of this association are spatially, and most likely paragenetically associated with pyrite mineralization [36]. There is a point of view according to which the distribution field of rocks of the ophiolite association developed within the Fiolent-Heraclea area is one of the westernmost elements of the Predgornaya Collision Suture[1] structure [9, 12].

As for the age and understanding of the geodynamic nature of the igneous formations in the Fiolent-Heraclea area, as well as other igneous areas of the MC, there is still no consensus. The main reason is the insufficient degree of geological knowledge of the areas of igneous formations development in the MC, as well as virtually complete absence of modern highly reliable and accurate geochronological datings of igneous rocks in the MC. This fully applies to the igneous rocks of the Fiolent-Heraclea area.

In early works, a massif of heterogeneous and diverse igneous rocks exposed in the area of Cape Fiolent was interpreted as a shield volcano, the base of which is the Upper Triassic-Lower Jurassic Taurian series deposits [8]. The igneous formations composing it were compared with the igneous rocks of Mt. Karadag, located in the east of the MC [5]. Based on these correlations, the age of the igneous formations in the Fiolent-Heraclea area was determined as Middle Jurassic (Bajocian).

In the works by V.V.Yudin, for example [9], the area of igneous formations distribution in the Fiolent-Heraclea area was interpreted as a melange zone, consisting of chaotical rootless blocks of igneous material. In the work by E.E.Shnyukova [18], the part of the field of igneous formations distribution in the Fiolent-Heraclea area exposed in the coastal band is divided into a series of areas, within which igneous rocks were formed during separate stages of magmatic activity. The works [25-29] developed ideas according to which the igneous formations of the Fiolent-Heraclea area, together with associated rocks, form an ophiolite association.

[1] The Jurassic-Early Cretaceous Predgornaya collisional suture in the Crimea was identified by V.V.Yudin [9]. The reason for this was the "traces" of the ophiolite association, serpentinized ultramafic rocks found in the core of a borehole drilled 15 km northeast of Simferopol [12]. According to V.V.Yudin, Predgornaya collisional suture is a fragment (part) of the "Mesotethys paleoocean suture".

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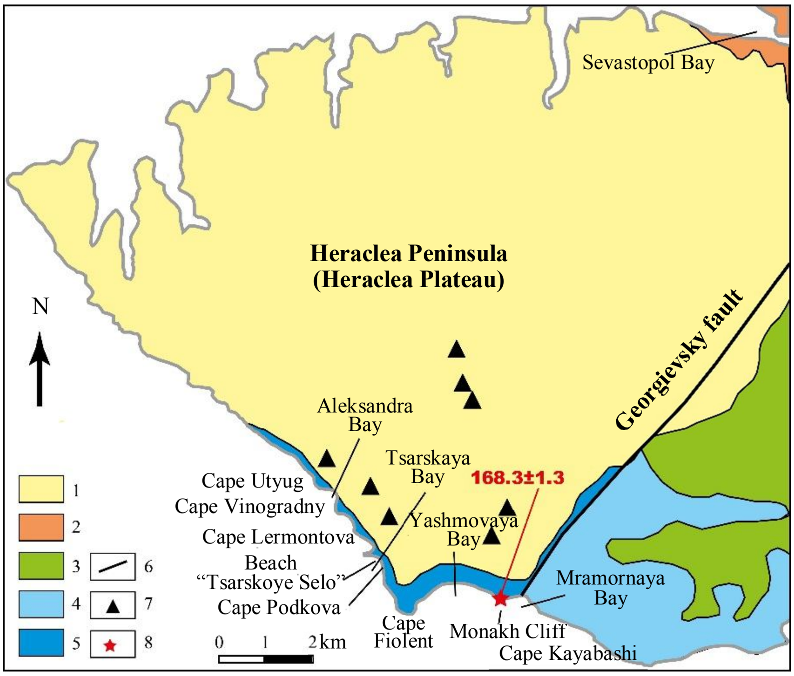

Fig.2. Scheme of the geological structure of the Heraclea Peninsula. Compiled on the basis of the medium-scale State Geological Map L-36-XXXIV, XXXV, 1965 (author I.V.Arkhipov, editor M.V.Muratov)

