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MAGNETOSTRATIGRAPHY OF THE UPPER BERRIASIAN "ZAVODSKAYA BALKA" SECTION (EAST CRIMEA, FEODOSIYA)

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Key words: magnetostratigraphy, Berriasian, Crimea, anisotropy of magnetic susceptibility, rock magnetism.

Abstract. The results of magnetostratigraphic investigations in the Upper Berriasian Zavodskaya Balka section (Feodosiya, Crimea) are presented: magnetic polarity information, data on magnetic susceptibility, its anisotropy (AMS), frequency dependence (FD-factor) and other petromagnetic parameters. The analysis of the thermomagnetic and magnetic saturation curves has proved the presence of magnetite, being the main carrier of the remanent magnetization. Magnetic cleaning with alternating field and with temperature mostly has revealed the two-component composition of the magnetization, and the magnetostratigraphy is based on the directions of the most stable of them, with unblocking field from 35–50 mT and temperature from 300 to 540°C. The palaeomagnetic column presented specifies four heteropolar magnetozones – analogous to the M16 and M15 magnetic chrons (full M16n and M15r, parts of M16r and M15n). The existence of the M16n.1r subchron ("Feodosiya") is substantiated, and it should be included into the Geomagnetic Polarity Time Scale. By bio- and magnetostratigraphic correlation, the section studied is an age analogue of the Paramimounum, Picteti and Alpillensis (probably Otopeta) subzones of the Boissieri Zone. The calculated sedimentation rate varied from 26.6 to 29.5 m/My.

INTRODUCTION

There is an operating clay quarry close to the mouth of an extensive "Zavodskaya Balka" ravine in the western suburbs of Feodosiya in east Crimea (45°01'47.7"N, 35°20'59.2"E). The uppermost part of the Berriasian Stage has been penetrated there (Fig. 1). Before 2009, the section was palaeontologically examined (ammonites) by V.V. Arkadiev (Arkadiev, 2007; Arkadiev, Bogdanova, 2009; Arkadiev *et al.*, 2012); in 2009–2010, the section was tested palaeomagnetically (Arkadiev *et al.*, 2010; Bagayeva *et al.*, 2011).

The section is represented by fairly homogeneous clays of the Sultanovskaya formation – carbonate, gray (dark gray and plastic when wet) slightly aleuritic (up to 5%), slightly micaceous (up to 5% of mica flakes), non-foliated, with rare bioturbations of light gray color. The layer dip azimuths vary from 50 to 82°, and the inclination angles – from 23 to 48°. The sampling interval is about 70 m thick.

The following ammonites have been found in the clays: *Neocosmoceras euthymi* (Pictet), *Neocosmoceras* sp., *Fauriella* cf. *boissieri* (Pictet), *Fauriella* sp., *Malbosiceras malbosi* (Pictet) (Arkadiev, Bogdanova, 2009; Arkadiev *et al.*, 2010); those are characteristic of the Boissieri Zone, Euthymi Subzone (Arkadiev *et al.*, 2012), which correlates with the Paramimounum Subzone of the Boissieri Zone from the standard scale of the Tethyan superregion (Reboulet *et al.*, 2014). All the finds come exclusively from the lower part of the section, about 20 m thick. However, some finds of *Thurmanniceras thurmanni* (Pictet) (Muratov, 1937) from the Zavodskaya Balka proper, probably from the overlying beds,

