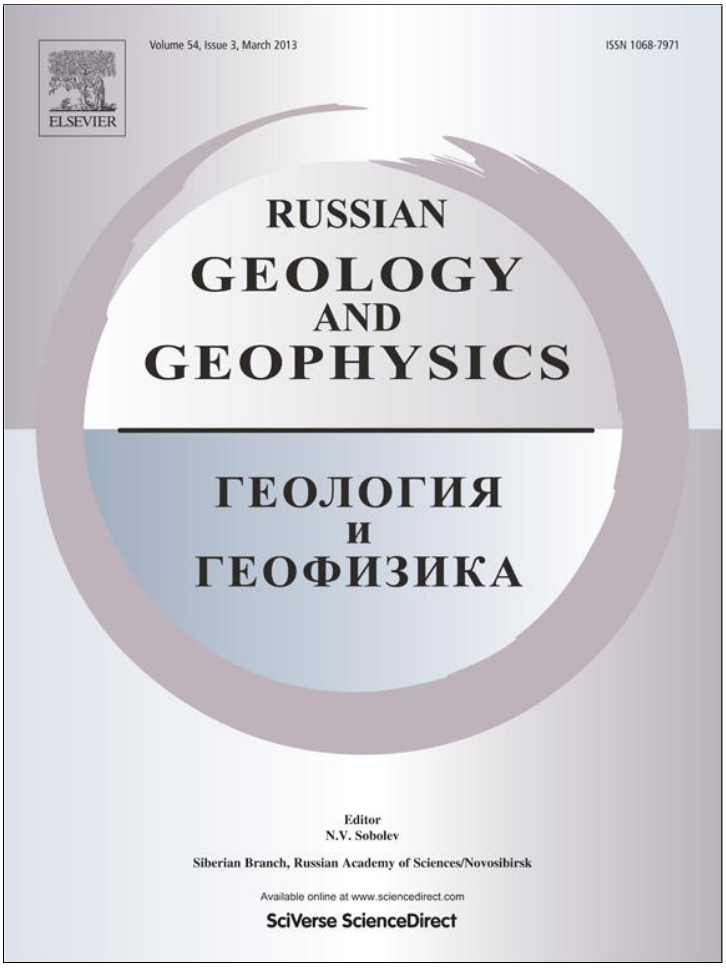
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New data on the magnetostratigraphy of the Jurassic–Cretaceous boundary interval, Nordvik Peninsula (*northern East Siberia*)

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Abstract

The results of this study were used to identify a reversed polarity magnetozone, referred to as M17r, in Berriasian sections of the Nordvik Peninsula (northern East Siberia) within the normal polarity magnetozone (M18n) from previous studies. The new magnetozone embraces the Volgian–Ryazanian boundary (Chetaites chetae/C. sibiricus zonal boundary). It was also found that the former magnetozone M17r at Nordvik, which includes the C. sibiricus/Hectoroceras kochi zonal boundary should correspond to magnetozone M16r. Using magnetostratigraphic and biostratigraphic criteria proves that the Boreal C. sibiricus Zone is correlated with at least the major part of the Tethyan Tirnovella occitanica Zone, and the Boreal H. kochi Zone is correlated with the lower part of the Malbosiceras paramimounum Subzone of the Tethyan Fauriella boissieri Zone.

Keywords: Jurassic–Cretaceous boundary; Northern Siberia; magnetostratigraphy; ammonites; belemnites; buchias; Tethyan–Boreal correlation