1 - terrigenous-argillaceous-carbonate sequence of the Sarmatian (Middle Miocene) regional stage; 2 – terrigenous-argillaceous-carbonate sequence of the Paleogene; 3 – carbonate-terrigenous and tuffaceous-argillaceous sequences of the Cretaceous; 4 – carbonate and argillaceous-terrigenous sequence of the Upper Jurassic; 5 – Middle Jurassic igneous formations of the Fiolent-Heraclea area; 6 – Georgievsky fault; 7 – boreholes [36]; 8 – sampling site of K20-088 from plagiorhyolites of the Monakh Cliff; red numbers – dating of plagiorhyolites of the Monakh Cliff, Ma

General information about the internal structure of the exposed part of the Fiolent-Heraclea igneous area. In the west of the part of the field of igneous formations distribution in the Fiolent-Heraclea area exposed in the coastal cliffs of Cape Fiolent, plutonic rocks are predominantly developed, gabbroids of several structural, textural, and material types (Aleksandra Bay with the apex at the point N44°31'19.3", E33°28 '06.6"; Cape Krokodil – N44°31'12.6", E33°28'04.0"; Cape Lermontova – N44°30'35.2", E33°28'41.3"), hosting rare small plate-like bodies of serpentinized hyperbasites: wehrlites, lherzolites, and dunites with relics of cumulative structures (a bridge connecting the rocky shore with Cape Utyug, N44°31'21.7", E33°27'59.3") and dolerite dikes. In the same area (Cape Vinogradny – N44°31'03.9", E33°28'09.2"), the arched (domed) part of a subvolcanic body of intensely fluid limonitized rhyolites bearing scattered disseminated sulphide mineralization is exposed.

On the right, northwestern side of Tsarskaya Bay, at the point with coordinates N44°30'35.4", E33°28'50.2", one can clearly see how the gabbroids along the tectonic contact (apparently, along a normal fault) flank with the gently sloping sequence of pillow basalts (Fig.4, *a*). Pillow basalts are exposed in the sides of this bay above the “Tsarskoye Selo” beach and on the rocky Cape Podkova (Fig.4, *b, c, d*). The space between individual pillows is often filled with carbonatized green hyaloclastites.

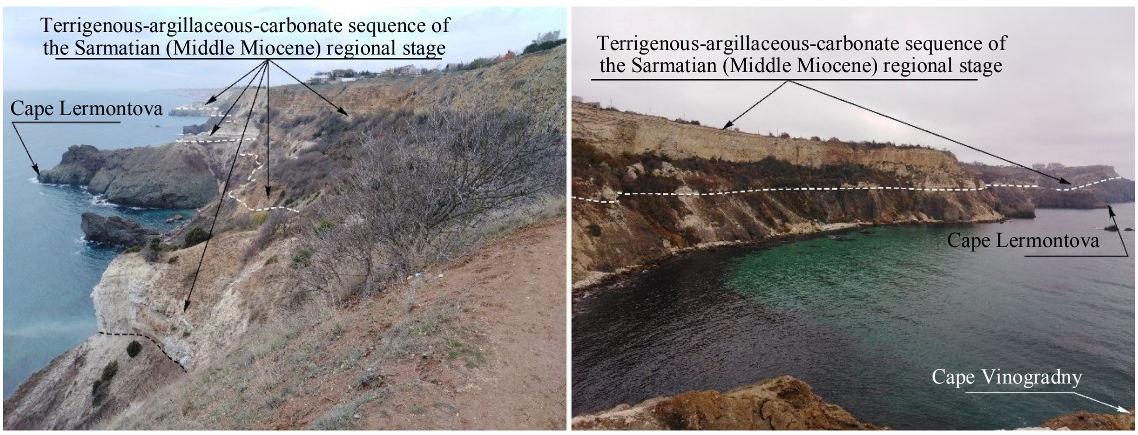

Fig.3. General view of outcrops of the Middle Jurassic igneous formations in the Fiolent-Heraclea area (dark tone, closer to the water edge), which form the basement of a high marine terrace in the area of Cape Fiolent, and the sequence of the Sarmatian regional stage that overlaps them (light tone)