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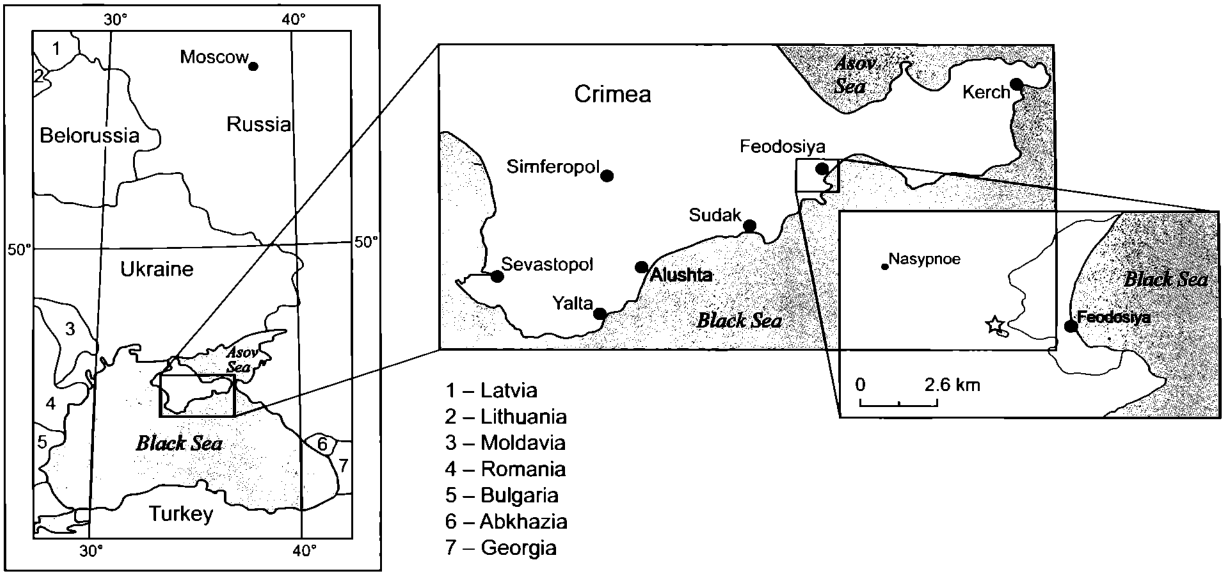

Fig. 1. Location of the Upper Berriasian Zavodskaya Baika section (marked with an asterisk)

have been specified as those characteristic of the base of the Valanginian from Crimea. Moreover, some finds of *Retowskiceras retowskyi* Kvant. an ammonite characteristic of the Occitanica Zone (layers with *Tirnovella occitanica* and *Retowskiceras retowskyi*) (Arkadiev *et al.*, 2012), are known from the Zavodskaya Balka. Those levels in the quarry still remain uncovered at present.

MAGNETOSTRATIGRAPHY

Oriented samples for palaeomagnetic analyses, later cut into three or four 2-cm cubes (8 cm^3), have been taken from 83 stratigraphic levels. Palaeomagnetic samples were collected at intervals of 0.9 m, starting from the quarry base, but in 2009, a 23 m thick sampling break had to be accepted due to lack of exposures; that was completed in 2010 (Fig. 2).

Specimens from every sample were subject to magnetic cleaning with an alternating field in a LDA-3 AF unit (within the range from 5 to 50 mT, in increments of 5 mT) and with temperature in a furnace designed by Aparin (from 100° to 300–500°C, in increments of 50–100°C), with subsequent measurement of natural remanent magnetization (J_n). The laboratory petromagnetic and magnetic mineralogical studies involved studying the magnetic susceptibility (K), its anisotropy (AMS) and FD-factor ($FD = [(K_{LF} - K_{HF})/K_{LF}] \cdot 100\%$, with K_{LF} and K_{HF} – K, measured at low and high field frequencies, respectively). Magnetic saturation experiments with the subsequent determination of the remanent saturation magnetization (J_{rs}) and remanent coercivity (H_{cr}) as well as differential thermomagnetic analysis (DTMA) were also carried out. The J_n measurements were made with a JR-6 spinner magnetometer, those of K – with a MFK-1FB multifrequency kappabridge. A TAF-2 fraction thermoanalyzer was used for DTMA. Component analyses were made by means of Remasoft 3.0 program, the AMS analyses – by means of Anisoft 4.2 software.

Judging from the DTMA curves, magnetite or related minerals are the principal magnetization carriers in the rocks. That is diagnosed from the magnetization decrease close to magnetite Curie temperature of 578°C (Fig. 3A). The DTMA curve bend at temperatures of ~220–280°C may be associated with maghemite (the product of Fe_3O_4 single-phase oxidation), which disappears turning into hematite when heated for the second time (Fig. 3A). The availability of a magnetically soft phase is confirmed by the data on magnetic saturation: the saturation field is generally about 100 mT, H_{cr} varies from 27 to 33 mT (Fig. 3B), which is characteristic of finely-dispersed magnetite.

The examined rocks are highly magnetic (Fig. 2): the average K and J_n values make $60 \cdot 10^{-5}$ SI units and $19 \cdot 10^{-3}$ A/m, respectively, which is indicative of high concentrations of ferromagnetic material (mostly magnetite).