Introduction

The direct zonal correlation of Boreal and Tethyan Jurassic–Cretaceous boundary sections has remained questionable until very recent. The application of only biostratigraphical approach for solution of this long-debated task has brought ambiguous results. Faunal and floral differentiation, which became more pronounced at the end of the Jurassic and the beginning of the Cretaceous, inhibits a detailed correlation due to the lack of reliable fossil markers (Wimbledon et al., 2011; Zakharov, 2011). However, recent magnetostratigraphic results from the Nordvik Peninsula (northern East Siberia) opened up new possibilities for direct correlations between the Boreal marine and Tethyan marine and continental sections. A continuous succession of magnetozones correlative with Chrons M20n-M17r which include Kysuca (M20n.1r) and Brodno (M19n.1r) subchrons was established within Jurassic–Cretaceous boundary beds at Nordvik (Houša et al., 2007). Tethyan–Boreal correlations showed that the Jurassic–Cretaceous boundary corresponding in the Tethyan sections to the base of the Berriasella jacobi ammonite Zone or calpionellid Zone B must be placed in Boreal regions within the Craspedites taimyrensis Zone of the Upper Volgian Substage of the Upper Jurassic. Additional paleomagnetic samples were collected during fieldwork in summer 2007 on the Urdyuk-Khaya Cape, Nordvik Peninsula, from a 4.8 m thick interval of a sedimentary deposits that crosses the Jurassic–Cretaceous and Volgian–Ryazanian boundaries (Fig. 1).

A detailed paleomagnetic resampling in the Jurassic–Cretaceous boundary beds at Nordvik was undertaken to: (1) test the reliability of the previous paleomagnetic data (Houša et al., 2007) for establishing a reliable magnetostratigraphy of the section; (2) acquire additional information on the nature of remanent magnetization, which was responsible for the preservation of the primary paleomagnetic signal, based on the magnetic mineralogy; (3) intercalibrate the stratigraphic subdivisions of this section obtained by different dating methods (paleontological and paleomagnetic), which could provide a solution to the problems of Tethyan–Boreal correlation around the Jurassic–Cretaceous boundary.

Paleomagnetic sampling

The Upper Jurassic and Lower Cretaceous section at Nordvik Peninsula is a reference section and has been recently proposed by Zakharov (2011) as a candidate for the Berriasian

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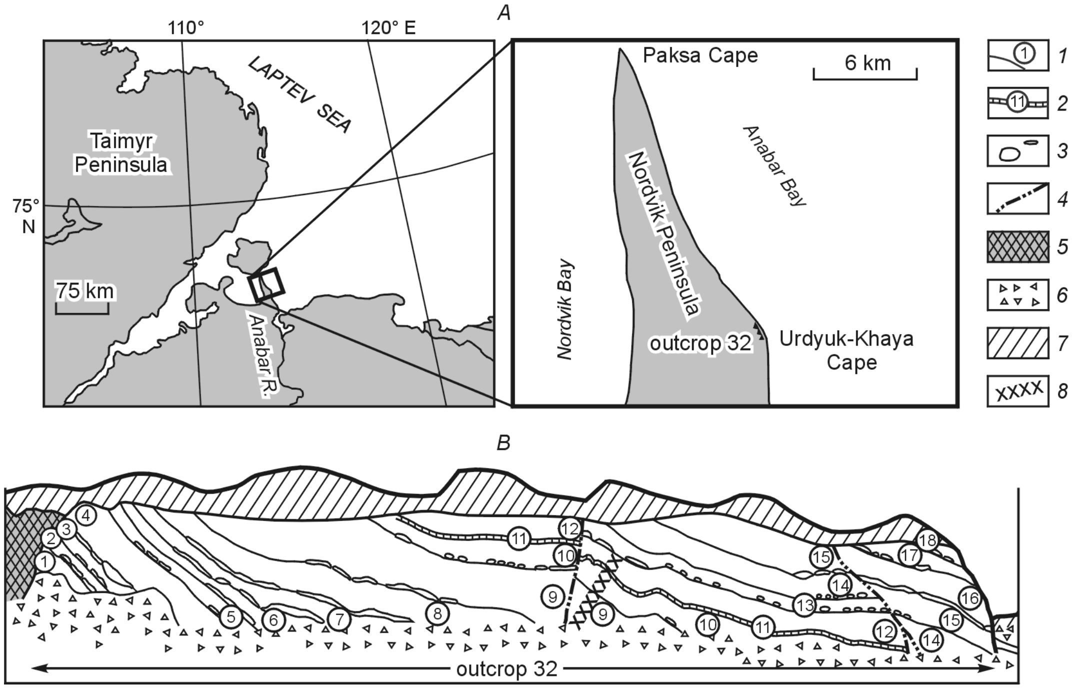