In the apex and on the eastern side of Tsarskaya Bay in the beach surf zone, there are extensive flat rocky outcrops (exposures) of variegated edaphogenic breccias (Fig.4, *e*). Here, at many points (for example, at points with coordinates N44°30'32.3", E33°28'51.1" and N44°30'30.5", E33°28'56.5"), the lower gentle contact of the pillow basalt sequence with their underlying variegated edaphogenic breccias is clearly visible (Fig.4, *f*). In this site, as well as in the west of the Fiolent-Heraclea area, dolerite dikes are noted, which cross the pillow lava sequence.

In the east of the Fiolent-Heraclea area, a series of closely spaced subvolcanic bodies is clearly distinguished: extrusive domes and stocks composed of light plagiorhyolites, forming the Monakh and Georgievsky cliffs, as well as the rocky islands of Iphigenia, Orest, and Pilat. At the base of the Miocene terrigenous-argillaceous-carbonate sequence overlying here plagiorhyolites with a distinct unconformity, in the zone of the pre-Miocene hypergene development, plagiorhyolites are transformed

Fig.4. Coastal rock outcrops of the ophiolite association, located in the coastal band to the northwest of Cape Fiolent:

a – tectonic contact (probably a normal fault, shown by the white dotted line), along which the gabbroids that make up Cape Lermontov flank with a gently sloping sequence of pillow basalts; *b, c, d* – pillow basalts in the sides of Tsarskaya Bay above “Tsarskoye Selo” beach; *e* – variegated edaphogenic breccias in the apex of Tsarskaya Bay; *f* – gentle onlap of pillow basalts (brown tone) on variegated edaphogenic breccias (green tone) at Cape Podkova

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into light porcelaineous rocks with relics of isometric grains of high-temperature quartz. Along the periphery of extrusive domes and stocks, plagiorhytholites show automagmatic (?) brec-ciation, while the central parts of plagiorhyolite bodies are characterized by distinct columnar jointing (Fig.5). This is especially clearly seen exemplified by the Monakh Cliff (N44°30'13.6", E33°30'18.7"), which limits Yashmovaya Bay from the west.

In [27, 28] present some material (petrographic, petro- and geochemical) characteristics of plagiorhyolites from the Fiolent-Heraclea area. Plagiorhyolites are indistinctly porphyritic light greenish-grey rocks. Porphyry segregations to 1.5-2.0 mm in size are represented by tabular felsic plagioclase and isometric quartz crystals embedded in a cryptocrystalline quartz-plagioclase groundmass. Plagiorhyolites are obviously the youngest igneous formations in this area. Their age is the upper age limit of all igneous rocks developed here.

Rhyolites of the Monakh Cliff. Chemical and geochronological characteristics. The petrochemical and geochemical characteristics of the plagiorhyolites[2] under consideration make it possible to attribute these rocks to low- or moderate-potassium silicic rocks of the calc-alkaline series with a flat distribution spectrum of rare-earth elements and a quite distinct negative europium anomaly [27, 28]. The content of Zr and Hf in plagiorhyolites is quite typical for the composition of upper crustal rocks. Such contents of Zr and Hf in the rocks and, in particular, in the plagiorhyoliths of the Monakh Cliff, mean that zircon can be present in significant amounts in these rocks.

Fig.5. Plagiorhyolite outcrops on the right side of Yashmovaya Bay. Top left – in the background is a general view of Monakh Cliff. The rest of the photographs are details of the plagiorhyolites structure in the lower part of the Monakh Cliff

[2] Silicate analysis data for sample K20-088, from which zircon grains were extracted. The content of the main petrogenic components, %: SiO_2 70.86; TiO_2 0.20; Al_2O_3 14.43; Fe_2O_3 2.13; FeO 0.46; MnO 0.06; MgO 2.04; CaO 0.60; Na_2O 5.38; K_2O 1.46; P_2O_5 0.05; LoI 2.28; the sum is 99.94. The results were obtained by the X-ray fluorescence method at the LCPI, Common Use Centre, GIN RAS, Moscow.