The K/J_{rs} (Fig. 2) ratio is directly proportional to the average size of the ferromagnetic particles in the sample. The data on superparamagnetic (SPM) magnetite (with the grain sizes of <0.029 µm) presence in the rocks provides the FD-factor. The FD values are above 2% (generally about

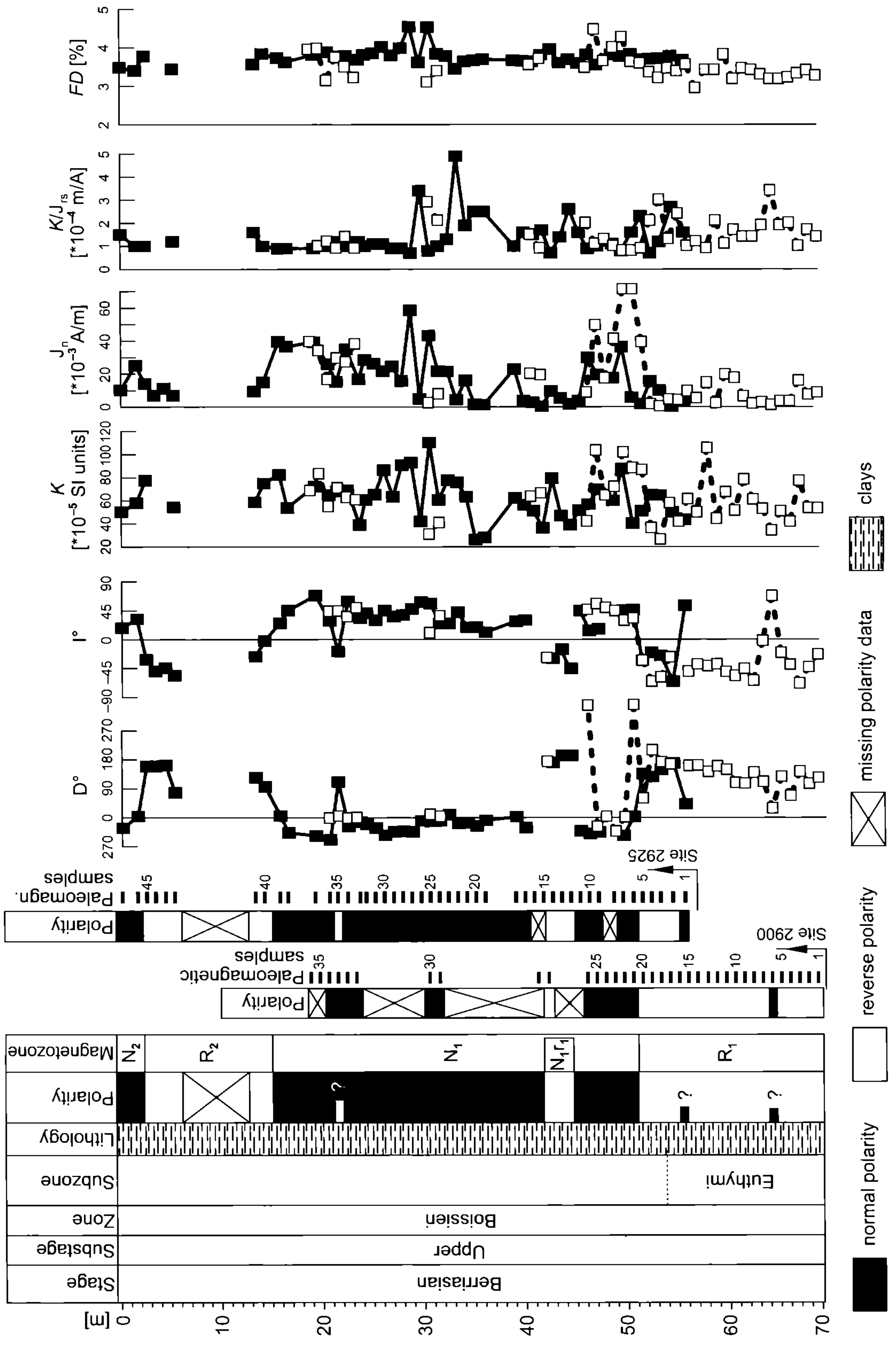

Fig. 2. Stratigraphic sequence of the Upper Berriasian from the Zavodskaya Balka section

D, I – palaeomagnetic declination and inclination, respectively; *K* – magnetic susceptibility; J_n – natural remanent magnetization; J_{rs} – remanent saturation magnetization; *FD* – *FD*-factor. White and gray symbols on the graphs correspond to samples from the site 2900 and site 2925, respectively

