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New Paleomagnetic Data of the Middle Jurassic Igneous Complex in the Bodrak River Valley, Mountainous Crimea

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Abstract—In this paper, the results of paleomagnetic studies for the Middle Jurassic subvolcanic bodies and volcanogenic–sedimentary rocks that are exposed in the Bodrak River valley within the limits of the second range of the Crimean Mountains are presented. Detailed magnetic cleanings showed the applicability of most of the sampled objects for paleomagnetic studies. The natural remanent magnetization of the examined sample is usually the sum of two components; the most stable of them possesses a bipolar distribution, indicating its primary character. The similarity between the paleomagnetic directions of subvolcanic bodies and nearly coeval volcanogenic–sedimentary rocks, which occur at angles of about 60°, suggests the disturbed occurrence of the igneous bodies. These results can be used for further detailed paleomagnetic studies of the Middle Jurassic igneous complexes in Mountainous Crimea for paleomagnetic reconstruction and the solution of local geological and structural geological problems.

Keywords: paleomagnetism, Middle Jurassic, Mountainous Crimea, Bodrak subvolcanic complex
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INTRODUCTION

Paleomagnetic studies of igneous and sedimentary complexes in Mountainous Crimea have been carried out for more than 40 years; however, a review of the literature indicates that the use of paleomagnetic data for paleotectonic reconstructions and solution of local structural geological problems is complicated. In the case of Middle Jurassic objects, this is related to the low reliability of the published data due to, in particular, the absence of a clearly developed scheme of paleomagnetic studies within such a complex geological object as the Crimean Peninsula. The most widespread and representative paleomagnetic studies of primarily Jurassic rocks were carried out by D.M. Pechersky et al. (Pechersky et al., 1991; Pechersky and Safonov, 1993) in 1986–1991. However, these works dealt with objects that are located mostly along the southern coast of Crimea and not in the internal areas.

In contrast, there are widespread manifestations of multiphase intrusive magmatism, viz., dikes, sills, and boss-shaped bodies of average and basic igneous rocks, within the limits of the second range of the Crimean Mountains (Spiridonov, Fedorov, and Ryakhovskii, 1990a). Paleomagnetic studies of these objects are sparse (Yudin, 2007; Meijers, 2010); however, the valid paleomagnetic data on them are important for the development of new and testing of the existing tectonic evolutionary models for the Crimean Peninsula, and for solving a series of structural geology problems. The $^{40}Ar/^{39}Ar$ (Meijers, 2010) and U–Pb (Morozova, Sergeev, and Sufiev, 2012) isotope datings that were obtained recently for the igneous bodies in the Bodrak River valley indicate their almost coeval age (Bajocian), making them objects that should be primarily studied by modern paleomagnetic methods. It is expected that the study results can be used to derive a valid paleomagnetic (Middle Jurassic) pole for Crimea.

In the present work, the results of field paleomagnetic reconnaissance for the Middle Jurassic sedimentary and igneous rocks that are exposed within the limits of the second range of the Crimea Mountains (Kacha Uplift) are presented. The main aim of the work was to assess the prospects of the studied objects for detailed paleomagnetic studies.

STUDY AREA AND OBJECTS

The studied objects are located within the Kacha Uplift, in SW Mountainous Crimea, which covers the basins of the upper streams of the Belbek, Kacha, Bodrak, and Alma rivers and those of the left tributaries of the Salgir River (*Geologicheskoe* ..., 1989). We studied the subvolcanic bodies and volcanogenic–sedimentary rocks of Middle Jurassic (Bajocian) age (Lebedinskii and Shalimov, 1967), which are exposed in the middle stream of the Bodrak River, in the vicinities of the villages of Trudolyubovka and Prokhlad-

