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Ammonites and magnetostratigraphy of the Berriasian–Valanginian boundary deposits from eastern Crimea

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Abstract: Euthymi, Crassicostatum and Callisto ammonite subzones, correlable with Paramimounum, Picteti, and Alpillensis subzones and probably with the Late Berriasian Otopeta Subzone of the Boissieri Standard Zone have been recognized in calcareous clays of the Berriasian–Valanginian boundary sequence in the Feodosiya district (eastern Crimea). The ammonite *Leptoceras studeri* (Ooster) suggests Late Berriasian to Early Valanginian age. Geomagnetic polarity indicates M16–M14r magnetozones. Therefore, the base of the Valanginian sequence in eastern Crimea should be placed within the M14r magnetozone.

Keywords: Mountainous Crimea, Berriasian, Valanginian, ammonites, biostratigraphy, magnetostratigraphy, geomagnetic polarity, correlation.

Introduction

The matter of fixing the Berriasian–Valanginian boundary in the Tethyan super-region has not been settled up to now. This is accounted for by ambiguous data on ammonite occurrences in the boundary interval. The authors have earlier considered the background of the problem (Arkadiev et al. 2016). In the current western Tethyan zonal ammonite scale, the Otopeta subzone is regarded as the upper subzone of the Boissieri zone (Reboulet et al. 2014). At the Brussels Congress (Bulot 1996), it was decided to draw the Berriasian–Valanginian boundary in accord with the first occurrence of *Calpionellites darderi* (Colom) at the base of the Calpionella E zone. It is at about this level that the typically Valanginian species *Tirnovella pertransiens* (Sayn) first appears. Analogous data has recently been acquired from examination of the Berriasian–Valanginian sections in Bulgaria (Petrova et al. 2011).

In the early publications on Mountainous Crimea, Valanginian ammonite occurrences were recorded in the lists of clays from the Novobobrovsk "series" where developed in south-western Crimea, resting on underlying Tithonian and Berriasian beds with a substantial stratigraphic break. These ammonites were: *Kilianella roubaudiana* (d'Orb.), *Neocomites neocomiensis* (d'Orb.) (Lysenko 1964; Astakhova et al. 1984).

The south-western Crimea is the only place provided with the Valanginian zonal scale (Baraboshkin & Yanin 1997; Baraboshkin & Mikhailova 2000).

The aim of this work is to study the Berriasian–Valanginian boundary in the bio- and magnetostratigraphic data.

Location of the studied sections

Continuous Berriasian–Valanginian sequences are known only from the Feodosiya district of eastern Crimea. In 2009–2015, the authors of the present paper made thorough bio- and magnetostratigraphic examinations of the Zavodskaya Balka, Koklyuk and Sultanovka sections (Fig. 1). The Zavodskaya Balka profile is in an active clay quarry in the northern suburbs of Feodosiya. Results on the Berriasian at Zavodskaya Balka have been published earlier (Arkadiev et al. 2010, 2015; Guzhikov et al. 2014; Arkadiev 2015). In 2015, the overlying Berriasian–Valanginian boundary interval in that section was sampled (outcrop 3058, coordinates: N 45°01'49.1", E 35°20'59.5"). The examination results are presented in this paper. The profile at Koklyuk (outcrop 3030: N 45°00'08.5", E 35°12'27.5"; outcrop 3060: N 45°00'08.6", E 35°12'31.3") lies near the village of Nanikovo, in ravines on the slopes of Koklyuk Mountain. The Sultanovka locality (outcrop 2926: N 45°00'09.9", E 35°17'38.2") lies near the village of Sultanovka (Yuzhnoye), in the core of the Sultanovka syncline.

Geological setting

The geological structure of eastern Crimea was studied in detail by M.V. Muratov (1937), who developed a tectonic map of the region and singled out the Feodosiya block. Within that block, he recognized the Tepe-Oba, the Sultanovka and

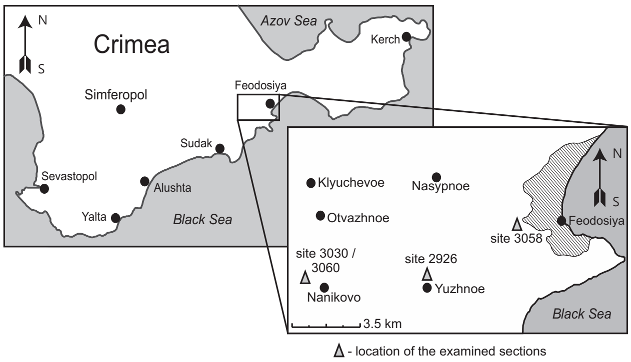

Fig. 1. Location chart of the examined sections: Sultanovka (site 2926), Koklyuk (site 3030/3060), Zavodskaya Balka (site 3058).

the Dvuyakornaya Valley synclines, affecting Upper Jurassic–Berriasian carbonate-clay rocks. The beds are complicated by plicative (folds) and disjunctive (faults) dislocations. Many of those are hard to fix in homogenous clay series. In the context of the present-day concepts, the study area is a part of the Orta-Syrt tectonic cover (Kazantsev et al. 1989).

Sediments are represented by monotonous grey clays with rare intercalations of marls and limestones.

Biostratigraphic and palaeomagnetic methods

Macrofauna (ammonites, belemnites, aptychi etc.) were collected throughout the section. In addition, samples were taken on microfauna (foraminifers, ostracods) and palynomorph (dinocysts). Foraminifera, ostracods and dinocysts are described in a separate article (Savelieva et al. 2017).

Oriented masses of clay were selected from 146 stratigraphic levels in the examined sections (Figs. 2, 3, 4); the spacing between varied from 0.3 m to 0.6 m (generally 0.5 m). Three or four 2-cm cubes were sawn out of each lump and subjected to a standard complex of palaeo- and petromagnetic examinations: magnetic cleaning with alternating magnetic field in a LDA-3 unit, remanent magnetization (J_n) measurement in a JR-6 spin-magnetometer, magnetic susceptibility (K) and its anisotropy measured in a MFK1-FB kappabridge, and thermomagnetic analysis (TMA) with a TAF-2 device (ferromagnetic fraction thermoanalyser — the device for recording the change in magnetization from sample heating to 700 ^{o}C), and magnetic saturation experiments with the subsequent determination of the saturation field (H_s), remanent saturation magnetization ($\mathbf{J}_{rs}$) and remanent coercivity (H_{cr}). Magnetic saturation was acquired with a controllable electric magnet with a maximum field strength of 700 mT.

Analyses of the data on anisotropy of magnetic susceptibility (AMS) and the component analyses were performed using, respectively, Anisoft 4.2 and Remasoft 3.0 software.

The examinations were carried out in the petrophysics laboratory at the Geology Faculty of Saratov University.