To extract zircon from the Monakh Cliff plagiorhyolites, we took sample K20-088 weighing about 5 kg (at the point with coordinates N44°30'14.5", E33°30'21.0") in 2020. About 200 zircon crystals were extracted from this sample in a specialized laboratory of the GIN RAS using the standard method (grinding, washing, separation in bromoform, magnetic separation, isolation of the zircon monofraction manually under a binocular).

The isolated crystals of accessory zircon are characterized by distinct crystallographic outlines typical of igneous zircon. Zircon is light, transparent with a barely noticeable yellowish tint. The crystal sizes vary from 50 to 200 μm. In some zircon crystals, mineral inclusions are visible, as well as inclusions and voids of an incomprehensible nature. For U-Pb isotope dating, 50 zircon grains most suitable for this purpose were selected. They were transferred to VSEGEI Centre of Isotopic Research (St. Petersburg), where they were implanted in an epoxy disk and polished. After photographing in transmitted light (with parallel and crossed nicols) and in cathode rays, areas of at least 20 μm were outlined in images in 20 grains, devoid of visible inclusions, cracks, metamict zones, and other deformations (Fig.6).

U-Pb isotope dating was conducted at the VSEGEI Centre of Isotopic Research using SHRIMP-II according to the standard method (description of the method: http://www.vsegei. com/ru/activity/labanalytics/cir/cirpribor/index.php). The results of 20 U-Pb isotopic analyses performed are shown in the Table. Based on them, a weighted average concordant dating was obtained, 168.3±1.3 (2σ) Ma,

Fig.6. Montage of cathode luminescent (CL) and optical images of 20 studied zircon crystals from plagiorhyolites of the Monakh Cliff, Cape Fiolent. For each image, its number is indicated in black in the upper left corner. The position of the crater (circle, diameter 20 μm) and the obtained age estimates (Ma) with a measurement error of 1σ are shown in red

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Results of U-Pb isotope analysis of zircon crystals extracted from sample K20-088 taken from plagiorhyolites of Monakh Cliff (Cape Fiolent, west of the MC)