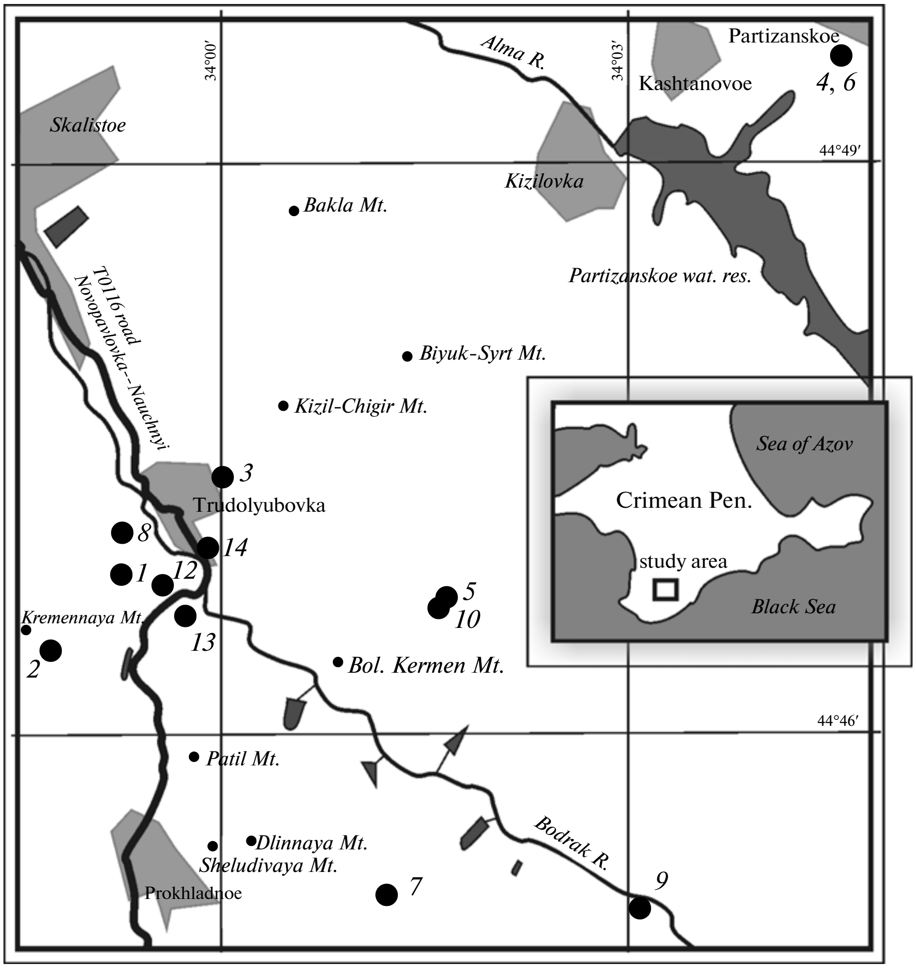


Fig. 1. Study area location within the Crimea Peninsula (rectangle) and positions of the studied objects (points).

noe. Most of the studied objects are located within the research area, where annual geological practices are carried out for students from geological faculties of Moscow State University, St. Petersburg State University, Moscow Academy for Mining and Geology, and other organizations.

The positions of the studied objects are shown in Fig. 1 and described in the table.

Middle Jurassic volcanogenic–sedimentary rocks belong to the Bodrak Formation of the Karadag Group, which correspond to the Bajocian stage with a sharp angular unconformity (Bagdasaryan and Lebedinskii, 1967). The formation superimposes the double-fold flysch deposits of the Tauric Group (or its facies analog, the Eski-Orda Formation of the Upper Triassic–Lower Jurassic). The Bodrak Formation comprises three members (Fedorchuk and Glukhov, 1980); we sampled the rocks from the middle member, which is composed of greenish-gray tuffaceous sandstones and tuffaceous siltstones, which are available for direct investigation at the "Baiosskii tsirk" site (hereinafter "Bajocian cirque") outcrop located in left bank of Bodrak River valley, near the village of Trudolyubovka. Tuffaceous sandstones of Bodrak Formation at this outcrop are obliquely bedding: the dip azimuth is NW (330°) and the dip angle is 60° (on average in both cases).

Intrusive bodies in the Bodrak River valley refer to the Bodrak subvolcanic complex, which formed in several phases of magmatic activity (Spiridonov, Fedorov, and Ryakhovskii, 1990b). The studied (subvolcanic) intrusive bodies pierce the deposits of the Tauric Group (Eski-Orda Formation), but they are absent in the upperlying Lower Cretaceous rocks. Intrusive bodies are represented by small andesibasaltic and basaltic (dolerite) dikes, bosses, and sills (Fedorchuk and Glukhov, 1980). In the Pervomaiskii open pit, which is located on the right side of the Bodrak River valley, a large intrusive body of microdiorites, presumably of laccolite shape (Fedorchuk and Glukhov, 1980), was studied. As was reported in (Spiridonov, Fedorov, and Ryakhovskii, 1990a), metamorphization of the volcanic rocks in the Karadag subvolcanic complex commonly corresponds to zeolite facies (this term is obsolete now), which cor-