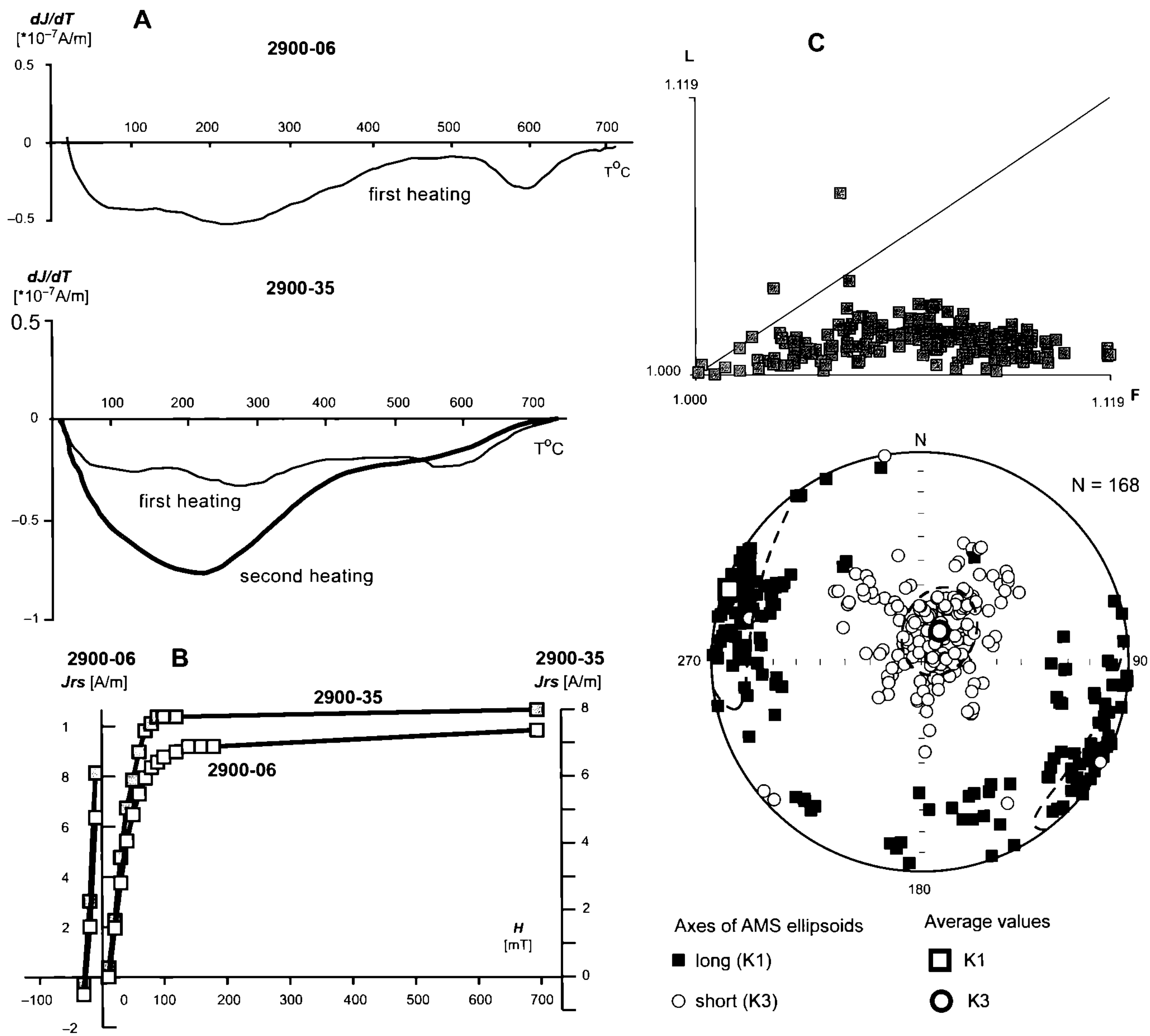

Fig. 3. Results of magnetic-mineralogic analysis

A – DTMA curves (first-order derivatives from thermomagnetic analysis) from the first and the second heatings. **B** – magnetic saturation plots. **C** – AMS characteristics (relationship of L and F parameters and distribution of projections of AMS ellipsoid axes over the sphere in a stratigraphic coordinate system). N – a number of samples in a set

3%, as high as 4.5% at some levels), which may be regarded as an indication of the ubiquitous presence of SPM magnetite in the section.