Analysis points	$^{206}Pb_c$, %	U, g/t	Th, g/t	$^{232}Th/^{238}U$, g/t	$^{206}Pb^*$, g/t	$^{206}Pb/^{238}U$, age±1σ, Ma		$^{207}Pb/^{235}U$, age±1σ, Ma		Tot. $^{238}U/^{206}Pb$±1σ,%		Tot. $^{207}Pb/^{206}Pb$ ±1σ, %		$^{238}U/^{206}Pb^*$±1σ, %		$^{207}Pb^*/^{206}Pb^*$±1σ, %		$^{207}Pb^*/^{235}U$±1σ, %		$^{206}Pb^*/^{238}U$ ±1σ, %		EC
1.1	0.70	158	143	0.93	3.52	163.9	±2.7	163.1	±2.7	38.57	1.6	0.0584	5.8	38.84	1.7	0.0528	9.0	0.1880	9.1	0.02574	1.7	0.182
2.1	0.92	54	28	0.53	1.26	170.0	±4.2	168.1	±4.3	37.09	2.4	0.0662	12.0	37.43	2.5	0.0587	16.0	0.2160	16.0	0.02671	2.5	0.155
3.1	0.47	109	57	0.54	2.5	169.7	±3.1	169	±3.1	37.31	1.8	0.0566	5.2	37.48	1.9	0.0529	7.1	0.1940	7.4	0.02668	1.9	0.252
4.1	0.38	174	144	0.85	3.98	168.4	±2.7	168.4	±2.7	37.63	1.6	0.0527	4.2	37.77	1.6	0.0497	6.2	0.1810	6.4	0.02647	1.6	0.249
5.1	0.47	218	175	0.83	5.11	173.1	±2.5	173	±2.5	36.57	1.4	0.0537	3.7	36.75	1.5	0.0499	5.5	0.1870	5.7	0.02721	1.5	0.256
6.1	0.63	178	160	0.93	3.99	165.3	±2.6	165.2	±2.6	38.25	1.5	0.0549	4.3	38.49	1.6	0.0499	7.5	0.1790	7.7	0.02598	1.6	0.207
7.1	1.01	47	23	0.51	1.14	176.7	±5.1	175.4	±5.0	35.60	2.8	0.0639	7.0	36.00	2.9	0.0558	12.0	0.2140	13.0	0.0278	2.9	0.231
8.1	0.28	249	242	1.00	5.62	166.6	±2.3	166.3	±2.4	38.09	1.4	0.0529	3.6	38.20	1.4	0.0507	4.8	0.1830	5.1	0.02618	1.4	0.282
9.1	0.50	218	205	0.97	4.92	166.2	±2.4	165.7	±2.4	38.10	1.4	0.0556	5.1	38.29	1.5	0.0516	7.1	0.1860	7.3	0.02611	1.5	0.203
10.1	0.50	98	57	0.60	2.28	170.7	±3.2	169.9	±3.2	37.07	1.9	0.0574	5.3	37.26	1.9	0.0533	7.4	0.1970	7.6	0.02684	1.9	0.248
11.1	0.65	171	129	0.78	3.92	168.6	±2.7	168.2	±2.6	37.49	1.6	0.0568	4.0	37.74	1.6	0.0516	7.3	0.1890	7.5	0.0265	1.6	0.214
12.1	0.77	135	96	0.73	3.16	172.0	±3.2	172.7	±3.2	36.69	1.8	0.0526	4.6	36.98	1.9	0.0465	9.3	0.1730	9.5	0.02704	1.9	0.198
13.1	1.09	96	55	0.59	2.25	171.6	±3.4	170.2	±3.5	36.66	1.9	0.0651	10	37.07	2.0	0.0563	14.0	0.2090	14.0	0.02698	2.0	0.142
14.1	1.05	101	85	0.87	2.24	163.2	±3.5	162.8	±3.5	38.60	2.1	0.0596	9.1	39.01	2.2	0.0512	14.0	0.1810	14.0	0.02563	2.2	0.149
15.1	0.53	66	32	0.49	1.52	169.2	±3.7	168.6	±3.8	37.40	2.2	0.0567	8.1	37.60	2.2	0.0524	10.0	0.1920	10.0	0.02659	2.2	0.215
16.1	0.33	305	264	0.89	7.01	169.7	±2.2	169.9	±2.2	37.36	1.3	0.0514	3.1	37.48	1.3	0.0488	4.2	0.1793	4.4	0.02668	1.3	0.298
17.1	0.35	596	670	1.16	13.3	165.3	±1.9	165.3	±1.9	38.37	1.1	0.0521	2.3	38.50	1.1	0.0494	3.2	0.1768	3.4	0.02597	1.1	0.337
18.1	0.53	95	51	0.55	2.21	171.0	±3.2	170.7	±3.3	37.00	1.9	0.0554	6.1	37.20	1.9	0.0512	8.4	0.1900	8.6	0.02688	1.9	0.224
19.1	0.60	86	43	0.52	1.93	165.1	±3.3	164	±3.3	38.31	2 .0	0.0596	5.6	38.54	2.0	0.0548	8.2	0.1960	8.5	0.02595	2.0	0.240
20.1	0.31	169	117	0.71	3.91	170.4	±2.6	169.9	±2.7	37.22	1.6	0.0544	4.2	37.34	1.6	0.0519	5.3	0.1920	5.5	0.02678	1.6	0.284

Note. Measurement error 1σ; Pbc and Pb* are the contents of total and radiogenic lead, respectively; standard calibration error 0.33%; correction for total lead is based on measured ^{204}Pb contents, $EC = \left(^{207}Pb^*/^{235}U\right)/\left(1\sigma_{(^{207}Pb^*/^{235}U)}\right) \;/\; \left(^{206}Pb^*/^{238}U\right)/\left(1\sigma_{(^{206}Pb^*/^{238}U)}\right)$.

with a probability of 0.12 and MSWD of 2.4 (Fig.7). This age estimate of the plagiorhyolites of Monakh Cliff exactly corresponds to the Bajocian/Bathonian boundary of the Middle Jurassic according to the International Chronostratigraphic Chart (February 2022 version [24]) and can be taken as the upper age boundary of all igneous formations of the ophiolite association on Cape Fiolent.