Paleomagnetic directions and the paleomagnetic pole

No.	Objects (samples nos.)	Slat	Slong	Paleomagnetic directions (geographic/stratigraphic coordinate system)				
				n/*N* (S)	*D*°	*I*°	*K*	α95
1	Koronovsky sill (1–16)	44°46.858′	33°59.238′	16/15	213.8	–70.8	101	3.8
					168.3	–20.3		
2	Boss (old mine in Shara gully) (17–28)	44°46.447′	33°58.720′	12/10	35.8	59.4	23	10.3
					358.7	14.5		
3	Dike, 500 m north of Trudolyubovka stop (41–52)	44°47.472′	34°00.020′	12/10	48.3	69.9	36	8.2
					351.6	24.2		
4	Shkol'nyi open pit (i1–i8)	44°49.735′	34°04.528′	8/7	358.6	69.9	20	14
					339.7	12.0		
5	Pervomaiskii open pit* (p21–p32)	44°46.777′	34°01.651′	12/11	111.6	68.8	30	8.5
					348.6	45.4		
6	Shkol'nyi open pit* (vl–v8)	44°49.735′	34°04.528′	8/5	300.2	51.1	46	11.4
					311.8	–4.7		
7	Dike, left side of Bodrak River valley (107–116)	44°45.192′	34°01.217′	10/4	359.4	50.5	47	13.6
					348.3	–5.4		
8	Tuffaceous sandstones (Bajocian cirque) (86–98)	44°47.122′	33°59.270′	13/10	4.6	57.1	58	6.4
					348.0	1.9		
9	Lebedinsky sill (117–126)	44°45.191′	34°03.053′	9/6	21.2	64.4	20	15.5
					350.2	12.5		
10	Pervomaiskii open pit (pl–p20)	44°46.767′	34°01.718′	20/20	36.7	76.4	39	15.0
					343.7	23.9		
11	Intrusive body (northern margin of Sokolinoe vil.) (21–33)	44°33.425′	33°57.067′	13/9	40.3	65.6	15	13.8
					354.4	19.6		
12	Boss (abandoned open pit in left side of Mender gully) (29–40)	44°46.745′	33°59.529′	12/0	–	–	–	–
13	Dike "in pink field"	44°46.652′	33°59.736′	12/0	–	–	–	–
14	Intrusive body in Trudolyubovka	44°47.062′	33°59.802′	8/0	–	–	–	–
	Mean	44°46′	34°00′	(9)	21.7	66.0	51	7.3
					349.2	13.8		
	Paleomagnetic pole		plat, deg	plong, deg	dp/dm, deg	paleolat, deg		
	geographic coord. sys.		74.7	102.8	10/12	48		
	stratigraphic coord. sys.		51.1	231.2	4/8	7		

Notes: Slat and Slong are the latitude and longitude of the sampling point, respectively; *n* is the number of treated samples; *N*, number of resulting samples; *S*, number of sites; *D* and *I*, declination and inclination of paleomagnetic direction, respectively; *K* and α95 are density and radius of 95% confidence circle (Fischer statistical parameters); plat and plong, latitude and longitude of paleomagnetic pole, respectively; dp/dm are values of half-axes of the 95% confidence oval; paleolat, paleolatitude of study area. The mean paleomagnetic direction was calculated for all studied bodies except those marked with a star.

responds to the low-temperature and insignificant alterations of primary igneous minerals.

The age of intrusive complex rocks has been considered Middle Jurassic (Bajocian) for a long time on the basis of singular isotopic datings falling within the interval of 175–160 Ma in terms of the K–Ar method (Lebedinskii, 1960). Recently, new $^{40}Ar/^{39}Ar$ and U–Pb ages have been obtained for a series of intrusive bodies and basaltic lavas (Meijers, 2010; Morozova, Sergeev, and Sufiev, 2012). The most remarkable of them are the following: (a) Lebedinskii sill, 171.3 ± 2.6 Ma, $^{40}Ar/^{39}Ar$ dating on plagioclase; (b) an intrusive body exposed in the Pervomaiskii open pit, 160.4 ± 2.0 Ma, $^{40}Ar/^{39}Ar$ dating on plagioclase; (c) basalts in the vicinity of the village of Trudolyubovka, on the path to the Bajocian cirque outcrop, 158.3 ± 7.0 Ma, $^{40}Ar/^{39}Ar$ dating on plagioclase; (d) basaltic lavas behind the hotel building in Trudolyubovka, 165.7 ± 1.3 Ma, $^{40}Ar/^{39}Ar$ dating on the entire rock; (e) Dzhidair intrusion in the right bank of the Bodrak River, 169.7 ± 1.5 Ma, U–Pb SHRIMP analysis on zircons.