Biostratigraphy

Ammonites, aptychi and belemnites

V.V. Arkadiev was the first to find the Upper Berriasian–Lower Valanginian *Leptoceras studeri* (Ooster) ammonites (Fig. 5A) in the vicinity of Sultanovka (site 2926) (Arkadiev et al. 2011). No ammonites assignable to the Valanginian have been found in the Koklyuk or Zavodskaya Balka sections, but the microfaunal (Savelieva et al. 2017) and magnetostratigraphic data suggest the presence of Lower Valanginian beds there.

Some important Upper Berriasian ammonite finds were previously made by the authors at Zavodskaya Balka and Koklyuk. In 2009, the *Neocosmoceras euthymi* (Pictet) (Fig. 5B, C, D, E), *Fauriella* cf. *boissieri* (Pictet) (Fig. 5K) and *Malbosiceras malbosi* (Pictet) (Fig. 5F) ammonites were found for the first time in the Zavodskaya Balka profile. In 2014, in the same section, above the levels with *Neocosmoceras*, the genus *Riasanites* was found, initially defined as *Riasanites* sp. (Arkadiev 2015). Additional collecting was carried out in 2015, and some good specimens were identified as *Riasanites crassicostatum* (Kvant. and Lys.) (Fig. 5H, I, J). At Zavodskaya Balka, a *Berriasella callisto* (d'Orb.) (Fig. 5G) was found above levels with *Riasanites crassicostatum.*

In the course of examining the Koklyuk section in 2014–2015, *Neocosmoceras euthymi* (Pictet) specimens were found for the first time, and aptychi and belemnites (*Didayilamellaptychus* sp. and *Pseudobelus* cf. *bipartitus* Blainville) were found about 40 m above the *Neocosmoceras* finds. The aptychi *Didayilamellaptychus didayi* (Coq.) and *D. angulicostatus* (Pict. et Camp.) are also found in the Sultanovka section, from the Nanikovo "series" clays (Kozlova & Arkadiev 2003).

The ammonites recorded in this paper are kept in the Central Scientific and Geological Survey Museum named after F.N. Chernyshev (No. 13175, 13220) and in the Palaeontology–Stratigraphy Museum at Saint-Petersburg University (No. 381, 409).

Magnetostratigraphy

Finely dispersed magnetite was found to be the principle carrier of $\mathbf{J}_n$ in the Sultanovka formation clays at Zavodskaya Balka (Arkadiev et al. 2010, 2015; Guzhikov et al. 2014) and confirmed by the data of the present investigations at the Koklyuk and Sultanovka sections. Magnetite can be diagnosed by a magnetization drop in the TMA curves at temperatures of about 578 °C (Fig. 6A), and the presence of magnetically 'soft' phase is confirmed by the magnetic saturation data (Fig. 6B). Samples from Koklyuk and Sultanovka as well as those from the Zavodskaya Balka are peculiar because they contain iron hydroxides, which are detected by bends in the plots of the TMA second derivative in the 100–200 °C (Fig. 6A) region at the first heating and the gentle increase of remanent saturation magnetization ($\mathbf{J}_{rs}$), up to 700 mT (Fig. 6B).

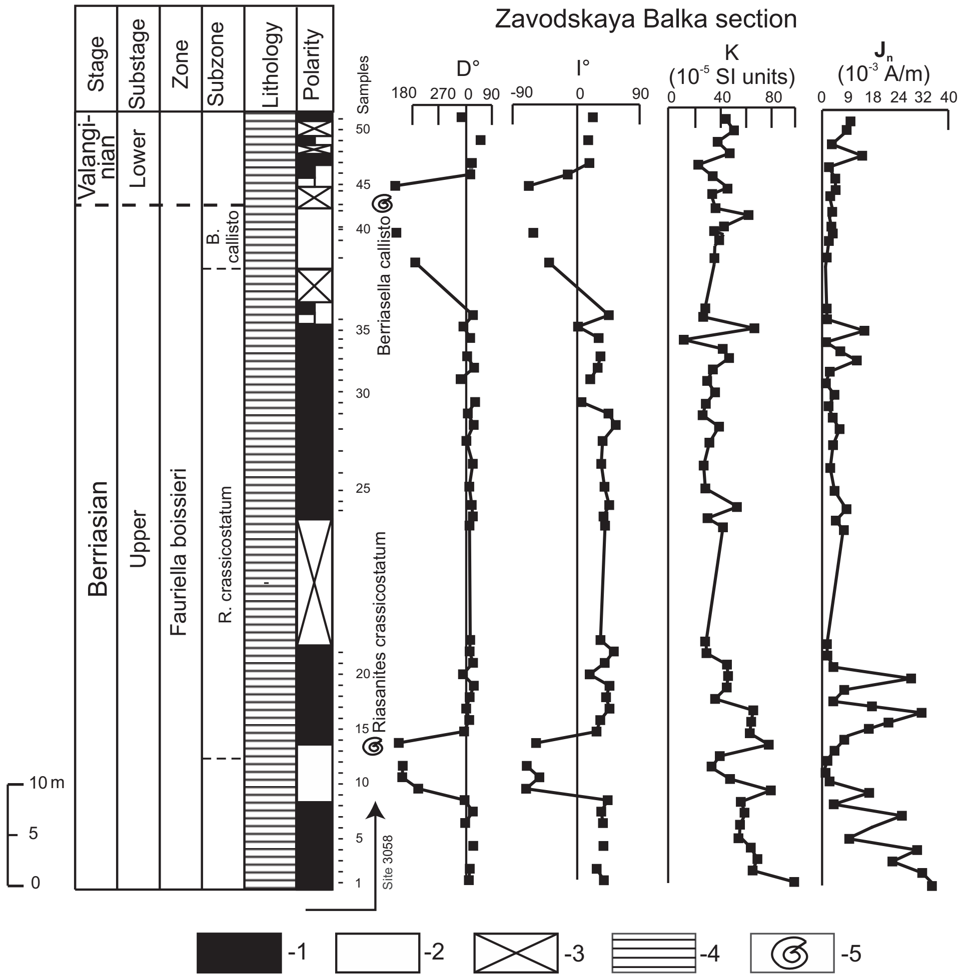

Fig. 2. The Zavodskaya Balka (site 3058) magnetostratigraphic section of the Berriasian–Valanginian. *Legend*: 1, 2 — normal and reverse geomagnetic polarity, respectively (in half of the column thickness – tentative determination of the polarity sign); 3 — no palaeomagnetic data available; 4 — clays; 5 — ammonite finds. D and I — palaeomagnetic declination and inclination in stratigraphic coordiantes; K — magnetic susceptibility.