All the particles defining the rock magnetic texture in the section are flattened, which is indicated by the character of interrelations between the L and F parameters ($L=K1/K2$, $F=K2/K3$, with K1, K2 and K3 – long, middle and short axes of magnetic ellipsoids, respectively) (Fig. 3C). Most likely, the finely dispersed ferromagnetic grains are aggregated on the flakes of clay minerals. Projection of the short axes average trend is deflected from the sphere center to the northeast (by 14°) (Fig. 3C), which may result from an unaccounted inclination of the ramp surface accumulating the sediment or from the magnetic moment orienting a clay particle by the field in an inclined position. The magnetic texture of the deposits from the Zavodskaya Balka section,

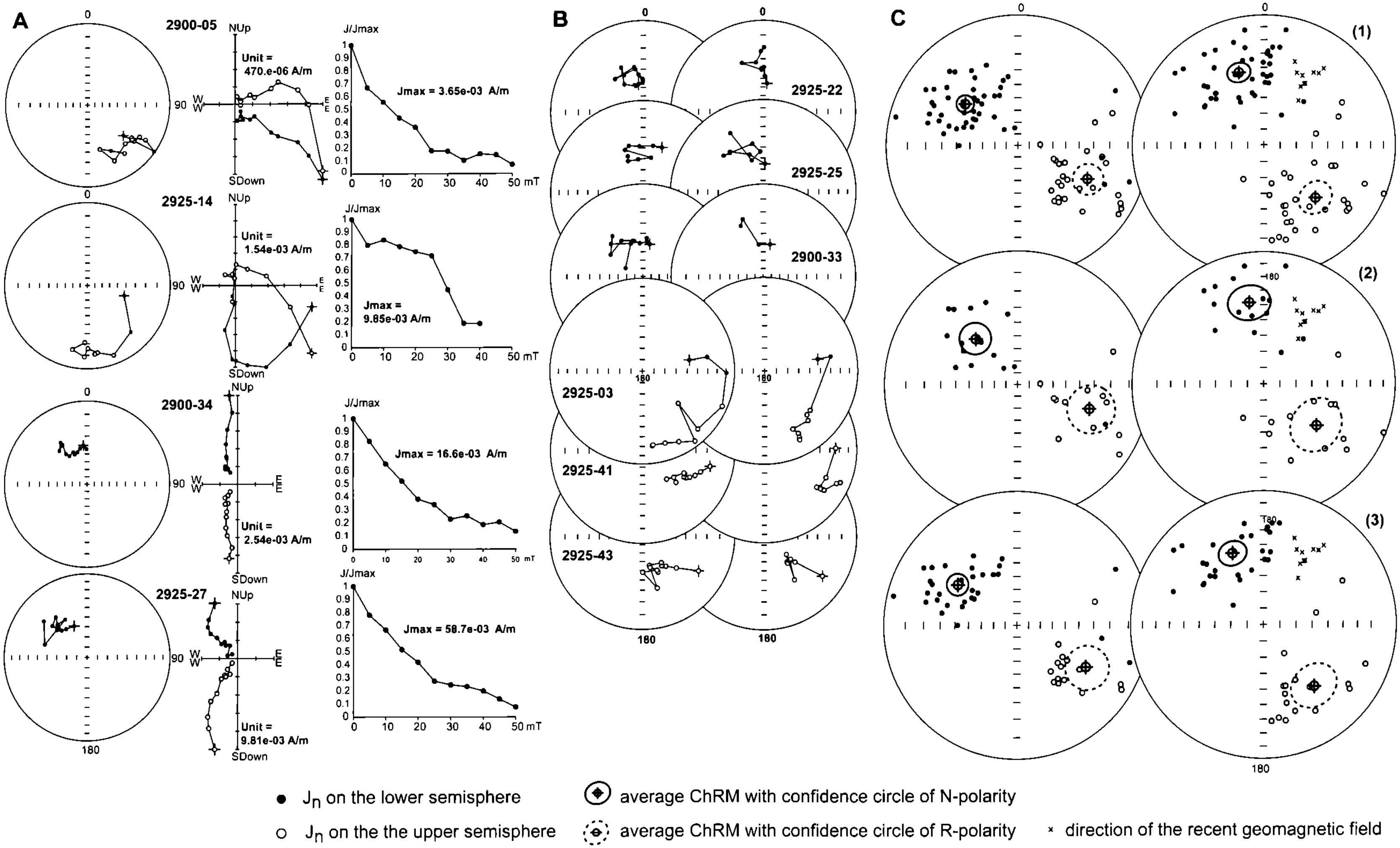

Fig. 4. Magnetic component analysis results

A – from left to right: stereographic presentation of J_n changes in the process of magnetic cleaning, Ziderweld diagrams, sample demagnetization plots. **B** – comparisons of stereograms with the changes of J_n in the course of cleaning by alternating field (left) and temperature (right) (all stratigraphic images are presented in the stratigraphic system of coordinates). **C** – ChRM stereographic projections before (left) and after (right) tectonic correction: (1) – for all samples; (2, 3) – for the samples with the largest and the smallest average sizes of ferromagnetic grains, respectively. See paleomagnetic statistics for various sets of samples in Table 1. For other explanations see Figure 3 similar to that of all clays from the Crimean Mountains (Bagayeva, Guzhikov, 2012), demonstrates weak sublatitudinal ordering of the long axes of magnetic ellipsoids; this is probably accounted for by tectonic contraction of the rocks (Fig. 3C).

According to Zijderveld diagrams, two-component J_n composition is recorded in the majority of the samples: a low-coercivity component, disintegrating after 5–15 mT (and probably associated with maghemite), and a high-coercivity one, persisting up to 35–50 mT (with magnetite as a carrier) and identified by the authors as ChRM (Fig. 4). ChRM components characterized by maximum deviation angles <15°. Thermal demagnetization of twin specimens revealed the same results as AF treatment (Fig. 4). The reproducibility of the results in the two different types of magnetic cleaning improves the quality and reliability of the acquired palaeomagnetic data.