The occurrence of the studied subvolcanic bodies is arguable. Most of these bodies (Fig. 1, points 1–7 and 9–14) are localized within the Tauric Group (Upper Triassic–Lower Jurassic) or the coeval Eski-Orda Formation; the deposits of both these units are intensively folded. The contacts between the subvolcanic bodies and host rocks are welded, with no disturbance of the integrity of the bodies (Spiridonov, Fedorov, and Ryakhovskii, 1990a); hence, intrusion took place after the folding of the rocks that belong to the Tauric Group (Eski-Orda Formation). However, the volcanogenic–sedimentary rocks of the Bodrak Formation, exposed in a narrow NE-striking zone in the area of Trudolyubovka, occur with a NW dip at steep angles (up to 40–60° and more), which indicates their dislocation in the period from Middle Jurassic (Bajocian) to Early Cretaceous (Valanginian–Hauterivian), because the youngest deposits of the Lower Cretaceous occur in the Bodrak River valley at small dipping angles of a few degrees. However, it is unclear from the geological setting when penetration of subvolcanic bodies into the Bodrak Formation took place, prior to, during or after its dislocation: e.g., the modern occurrence of the Koronovsky sill, which is of NE strike (40–50°) and NW-dipping angle 40° (Spiridonov, Fedorov, and Ryakhovskii, 1990b), can be considered as either primary if magma penetrated into already dislocated rocks of the Bodrak Formation, or secondary if the sill formed prior to dislocation of the volcanogenic–sedimentary stratum.

Note that issues of definition for the occurrence of intrusive bodies in Mountainous Crimea have been faced by other researchers, in particular, by D.M. Pechersky et al. (1991).

STUDY METHODS

The studies were only of reconnaissance type, for the purpose of sampling the maximal possible number of igneous objects to reveal the most suitable of them for further more detailed study. The samples were collected in summer 2010 and in summer 2011. For every object, 10–15 oriented samples were collected on average. Where possible, the intrusive bodies were tested from endocontact zones. The total volume of the paleomagnetic collection was 156 samples. Collecting of samples from the intrusive bodies outcropping the Pervomaiskii and Shkol'nyi open pits was implemented (for both cases) in two sites, which spanned several tens of meters. The samples were oriented in space with the use of a dip compass with constant control of the possible influence of strong magnetic rocks on the dip needle. The value of the local magnetic declination was calculated based on the IGRF model (11th generation).

The laboratory paleomagnetic studies and processing of magnetic cleaning results were performed in the Petromagnetic Laboratory at the Faculty of Geology of Moscow State University, via the standard technique (Khramov et al., 1982). The control measurements were carried out in the Laboratory for Main Geomagnetic Field and Petromagnetism of the Institute of Physics of the Earth of the Russian Academy of Sciences (IPE RAS).