The character of the anisotropy of magnetic susceptibility (AMS) in the uppermost part of the Zavodskaya Balka profile is different from that in the underlying Berriasian beds. The earlier-published data on the lower part of the section (Guzhikov et al. 2014) in the stratigraphic coordinate system records a distribution of projections of magnetic susceptibility ellipsoids that is typical of the Upper Jurassic–Lower Cretaceous clays in eastern Crimea (Bagayeva & Guzhikov 2014): the short axes projections (K3) tend to be clustered in the centre of the stereogram, thus, indicating sediment formation in calm hydrodynamic settings, whereas the long axes projections (K1) are arranged with a sublatitudinal direction, generated by collisional compression (Fig. 7-1A and B). More significant variance of K3 projections may be observed on the stereoprojections, corresponding to the upper part of the section (Fig. 7-2A, B). Such character of AMS may be related to the viscous-plastic deformations in clay that could happen during the diagenesis or are probably caused by landslide process near the surface (Arkadiev et al. 2015, 2016). A similar pattern is characteristic of the clay magnetic texture at Koklyuk (Fig. 7-3A and B) and is probably accounted for by the same causes. In this section, intense landslide dislocations can be detected visually in the marl layers in the base of outcrop 3030. There is no reason to assume that the anomalous nature of AMS in the studied sections is associated with mineralogical effects, for example, with the presence of siderite, because thermomagnetic susceptibility data (controlling of phase transition of siderite to strongly magnetic magnetite at a temperature above 350 °C) do not indicate the finely dispersed siderite in the clays.

A paradoxical AMS character was also observed in Sultanovka. A peculiarity of the data in those sections, sampled from three natural exposures in various limbs of the Sultanovka syncline (Grishchenko & Bagayeva 2014), is that distribution of the magnetic ellipsoid axes seems to be regular, not in the stratigraphic coordinate system (Fig. 7-4B), but in the geographical coordinate system (Fig.7-4A). In the latter, it corresponds to the model of the deposits formed in calm hydrodynamic conditions which were subsequently subjected to weak tectonic compression (Bagayeva & Guzhikov 2014).

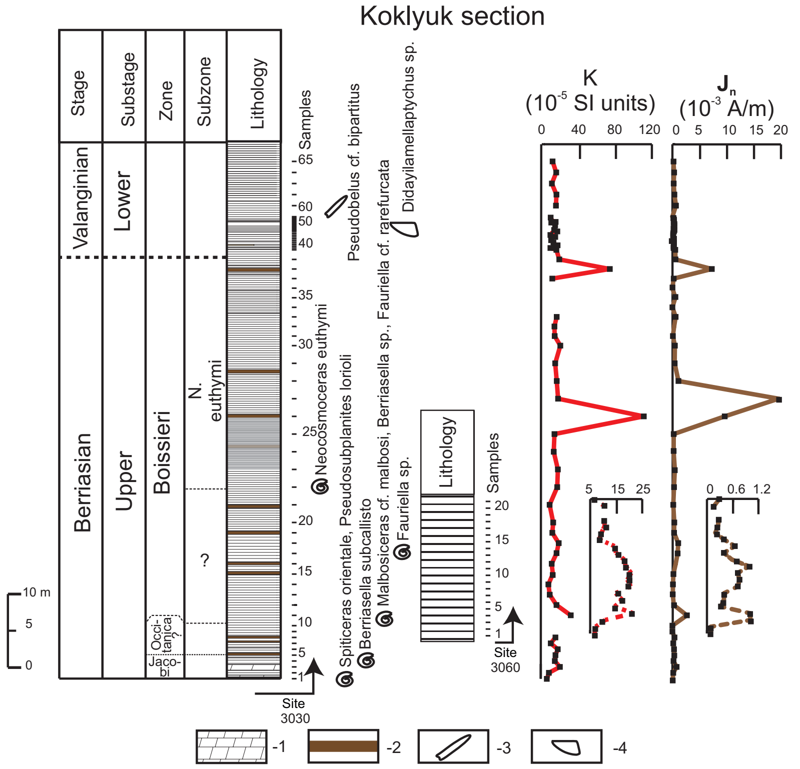

Fig. 3. The Koklyuk magnetostratigraphic section of the Berriasian-Valanginian. *Legend:* 1 — marl; 2 — ankerite and siderite intercalations; 3, 4 — belemnite and aptychi finds, respectively. See Fig. 2 for other explanations.

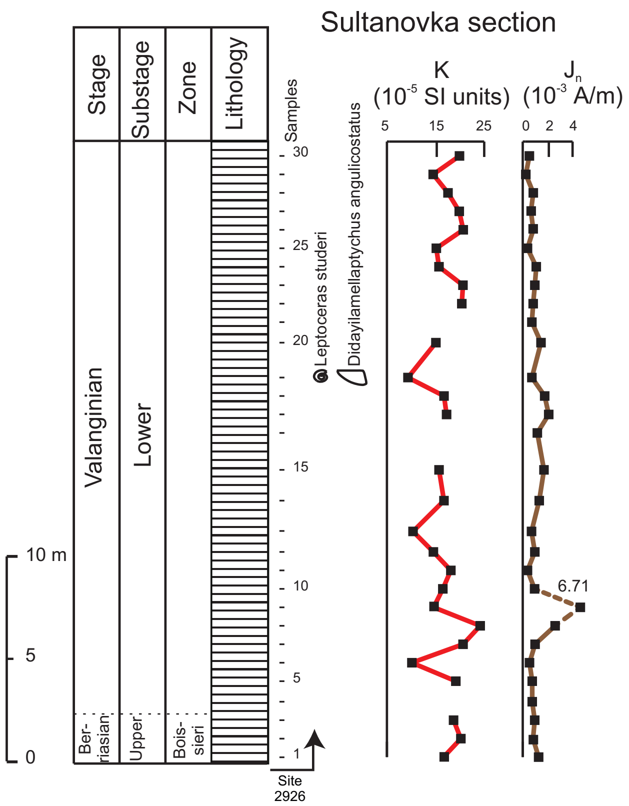

Fig. 4. The Sultanovka magnetostratigraphic section of the Berriasian–Valanginian. See Figs. 2, 3 for the Legend.

One may surmise that the Sultanovka syncline represents a synsedimentary structure formed at about the Berriasian–Valanginian boundary. This is reasonable, because the end of the Late Cimmerian folding event in Crimea falls at the end of the Berriasian age (Nikishin et al. 1997). Presumably, within slightly lithified sediment with an anomalously high water content, flat clay particles with finely dispersed magnetite aggregated on them, might remain during folding. This accounts for the paradoxical character of the AMS anomalous character. Grishchenko & Bagayeva (2014) earlier specified low clay viscosity as the cause of the abnormal AMS.

Component analysis results are presented in Fig. 8. It was impossible to recognize a stable $\mathbf{J_n}$ component characterized by maximum deviation angles of less than 15° in some samples; their number did not exceed 5 % of the total amount of the palaeomagnetic collection. According to Zijderveld diagrams, in most cases, a two component $\mathbf{J_n}$ composition is recorded: a low-coercivity component that is disintegrated after 5–15 mT, and a high-coercivity (stable) one, sustained up to 35–50 mT (Fig. 8). $\mathbf{J_n}$ directions close to the high-coercivity component vectors have also been recognized after the control thermal cleaning of duplicate cubes. Reproducibility of the results applying two different types of magnetic cleaning increases the reliability of the acquired palaeomagnetic data.