In stereograms, ChRM exhibits an obvious tendency for isolation in two groups: in the N-NW sector of the lower hemisphere and in the SE sector of the upper hemisphere (Fig. 4). By assuming that the directions of the first group correspond to the normal (N) and those of the second one – to the reverse (R) polarity of the geomagnetic field, the magnetostratigraphic column (Fig. 2) has been constructed, with four magnetozones recognized within: two reverse polarity zones (R_1, with an apparent thickness of 19 m, and R_2, with a thickness of 12.5 m) and two normal polarity zones (N_1, 36 m thick, and N_2, with an apparent thickness of 2.5 m) (Fig. 2). In the lower part of the N_1 magnetozone, a narrow (~2.5 m thick) reverse polarity interval (N_1r_1) was recorded, substantiated by samples from four levels.

NATURE OF MAGNETIZATION AND DISCUSSION OF THE RESULTS

The following observations and test results testify to the ancient nature of the J_n components used to determine polarity signs:

1. The ChRM average trend, corresponding to N-polarity, is markedly different from the vector of remagnetization by the present-day geomagnetic field (Fig. 4C).

2. The ChRM trends, corresponding to both normal and reverse polarities, are recognized in a lithologically homogenous section (Fig. 2). The polarity sign is not dependant on lithology and petromagnetic variations reflecting the compositional features of the rock ferromagnetic fraction (Fig. 2).

Table 1

Statistic palaeomagnetic characteristics of the Upper Berriasian from the Zavodskaya Balka section

		Polarity	n	D_{av}/I_{av} [°]	k	α_{95} [°]	Angle [°] with **ChRM** (from Guzhikov *et al.*, 2012)	Reversal test (McFadden, McElhinny, 1990)		
								A[°]	A_c[°]	Cl.
All samples	before t.c.	N	43	308.6/36.0	13.60	6.1		12.7	11.2	–
		R	31	116.0/–29.0	7.66	10.0				
	after t. c.	N	43	341.2/40.3	11.83	6.6	7.3 ±10.5	19.3	12.0	–
		R	31	135.6/–43.4	7.46	10.1	17.0 ±11.8			
K/J_{rs} >1.5 · 10^{-4}	before t.c.	N	15	317.3/40.3	12.71	11.2		25.0	20.0	–
		R	13	108.8/–30.5	8.15	15.5				
	after t. c.	N	15	349.8/37.6	11.23	11.9	11.9 ±12.7	31.9	19.0	–
		R	13	128.1/–47.7	7.57	16.1	20.6 ±11.0			
K/J_{rs} <1.5 · 10^{-4}	before t.c.	N	28	304.4/33.5	15.19	7.2		6.6	15.1	C
		R	18	121.2/–27.6	7.34	13.7				
	after t. c.	N	28	336.4/41.4	12.62	8.0	7.9 ±11.0	12.2	15.1	C
		R	18	140.4/–40.0	7.46	10.1	15.5 ±13.4			

Before t. c. – before tectonic correction, After t. c. – after tectonic correction, *n* – number of samples in the selection, D_{av}/I_{av} – average palaeomagnetic declination / inclination, k – palaeomagnetic precision parameter, α_{95} – radius of the vector confidence circle, A – angle between average N and R vectors, A_c – critical angle, Cl. – classification after McFadden and McElhinny (1990)