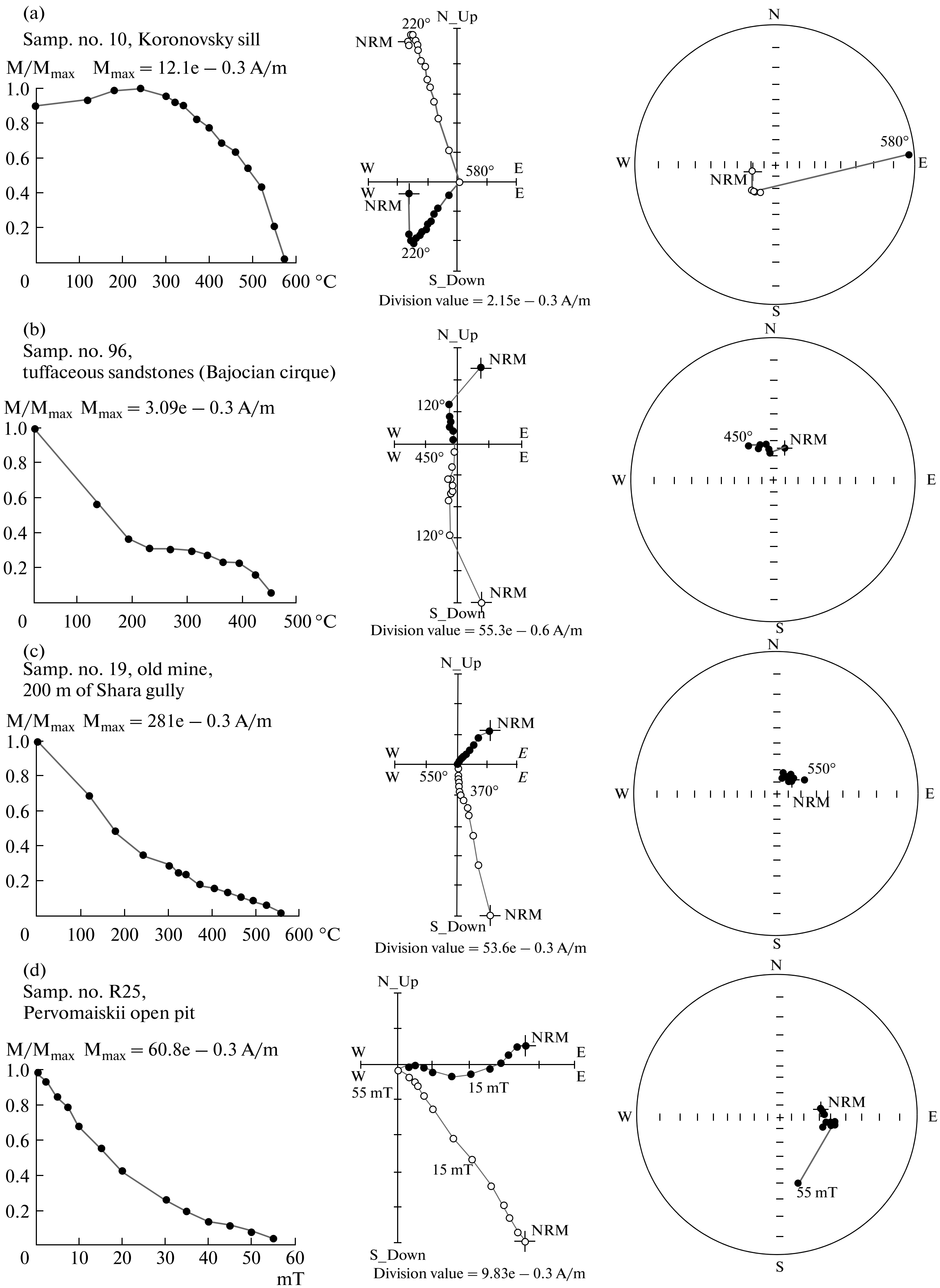
All the samples were treated by detailed temperature cleaning, up to 590–620°C in most cases. The number of cleaning stages was usually 10–12 at a minimum, but degree of cleaning detail was increased if necessary. Thermal demagnetization of the samples was made using a TD-48 nonmagnetic oven (manufactured by ASC Scientific company, USA) at the value of noncompensated magnetic field of no more than 5–10 nT. Control cleanings with an alternating magnetic field were carried out with a demagnetization device that was designed by K.S. Burakov (IPE RAS). Residual magnetization was measured with JR-6 spin-magnetometers (manufactured by AGICO company, Czech Republic). Processing of remanent magnetization measurements was made using a software package by R.J. Enkin (1994) and Remasoft (Chadima and Hrouda, 2006), that utilizes the PCA method for detection of a magnetization component (Kirschvink, 1980).

RESULTS AND DISCUSSION

As a result of the magnetic cleaning, mostly good quality paleomagnetic records were removed from the samples collected in the studied objects. Only samples from three intrusive bodies were not analyzed for components due to their noisy signal (Fig. 1; table; points nos. 12–14).

The natural remanent magnetization (NRM) in most of the samples is the sum of two magnetization components (Fig. 2): one is low-temperature, (20–120°C) of a viscous nature and modern in age; the second is the most stable component (the interval of the demagnetization temperature is 180–620°C). In eight of nine valid objects, the stable component has a normal polarity. The mean direction of the low-temperature (low-coercive) magnetization component, which was calculated at the level of the sites (N = 11; D = 351.6; I = 65.9; K = 25; α95 = 3.6), is close to the

Fig. 2. Examples of demagnetization curves, Zijderveld diagrams, and stereograms of the studied samples in terms of the geographic coordinate system.


(a)
Samp. no. 10, Koronovsky sill
M/M$_{max}$ M$_{max}$ = 12.1e – 0.3 A/m
1.0
0.8
0.6
0.4
0.2
0 100 200 300 400 500 600 °C
220°
N_Up
NRM
W
E
580°
NRM
220°
S_Down
Division value = 2.15e – 0.3 A/m
N
W
E
S
580°
NRM
(b)
Samp. no. 96,
tuffaceous sandstones (Bajocian cirque)
M/M$_{max}$ M$_{max}$ = 3.09e – 0.3 A/m
1.0
0.8
0.6
0.4
0.2
0 100 200 300 400 500 °C
N_Up
NRM
120°
W
E
450°
120°
NRM
S_Down
Division value = 55.3e – 0.6 A/m
N
W
E
S
450°
NRM
(c)
Samp. no. 19, old mine,
200 m of Shara gully
M/M$_{max}$ M$_{max}$ = 281e – 0.3 A/m
1.0
0.8
0.6
0.4
0.2
0 100 200 300 400 500 600 °C
N_Up
NRM
W
E
550°
370°
NRM
S_Down
Division value = 53.6e – 0.3 A/m
N
W
E
S
550°
NRM
(d)
Samp. no. R25,
Pervomaiskii open pit
M/M$_{max}$ M$_{max}$ = 60.8e – 0.3 A/m
1.0
0.8
0.6
0.4
0.2
0 10 20 30 40 50 60
mT
N_Up
NRM
W
E
55 mT
15 mT
15 mT
NRM
S_Down
Division value = 9.83e – 0.3 A/m
N
W
E
S
NRM
55 mT