Analysis of the palaeomagnetic data from outcrop 3058 in the Zavodskaya Balka section shows that the inter-strata clustering of the $\mathbf{J_n}$ stable components in the lower parts of the section, unaffected by landslides (Fig. 9A, Table 1), is 3 to 4 times higher than in the highly deformed upper part of the quarry (Fig. 9B, Table 1). In the lower part of the section, a clear tendency is observed of clustering into two groups on the stereograms: in the N-NW rhumbs of the lower hemisphere and in the SE sector of the upper hemisphere (Fig. 9A and B), corresponding to a normal geomagnetic field (N) and reverse (R) polarities, respectively. In the uppermost beds of the profile, the characters of many palaeomagnetic directions are abnormal (e.g., negative dips with northern declinations) (Fig. 9B), which prevents any contemplations on the polarity direction, however provisional.

Nevertheless, analyses of the distributions of the magnetic ellipsoid axes and palaeomagnetic vectors through the entire Zavodskaya Balka section, with earlier data reconsidered (Arkadiev et al. 2010, 2015; Guzhikov et al. 2014), reveal a close relationship between distortions of petromagnetic and palaeomagnetic parameters (Fig. 10A). As an AMS "abnormality" measure (Δ_{AMS}) for each sample, the deviation of the K3 projection from the K3 average direction in the lowermost parts of the section (lower most Boissieri zone), probably

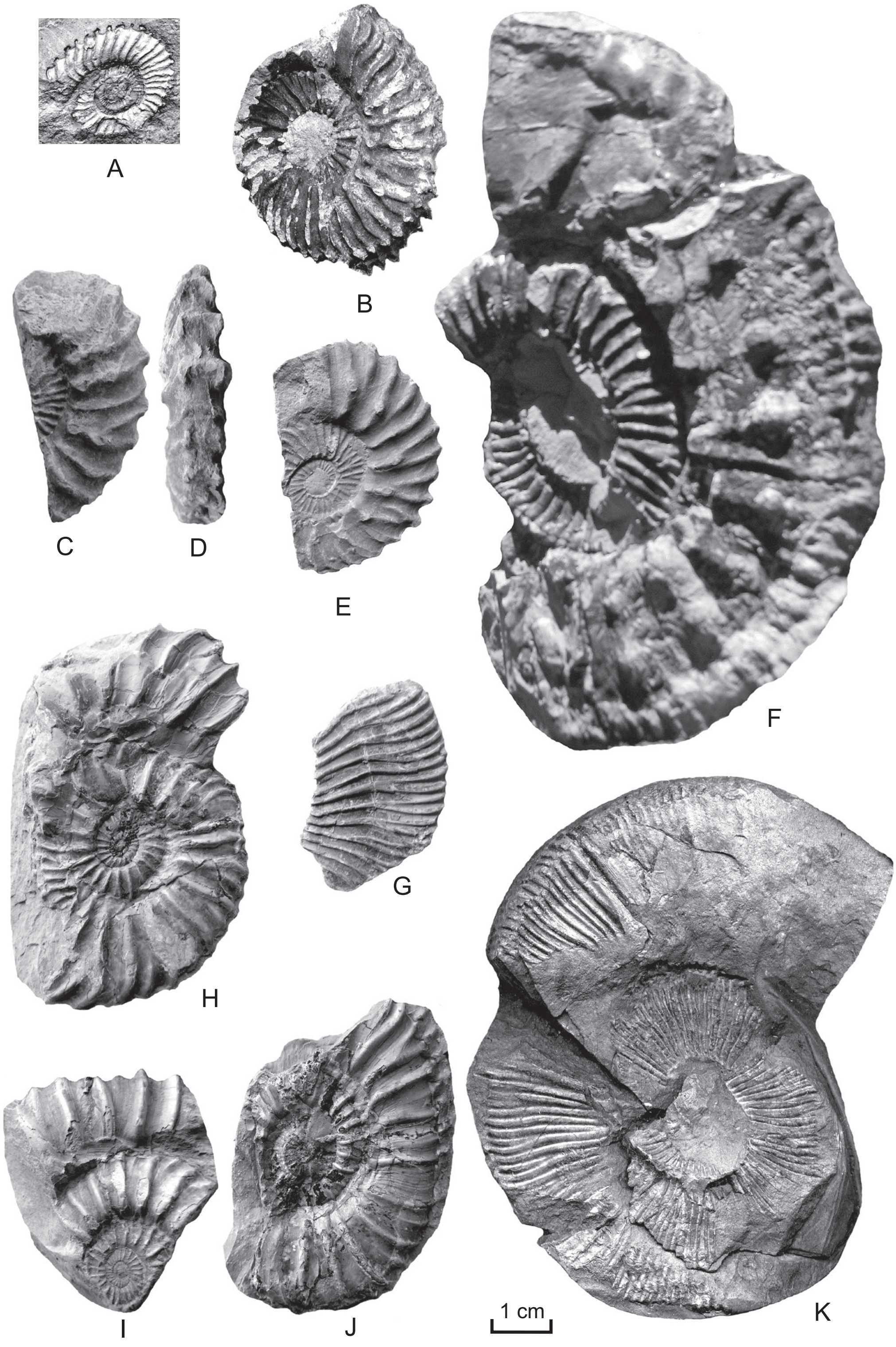

Fig. 5. Ammonites from the Sultanovka, Zavodskaya Balka and Koklyuk sections. **A** — *Leptoceras studeri* (Ooster), 5/13217, side view (x1), village of Sultanovka, Upper Berriasian–Lower Valanginian; **B–E:** *Neocosmoceras euthymi* (Pictet), B — 80/13175 in side view (x1), Feodosiya, Zavodskaya Balka section, Boissieri zone, Euthymi subzone; C, D — 16/409: C – side view (x1); D – ventral view (x1), village of Nanikovo, Koklyuk mountain, Boissieri zone, Euthymi subzone; E — specimen No. 12/409 side view (x1), village of Nanikovo, Koklyuk mountain, Boissieri zone, Euthymi subzone; **F** — *Malbosiceras malbosi* (Pictet), 2/381, side view (x1), Feodosiya, Zavodskaya Balka section, Boissieri zone, Euthymi subzone; **G** — *Berriasella callisto* (d'Orb.), 11/409, side view (x1), Feodosiya, Zavodskaya Balka section, Boissieri zone, Callisto subzone; **H–J:** *Riasanites crassicostatum* (Kvant. et Lys.), H — No. 9/409, side view (x1); I — No. 8/409, side view (x1); J — 10/409, side view (x1), Feodosiya, Zavodskaya Balka section, Boissieri zone, Crassicostatum subzone; **K** — *Fauriella* cf. *boissieri* (Pictet), 1/381, side view (x1), Feodosiya, Zavodskaya balka section, Boissieri zone.