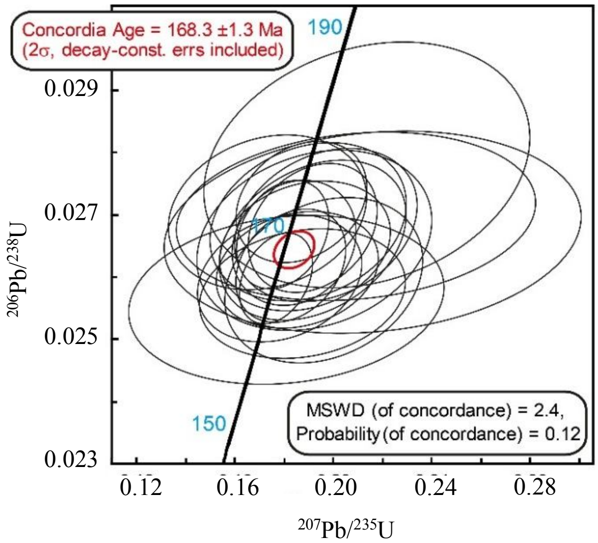

Fig.7. Diagram with concordia of U-Pb datings of studied zircon grains from plagiorhyolites of the Monakh Cliff, Cape Fiolent. Concordant value – red ellipse

Discussion. The obtained new U-Pb isotopic (SHRIMP-II) concordant age estimate of 168.3±1.3 Ma for the Monakh Cliff rhyolites in the vicinity of Cape Fiolent is currently the most methodologically and metrologically reliable geochronological dating of Crimean igneous formations. The accumulation of new high-precision datings substantially refines, and in some cases even casts doubt on the reliability of most of the previously obtained K-Ar and Ar-Ar datings of the MC igneous rocks. Thus, the Ar-Ar isotope age of 172.8±4.5 Ma was recently obtained for the Karadag volcanics [33] and, thus, the results of dating the igneous rocks of the Karadag area, pre-viously performed by the same method [30] and giving younger ages (142-151 Ma) were not confirmed. Thus, at present, there are no reliable geochronological data substantiating a long interval of magma manifestations or the existence of various stages of magmatic activity in the MC. The available reliable geochronological data, together with our new dating, indicate a narrow time interval of the simultaneous manifestation of non-suprasubduction magmatic activity in the MC in the interval of 175-168 Ma. Together with other data, this magmatic activity can be interpreted as an indicator of the opening of a single Crimea-Western Caucasus Aalenian-Bajosian back-arc basin.

Conclusion. The paper presents the results of U-Pb isotope dating (SHRIMP-II, VSEGEI, Saint Petersburg) of zircon crystals from plagiorhyolites of the Monakh Cliff in the area of Cape Fiolent in the west of the MC. A concordant age estimate of 168.3±1.3 Ma was obtained, which exactly corresponds to the Bajocian/Bathonian boundary of the Middle Jurassic. The new data allow us to draw the following conclusions.

1. The new U-Pb isotopic age estimate of the Monakh Cliff rhyolites is currently the most methodologically and metrologically reliable geochronological dating of Crimean igneous formations.

2. The plagiorhyolites of Cape Fiolent are spatially, and most likely paragenetically associated with ore and wallrock pyrite formations, as well as rocks that are combined into the ophiolite association of Cape Fiolent. The dating obtained is the upper age constraint for the entire ophiolite association at Cape Fiolent.

3. The accumulated new high-precision U-Pb isotope datings of the MC igneous rocks significantly refine, and in some cases even cast doubt on the reliability of most previously obtained K-Ar and Ar-Ar datings of the MC igneous rocks.

4. New reliable dates of igneous rocks from the MC indicate the manifestation of magmatism in the Aalenian-Bajocian (175-168 Ma) throughout the MC.

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