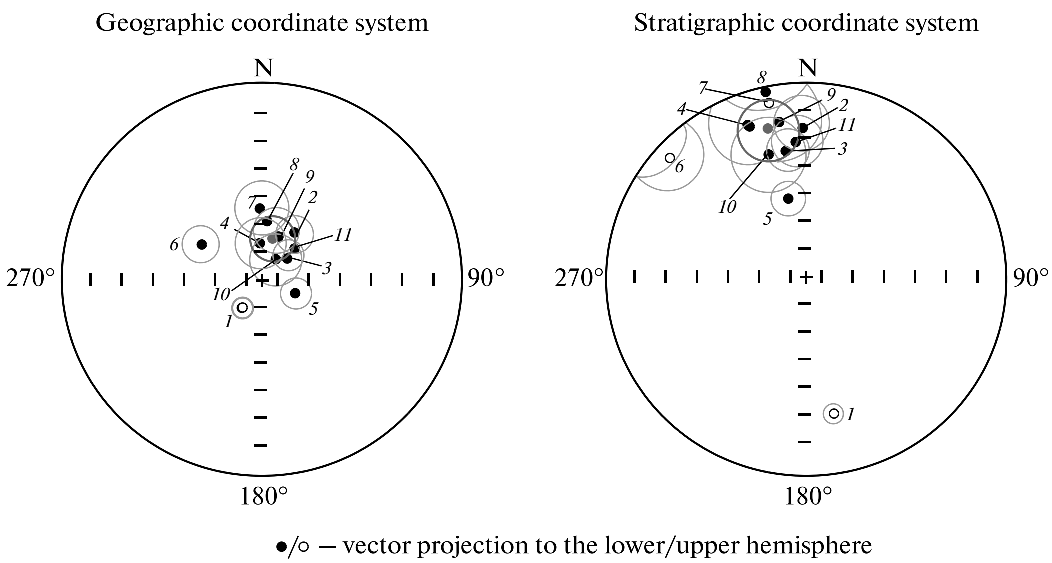


Fig. 3. Paleomagnetic directions of the studied objects and mean paleomagnetic direction.

modern field direction in the study area ($D_{mod} = 6.0°$; $I_{mod} = 62.6°$).

The mean direction of the stable magnetization component for the Koronovsky sill is of reverse polarity and antipodal to the mean paleomagnetic direction of the normal polarity component for the other objects: the reversal test (McFadden and McElhinny, 1990) was passed at the C level ($\gamma/\gamma_c = 10.7°/15.4°$). The mean paleomagnetic direction calculated for nine intrusive bodies and tuffaceous sandstones at the site level is given in Fig. 3 and in the table. The mean paleomagnetic directions in the Pervomaiskii (point 5) and Shkol'nyi (point 6) open pits are located on a sphere relatively far from the dense group of directions for other sites; therefore they were not taken into account when calculating the general mean direction.

The shapes of thermal demagnetization for samples from the studied objects (Fig. 2) suggest that the main magnetization-carrying minerals in the studied rocks are represented primarily by titanomagnetite with different titanium contents. In some objects, the samples possess magnetization that sharply increased under heating to >350–400°C; we interpret this as a result of pyrite oxidation to magnetite.

The main result of the magnetic cleaning was the identification of the most stable magnetization component, which has a bipolar distribution and passed the reversal test. Due to the geological setting, which was unfavorable from the viewpoint of paleomagnetic studies, dating of the defined magnetization component is impossible. Hence, the most convincing argument that this magnetization component is a primary one is its bipolarity. In addition, the presence of oppositely directed magnetization components in the objects located at a distance 300 m from each other (Koronovsky sill and tuffaceous sandstones of Bajocian cirque) suggests the absence of local remagnetization in the study area.