non-affected by deformations during diagenetic processes, because the maximum of the folding epoch falls on the end of the Berriasian age (Nikishin et al. 1997) . The angle between the stable component $\mathbf{J_n}$ and the average palaeomagnetic vector in the lowermost of the section served as the palaeomagnetic "abnormality" measure (Δ_{Jn}). The linear correlation coefficient between Δ_{AMS} and Δ_{Jn}, determined from 132 samples and equal to 0.35, is significant at the level of p=0.001. This means that significant variance of K3 in the AMS stereograms and low interlayer palaeomagnetic clustering in the uppermost of the Berriasian most probably resulted from the same cause — viscous-plastic deformations at the end of the Berriasian age (or deformation by landslides at the Quaternary). Similar changes in the magnetic fabric and remanence of clays due to the close interaction of weak tectonic deformation and diagenetic processes are indicated in (Parés et al. 1999; Parés

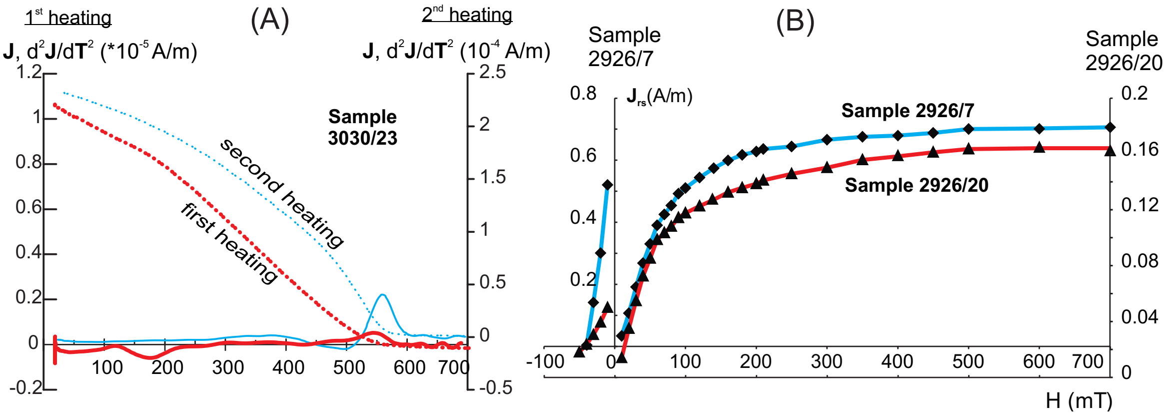

Fig. 6. Results of magnetic-mineralogical examinations: **A** — The curves characterizing dependence of the magnetization on temperature (dotted line) and second derivatives of these curves: the wide curve corresponds to the first heating, the thin curve is related to the second. **B** — The curves of magnetic saturation.

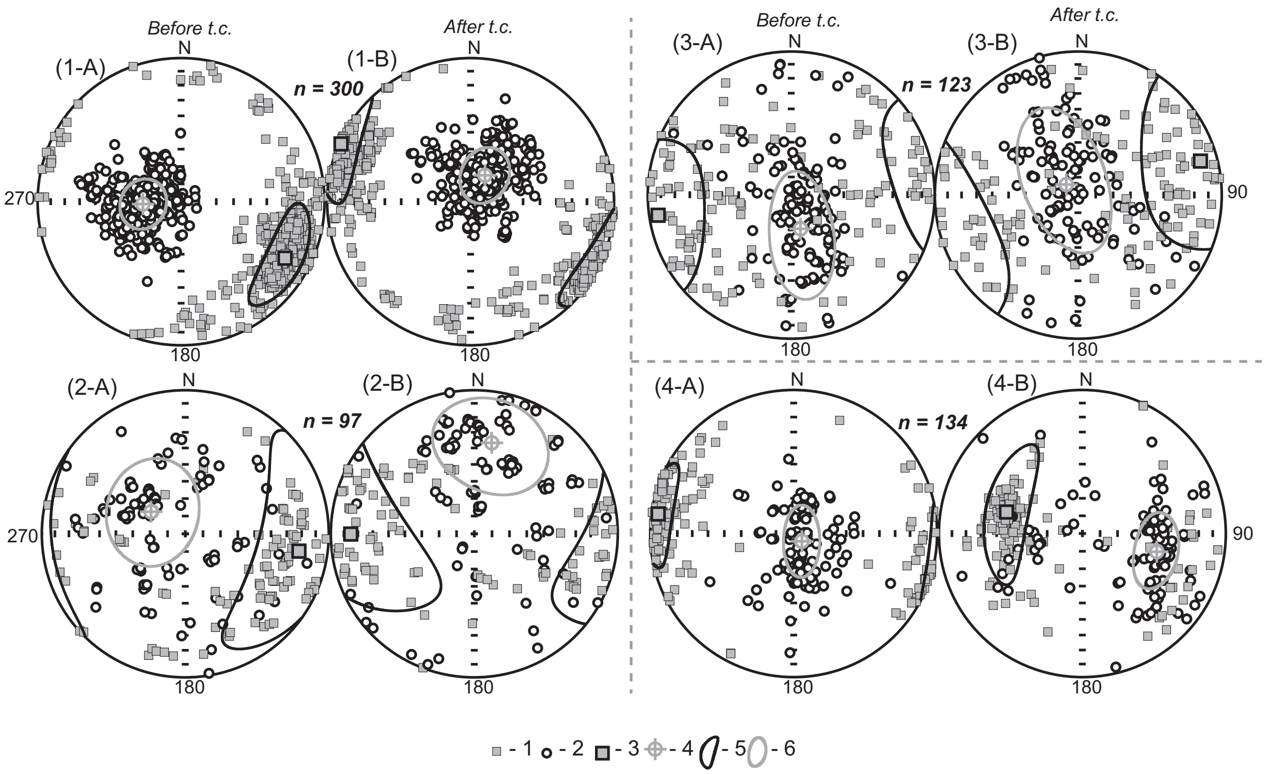

Fig. 7. Anisotropy of magnetic susceptibility: **1-A, B** — the lowermost of the Zavodskaya Balka section (Guzhikov et al. 2014, site 2900); **2-A, B** — the uppermost of the Zavodskaya Balka section (site 3058); **3-A, B** — Koklyuk (sites 3030 and 3060); **4-A, B** — Sultanovka (site 2926). *Legend*: 1, 2 — projections of the long (*K1*) and short (*K3*) axes of magnetic ellipsoids, respectively; 3, 4 — K1 and K3 average directions respectively; 5, 6 — confidence ellipsoids for *K1*and *K3* respectively, n — the number of samples.