Angles formed by ChRM vectors from Zavodskaya Balka section and angle with ChRM from Guzhikov *et al.* (2013) are given with errors (±) determined by statistics of these vectors according to Debiche and Watson (1995)

3. Inversion (reversal) tests (McFadden, McElhinny, 1990) are negative for the entirety of palaeomagnetic vectors en bloc (Table 1). The results of AMS studies (Fig. 3C) indicate the probable reason why the average J_n vectors, corresponding to different polarities, are not antiparallel. Substantial deviations of the short axes of the AMS ellipsoids from their average trend are indicative of additional deformation of clays in corresponding layers; those deformations might have occurred either during diagenesis – as the result of semiliquid sediment sliding along the ramp slope, or happened as a consequence of recent landslide processes. The inversion test is positive for a set of samples with minimum average size of ferromagnetic grains ($K/J_{rs} < 1.5 \cdot 10^{-4}$), but negative for the samples with larger ferromagnetic particles ($K/J_{rs} > 1.5 \cdot 10^{-4}$) (Table 1). This testifies for clay deformation at the stage of semiliquid sediments, when fine particles could restore their orientation by the field, while the larger ones could not. This version explains why the fold test (McFadden, 1990) either is incorrect or indicative of a post-folding origin for ChRM in case of samples with fine grained size.