Coincidence in the directions of the stable magnetization component in the subvolcanic bodies and tuffaceous sandstones of the Bodrak Formation indicates that penetration of igneous bodies took place prior to dislocation of the volcanogenic–sedimentary stratum. At present, we cannot completely exclude the possible remagnetization of Bodrak Formation rocks after dislocation, but prior to Koronovsky sill intrusion; however, this scenario seems to be very unlikely due to the absence of visible evidence of such a remagnetization.

The mentioned coincidence in the directions of stable magnetization components in the studied objects also suggests that all them belong to the same tectonic block that had been dislocated in post-Bajocian time (after penetration of intrusive bodies). The degree of dislocation is determined by the average dislocation elements of Bodrak Formation occurrence (dipping azimuth, NW, 330°; dipping angle, 60°).

The presence of a bipolar magnetization component can be considered as additional evidence of the similar ages of the studied geological objects. However, due to the small number of objects and insufficient collection of samples for every object, we can conclude for the moment that the studied subvolcanic bodies and tuffaceous sandstones are nearly coeval (with a difference of a few millions of years at a maximum).

It is interesting to compare the paleomagnetic pole (table) that corresponds to the mean direction of the defined stable magnetization component with the known Jurassic–Cretaceous poles of Crimea (Pechersky et al., 1991; Pecherskii and Safonov, 1993; Rusakov, 1969; Yudin, 2007; Yampol'skaya et al., 2006); see also (Meijers, 2010) and references therein, and digital table available via Internet at http://paleomag.ifz.ru/

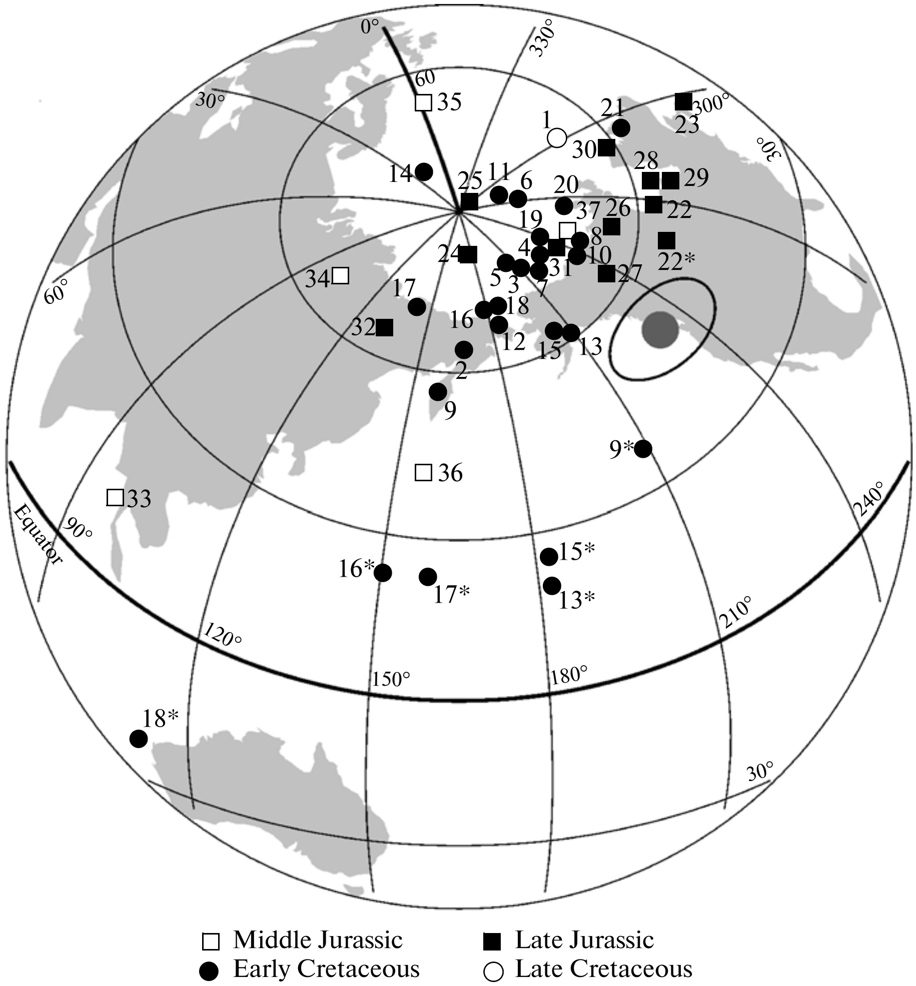


Fig. 4. Paleomagnetic poles of Crimea according to data from (http://paleomag.ifz.ru/files/table-2-Crimean-poles.pdf). The filled circle of bigger size and the ellipse around indicate the paleomagnetic pole calculated in the present work and its 95% confidence interval, respectively. The asterisk sign means that the pole is calculated for the mean paleomagnetic direction in the stratigraphic coordinate system.

files/table-2-Crimean-poles.pdf). To calculate the pole, we used the mean direction in the stratigraphic coordinate system: all paleomagnetic directions of subvolcanic bodies were recalculated with the error for the occurrence of Bajocian tuffaceous sandstones (table) taken into account. The respective paleomagnetic pole is located near the Late Jurassic–Early Cretaceous poles of Crimea (Fig. 4), but significantly differs from them and does not coincide with any previously derived paleomagnetic pole for the Middle Jurassic of Crimea.