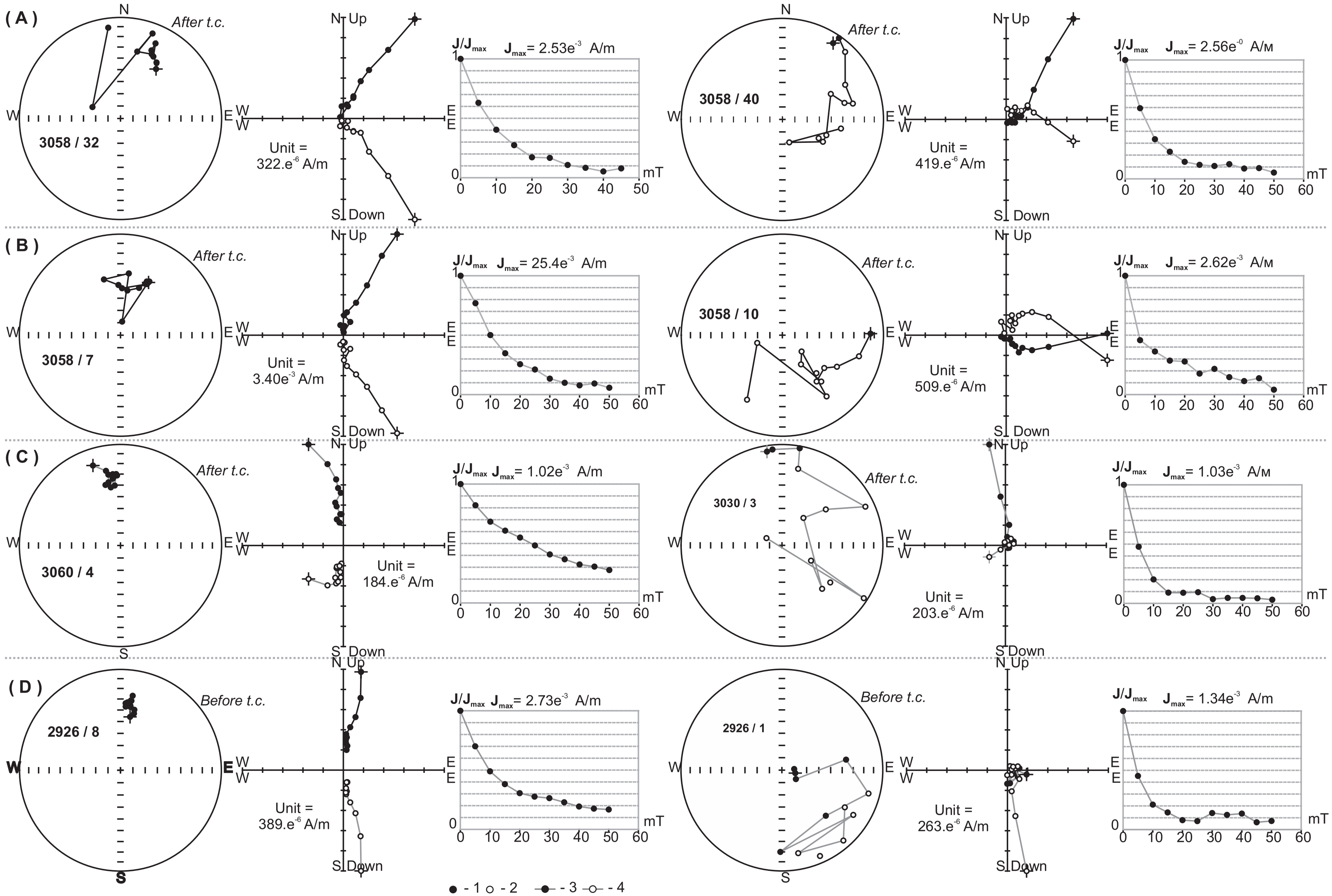

Fig. 8. Component analyses results for the Zavodskaya Balka (**A, B**), Koklyuk (**C**) and Sultanovka (**D**) sections. From left to right: stereographic projections of Jn changes in the course of magnetic cleanings, diagrams of Zijderveld, thermal demagnetization graphs. *Legend*: projections of the $\mathbf{J_n}$ directions: 1, 2 — on the lower and the upper semispheres respectively; 3, 4 — on the horizontal and the vertical planes respectively.

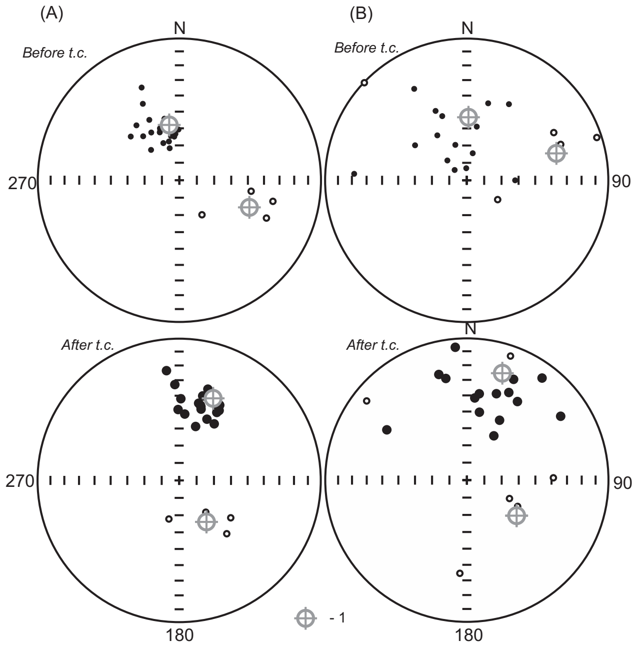

Fig. 9. Stereoprojections of the $\mathbf{J_n}$ stable components: **A, B** — Zavodskaya Balka, outcrop 3058 (the lowermost and the uppermost parts of the section respectively — should be before and after tectonic corrections. *Legend*: 1 — average direction of the $\mathbf{J_n}$ stable components. See Fig. 8 for other symbols.

Table 1: Statistical palaeomagnetic characteristics of the examined sections. *Legend:* Before t. c. — before tectonic correction; After t. c. — after tectonic correction; n – number of samples in the selection; Dec/Inc — average palaeomagnetic declination/inclination; k — palaeomagnetic precision parameter; α_{95} — radius of the vector confidence circle.

			Polarity	**n**	**Dec° / Inc°**	**k**	**α_{95}°**
3058	Uppermost	before t.c.	N	15	337.2 / 62.8	8.7	13.7
			R	4	73.3 / −34.2	6.8	38.0
		after t.c.	N	15	17.4 / 31.3	11.1	12.0
			R	4	127.3 / −55.2	6.8	38.0
	Lowermost	before t.c.	N	20	338.0 / 58.1	47.4	4.8
			R	4	111.2 / −46.0	16.4	23.4
		after t.c.	N	20	16.1 / 43.3	48.5	4.7
			R	4	144.6 / −60.8	22.9	19.6

2004 and others). Therefore we think, **ChRM** directions in the uppermost of Zavodskaya balka section may be reasonably used for polarity sign determinations after having turned them through an angle equal to the angle of the K3 deviation from the average direction of the magnetic ellipsoid short axes.

We think, the magnetic polarity interpretation of the data for Koklyuk and Sultanovka clays premature, because, for the time being, there is no satisfactory explanation of all the features of their magnetic textures. Despite the fact that in Koklyuk a significant relationship between the Δ_{AMS} and Δ_{Jn} at the level of p=0.05 (Fig. 10B) has been revealed, also.