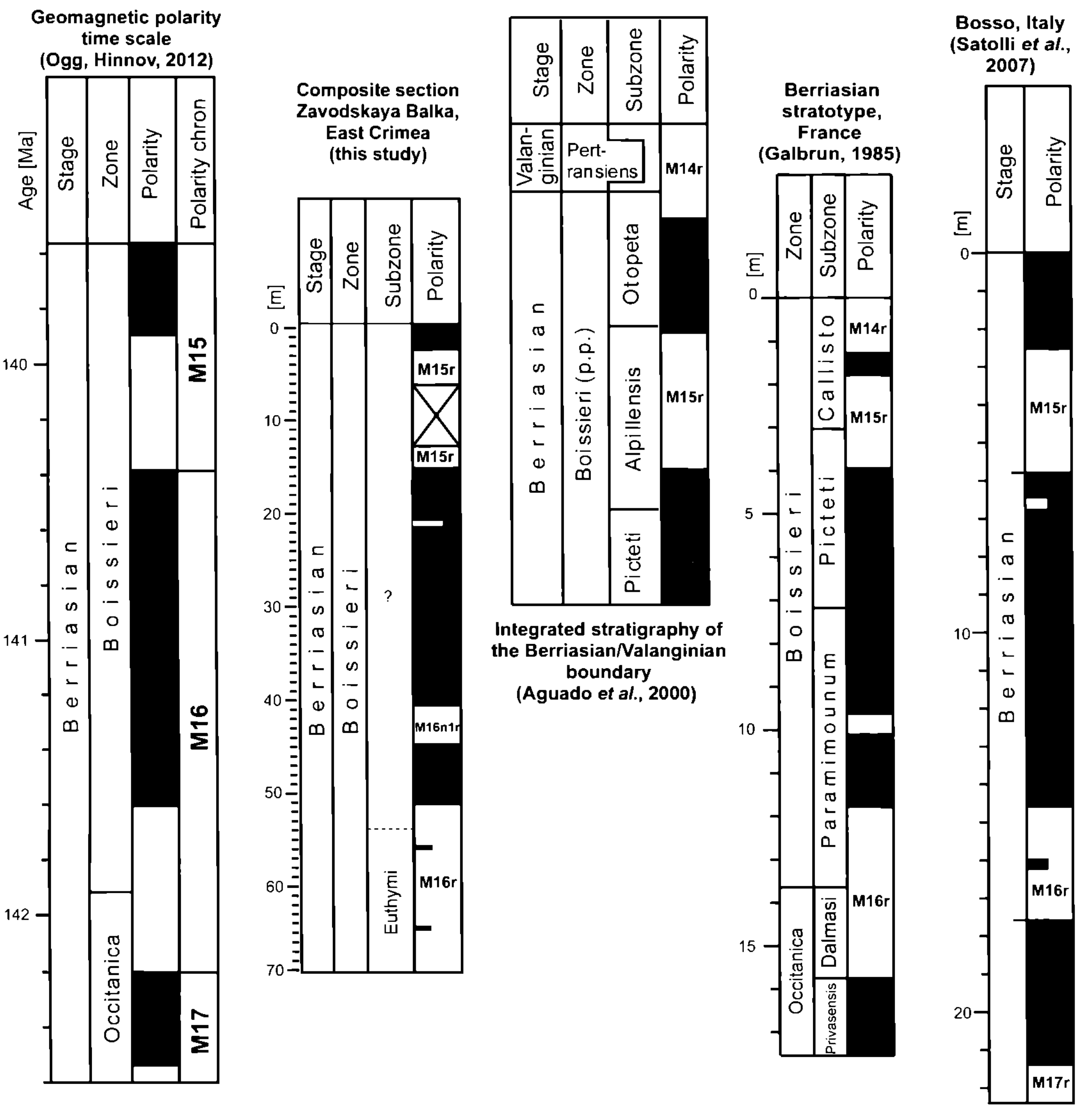

Fig. 5. Comparison of the Zavodskaya Balka magnetostratigraphic section with geomagnetic polarity time scale and sections from other regions

See conventional signs in Figure 2

4. The average directions, corresponding to N polarity, coincide statistically with the palaeomagnetic directions, acquired earlier from the Dvuyakornaya series (Tithonian-Lower Berriasian) in east Crimea (Guzhikov *et al.*, 2012) (Table 1).

5. The age analogues of the Zavodskaya Balka section in the stratotype of the Berriasian (France) – the Paramimounum Subzone of the Boissieri Zone – have identical palaeomagnetic zonality (Galbrun, 1985): reverse polarity corresponds to the lowermost part of the subzone, while normal polarity corresponds to the uppermost part of the subzone, moreover, a narrow reverse-polarity microzone is recorded within the normally magnetized Paramimounum Subzone part, both, in the Feodosiya section and in the stratotype (Fig. 5). Therefore, the R1 and N1 magnetozones are unambiguously identified with the M16 magnetic chron, and since no sedimentation gaps are recorded in the section examined, the overlying R_2 and N_2 magnetozones may be reliably identified with the M15 chron (Fig. 5).

The sum of the above statements, each one compliant with the assumption of primary magnetization, is strongly suggestive of the reliability of our determinations of magnetic polarity.

CONCLUSIONS

The magnetozones recognized in the Zavodskaya Balka section are correlated with the M16 and M15 (Ogg, Hinnov, 2012) magnetic chrons (Fig. 5). The smoothed sedimentation rate for magnetozone N_1 (analogue of M16n) and R_2 (analogue of M15r) has been deduced to vary from 26.6 to 29.5 m/My. Length of magnetic chrons are given by from GPTS 2012 (Ogg, 2012).

By reference to the results of complex bio- and magnetostratigraphic correlation, the studied section is an age analogue of the Paramimounum, Picteti and Alpillensis (probably Otopeta) subzones of the Boissieri Zone (Galbrun, 1985; Aguado *et al.*, 2000; Ogg, Hinnov, 2012) (Fig. 5). The levels of geomagnetic inversions in that case represent synchronous correlation references of global scale.

A reversed polarity interval N_1R_1, ~2 m thick, revealed within a normal-polarity zone (analogue of the M16n chron) in the Zavodskaya Balka and substantiated by samples from four levels, is of special interest. A similar reversed interval (~0.5 m thick, also substantiated by four samples), staying in the same position relative to biostratigraphic (the Paramimounum Subzone) and magnetochronological (the lowermost of the M16n chron) divisions, has been recognized earlier in the Berriasian stratotype in France (Galbrun, 1985) (Fig. 5). A solitary reverse-polarity interval has been recorded in the uppermost of the magnetozone analogous to the M16n chron in the Bosso section (Satolli *et al.*, 2007) in Italy (curiously, a similar r-interval has been recorded in the Zavodskaya Balka, as well) (Fig. 5). The N_1R_1 interval, both in terms of sample number and of lateral persistence (traced from the French Alps to Crimea), fully complies with the requirements of recognizing new magnetopolar units. The availability of a short-term reverse-sign interval within the anomaly, corresponding to the M16n chron, has recently been confirmed by the data of a marine magnetic survey, as well (Tominaga, Sager, 2010). Therefore, the new M16n.1r subchron should be included into the magnetostratigraphic scale. In accord with the tradition of giving specific names to subchrons in the boundary Jurassic-Cretaceous interval, set up by Czech palaeomagnetologists (Hoŭsa *et al.*, 1997), the name of "Feodosiya" is suggested.

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