Following D.M. Pechersky et al. (1991), we should explain the observed difference between the derived pole and the Middle Jurassic poles of Crimea by the low validity of the singular paleomagnetic definitions for the rocks of this age. Unfortunately, due to the absence of accurate coordinates for igneous objects within the Bodrak complex that were studied in (Yudin, 2007), the direct comparison of the paleomagnetic study results from this work with those obtained in our study is difficult. However, we note that the mean paleomagnetic directions for three objects (BS, LW, and WK) from the cited work are located on a sphere in a dense group of the derived mean directions for the Bodrak complex directions.

Almost all the rest of the defined paleomagnetic directions, given in (http://paleomag.ifz.ru/files/table-2-Crimean-poles.pdf) and depicted in Fig. 4, were taken from the literature and the paleomagnetic database (Pisarevsky, 2005). We note that most of these paleomagnetic definitions do not fit the modern requirements of paleomagnetic validity. For example, the definitions by K.I. Anferova (REFNO 929) do not enable one to assess the quality of the laboratory treatment of samples and to perform an accurate spatial and age reference of the investigated objects. The paleomagnetic definitions that were obtained by D.M. Pechersky et al. (1991) on hornfels from exocontacts of Middle

Jurassic intrusive bodies are also doubtful due to uncertainty on the occurrence of these bodies. The primary source of the paleomagnetic definition, which was made for the Koronovsky sill by I.V. Ivanova and mentioned in (Yudin, 2011), has not been found; however, we emphasize that the paleomagnetic direction of Koronovsky sill obtained by I.V. Ivanova fits the direction we obtained within the error limits.

We believe that the pole we derived is a paleomagnetic one with a high degree of confidence (i.e., centennial variations are averaged). Indeed, the mean direction used for pole calculation was obtained on the basis of nine objects that formed during a time interval of more than 10–100 ka, which is sufficient for averaging centennial variations (Khramov et al., 1982). Thus, the preliminary coordinates of the paleomagnetic pole that fit the mean direction of magnetization for the studied objects in the stratigraphic (ancient) coordinate system correspond to the formation time of the investigated igneous objects (i.e., to the Middle Jurassic).

The possibility of using the obtained paleomagnetic pole for making paleotectonic reconstructions in Mountainous Crimea is generally arguable. According to the modern view (Yudin, 2011), the Crimean Peninsula is a complex overthrust nappe structure formed, in particular, in the Late Mesozoic. In this case, every individual tectonic block within the present day structure of Crimea could suffer dislocations (rotations in different planes) in the post-Bajocian period and it is often impossible to perform quantitative estimates of these dislocations. We estimated the rotation of the tectonic block in the vertical plane; however, a significantly larger volume of paleomagnetic data (including those from the adjacent areas) is required to take possible horizontal rotations into account. It is thought that if the model by V.V. Yudin is correct, then reconstruction of the tectonic evolution for Mountainous Crimea by the paleomagnetic method (in particular, for the Middle Jurassic epoch) will be quite a difficult task, even more difficult than it was previously believed; it can be solved only if a significantly larger number of valid paleomagnetic definitions for different areas (corresponding to different tectonic blocks) of present day Crimea become available.

CONCLUSIONS

(1) Magnetic cleanings have shown that most of the studied igneous and Middle Jurassic volcanogenic-sedimentary rocks are suitable for detailed paleomagnetic studies using modern methods.

(2) We can suggest that the natural remanent magnetization of the studied bodies is the primary one; this is indicated by the bipolar distribution of magnetization components in the studied objects.

(3) The paleomagnetic directions of the most stable magnetization component for every investigated object have been calculated; based on the mean paleomagnetic pole, a new one has been calculated for the Bajocian age.

(4) The obtained paleomagnetic data allowed us to conclude that the intrusive bodies of the Bodrak subvolcanic complex are at a disturbed occurrence. The quantitative degree of their dislocation is defined by the occurrence elements.

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