Reversal tests (McFadden & McElhinny 1990) were negative in the uppermost of Zavodskaya Balka, and fold test results (McFadden 1990) were either incorrect or they indicated the presence of a post-folding component.

The negative reversal test does not contradict the hypothesis of magnetization ancient age, because it may be explained by distorting of palaeomagnetic directions due to the clay viscoplastic deformations (or mineralogical effects of AMS coupled with remagnetization).

If the model of the formation of the remenence due to the close interaction of weak tectonic deformation and diagenetic processes at the top of the Zavodskaya balka section is valid, then the negative results of the reversal test are natural. We carried out a magnetic polarity interpretation of the data in the assumption that for weak deformations the magnetization vector is distorted by no more than a few tens of degrees.

The data thus acquired (Figs. 2–4) supply a number of indicators of primary magnetization (Van der Voo 1993; Zhamoida et al. 2000; Guzhikov 2013): (1) determinations of different polarity signs are regularly grouped throughout the sequence, making large N- or R-magnetozones; (2) polarity sign is indifferent to lithological composition, since heteropolar magnetozones are recognized within a homogeneous clay sequence; (3) palaeomagnetic structures in the examined sections are in conformity one another (Galbrun et al. 1986; Aguado et al. 2000; Ogg & Ogg 2008; Grabowski et al. 2016; Satolli & Turtù 2016) (Fig. 11).

Thus, the entire set of acquired data does not fit into the framework of rock remagnetization theory, but may conform to a model of magnetization development in partially lithified sediment in the course of synsedimentary deformations. Therefore, in spite of negative fold and reversals tests, we consider them fit to be used for magnetostratigraphic interpretation.

Discussion

Finds of *Leptoceras studeri* at Sultanovka (site 2926) support the view that there are Lower Valanginian beds present (Thieuloy 1966; Nikolov 1967; Company & Tavera 1985; Arkadiev et al. 2011). *Neocosmoceras euthymi*, *Fauriella* cf. *boissieri* and *Malbosiceras malbosi*, found at Zavodskaya Balka, characterize the Euthymi subzone of the Upper Berriasian Boissieri zone (Arkadiev et al. 2010). This allows comparison of those levels with the Paramimounum subzone in France etc. (Le Hégarat 1973; Tavera 1985). *Riasanites crassicostatum*, found in the higher part of the same section, characterize the Crassicostatum subzone of the Boissieri zone (Arkadiev et al. 2012). This subzone correlates with the lower part of the Picteti subzone of the Boissieri zone in the Mediterranean Tethys. The species *R. crassicostatum* was previously known only from the Berriasian of the central Crimea (Kvantaliani & Lysenko 1982). The Callisto subzone was previously assigned to the upper Berriasian of France (Le Hégarat

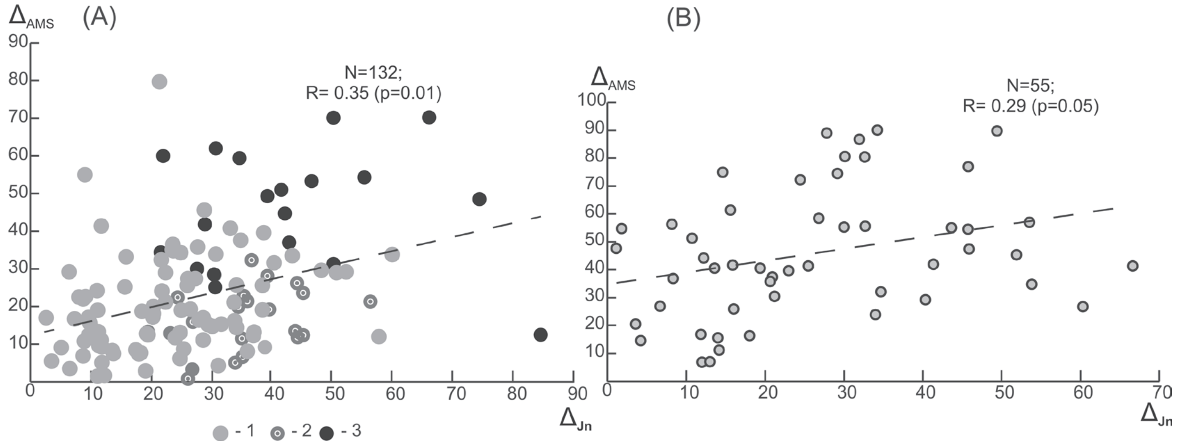

Fig. 10. Graph of the angular distance of the short axes projections from the projection average direction K3 (Δ_{AMS}) and the angular distance of palaeomagnetic direction $\mathbf{J_n}$ against the average direction of stable component $\mathbf{J_n}$ (Δ_{Jn}) for the Zavodskaya Balka (**A**) and the Koklyuk (**B**) sections. Average directions of the K3 projections and of the $\mathbf{J_n}$ stable components in the Zavodskaya Balka are taken from (Guzhikov et al. 2014). *Legend*: 1 — the lowermost part of the Zavodskaya Balka section: outcrops 2900, 2925, 3032, 3031 (Guzhikov et al. 2014; Arkadiev et al. 2015); 2 — the lowermost part of the outcrop 3058; 3 — the uppermost part of the outcrop 3058.

& Remane 1968). A.Y. Glushkov earlier (1997) proposed the distinction of a Berriasella callisto zone in the Berriasian of Crimea, but without proper grounds at that time, however. Discovery of that species in the continuous section in eastern Crimea makes it possible to reconsider Glushkov's chart and to recognize a Callisto subzone. This may be correlated with the upper part of the Picteti subzone, the Alpillensis subzone and probably with the Otopeta, since in Spanish sections *B. callisto* is known from the Otopeta subzone (Tavera 1985). Obviously, the same Callisto subzone may be traced into the North Caucasus (Sey & Kalacheva 2000).

Specimens of *Neocosmoceras euthymi* from Koklyuk suggest the presence of the eponymous subzone of the Boissieri zone.

The belemnite *P. bipartitus* has traditionally been regarded as a Valanginian marker, but the recent study of the occurrence of that species in the Río-Argos section in Spain has shown its stratigraphic range to comprise the Upper Berriasian (the Picteti subzone) to the Lower Valanginian (the Pertransiens zone) (Janssen 2003). Aptychi, *D. angulicostatus*, from Crimea and Spain have been described from the Upper Hauterivian and *D. didayi* from the Valanginian (?) of Crimea and the Valanginian–Lower Hauterivian of the Mediterranean region (Kozlova & Arkadiev 2003; Vašíček et al. 2015). On the whole, belemnites and aptychi indirectly confirm the identification of beds attributable to the Valanginian Stage in the examined sections.

The set of palaeontological data allows reliable identification of the magnetozones M16n, M15r, M15n and M14r within the complicated alternating palaeomagnetic zonation of the Zavodskaya Balka sequence (Arkadiev et al. 2010, 2016; Guzhikov et al. 2014) (Fig. 11). Since the Neocosmoceras euthymi subzone is the age analogue of the lower Paramimounum subzone of the Boissieri zone (Arkadiev et al. 2010; Guzhikov et al. 2014), the lower reverse-polarity magnetozone in the Zavodskaya Balka (site 2900) should correspond to M16r. Discovery of *Berriasella callisto* (Arkadiev et al. 2016) in the topmost reversely magnetized beds of site 3058 allow us to regard them as being not younger than M14r.

Comparison of the Zavodskaya Balka palaeomagnetic record with current notions of magnetozone, calpionellid and ammonite subzone interrelations in the Berriasian–Valanginian boundary interval (Aguado et al. 2000; Ogg & Ogg 2008; Grabowski et al. 2016) confirms the correlation of the Euthymi and Paramimounum subzones, and does not contradict the correlation of the Crassicostatum and Picteti subzones, but leads to the conclusion, that only the lower part of the Crassicostatum subzone may correspond to the Picteti subzone. In any case, the Crassicostatum subzone, the whole of it or just the upper part, should be correlated with the Alpillensis subzone, because the finding of *R. crassicostatum* (Fig. 11) is associated with the analogue of the M15r chron, peculiar for this Tethyan subzone. The Callisto subzone in Crimea in terms of palaeomagnetic correlation (Fig. 11) should correlate with the Otopeta subzone, but the uppermost of the Crassicostatum subzone (Fig. 11) may correspond to the lowermost of the Otopeta.

Regrettably, solitary ammonite finds do not allow unambiguous conclusions, but the outlined version of scale comparisons is a first attempt at a comprehensive (bio- and magnetostratigraphic) Upper Berriasian correlation from Western Europe to Crimea. We hope it will be fully worked out in the near future.

Conclusions

In the Zavodskaya Balka section, Upper Berriasian biostratigraphic subdivisions have been recognized for the first time in a continuous succession: the Euthymi, Crassicostatum and Callisto subzones and magnetozone analogues from M16n to

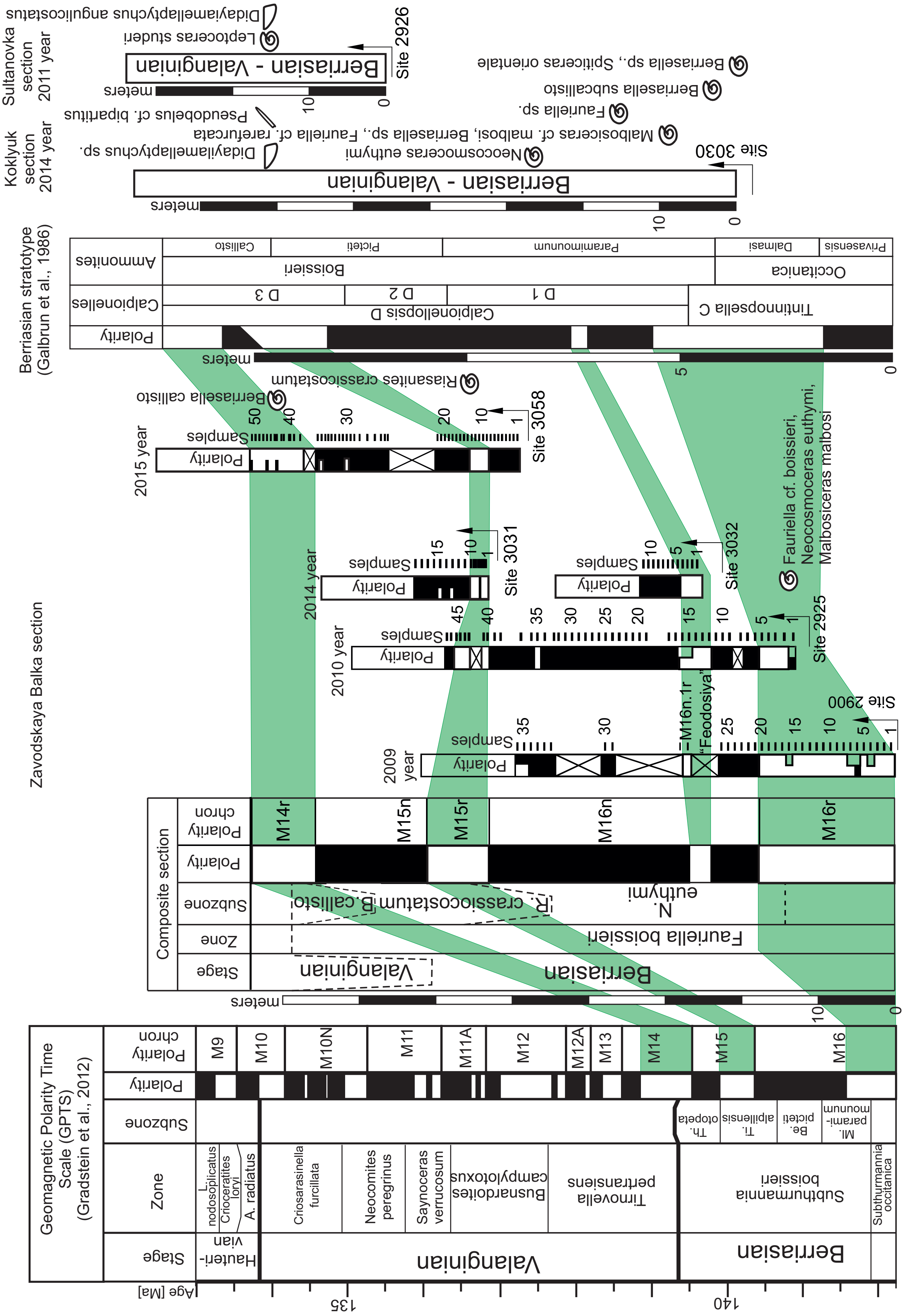

Fig. 11. Magnetostratigraphic correlation of the Berriasian–Valanginian boundary interval in the Feodosiya district. See Figs. 2, 3, 4 for the Legend.

M14r. With the magnetostratigraphic data considered, the described interval correlates with the upper part of the Paramimounum subzone and with the Picteti, Alpillensis, Otopeta subzones of the Boissieri zone from the Tethyan region (Aguado et al. 2000; Reboulet et al. 2014).

In the Koklyuk profile, the Upper Berriasian Euthymi subzone was substantiated for the first time. Discovery of *Leptoceras studeri* at Sultanovka allows the deposits to be referred to the Upper Berriasian–Lower Valanginian. Discovery of the analogue of the M14r magnetic polarity zone in the Koklyuk and Sultanovka sections allows us to use it for substantiating the level of the base of the Valanginian in eastern Crimea, by the analogy with Western European sections where the Berriasian–Valanginian boundary occurs in the lower part of M14r.

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