Fig. 1. Location map (*A*) and a simplified outcrop section (*B*) of Volgian and Ryazanian rocks, outcrop 32 (Urdyuk-Khaya Cape, Nordvik Peninsula, northern East Siberia). *1*, boundaries and bed numbers; *2,* condensed phosphatized limestone layer (bed 11) at the base of the Ryazanian Stage; *3*, concretions; *4*, faults; *5*, fractured rock; *6*, slumps; *7*, grassed area; *8*, interval sampled for paleomagnetic study.

GSSP in Boreal regions as an alternative to the Tethyan GSSP-candidates. The sections of Volgian and Ryazanian (=Boreal Berriasian) strata are well exposed on the Urdyuk-Khaya Cape, which pushes out into the Anabar Bay of the Laptev Sea. These strata consist of silty-clayey deposits with abundant concretions and concretionary horizons and attain a thickness of up to 22 m at outcrop 32, which was sampled for paleomagnetic studies (Dzyuba, 2012). They represent the continuous stratigraphic and sedimentary sequence with well-established successive ammonite, belemnite, buchia, foraminifer and dynocyst zones (Dzyuba, 2012; Nikitenko et al., 2008; Zakharov and Rogov, 2008; Zakharov et al., 1983).

All samples were obtained at outcrop 32, above and below a 4–6 cm thick phosphatized limestone layer, PLL (bed 11), with the base corresponding to the Volgian–Ryazanian boundary (Basov et al., 1970; Houša et al., 2007; Zakharov et al., 1983). This PLL has been formerly considered in recent studies on the Jurassic–Cretaceous boundary in northern Siberia as being composed of condensed deposits (due to a low sedimentation rate) enriched in iridium and other precious metals, as well as rare-earth elements (Mizera et al., 2010; Zakharov et al., 1993).

Hand samples were collected from the outcrop after removal of any weathered surfaces and oriented with a sun and magnetic compass. With previous studies in mind (Chadima et al., 2006), siderite-bearing concretions and concretionary layers that did not retain their primary magnetizations were avoided (Houša et al., 2007). A total of 83 oriented samples were collected from the 4.8 m in thick interval of the secton with a step of 5 cm (where possible), i.e., 12 samples were collected from the 1. 3 m thick Ryazanian interval (above the PLL), and 71 samples were collected from the 3.5 m thick Volgian interval (below the PLL) (Fig. 2). Hand samples were cut in the laboratory into two oriented duplicate specimens placed into the 8 cm^3 plastic boxes, and a number of unoriented specimens for rock magnetic studies.

Rock magnetic properties and magnetic mineralogy

The magnetic mineralogy and rock magnetic properties of samples were studied to assess their suitability for polarity determinations and obtain additional information on sediment lithology, e.g., the distribution of ferrimagnetic minerals. Rock magnetic measurements included magnetic susceptibility (k), natural remanent magnetization (NRM), thermomagnetic analysis and hysteresis measurements. Magnetic susceptibility measurements were made on a Bartington MS2 susceptibility meter; NRM intensities and directions were measured on a 2G Enterprises cryogenic magnetometer; Curie temperature measurements were performed using a TAF-2 thermoanalyzer (Curie balance). Hysteresis measurements were carried out on a J-meter coercivity spectrometer (Jasonov et al., 1998).

Concentration dependent rock magnetic parameters. The samples analyzed display low values of the NRM intensity (0.07–1.88 mA/m) and susceptibility (k = 9–30 × 10^{-5} SI). Note, however, that variations in susceptibility and NRM intensity across the sampled section are generally lower (Figs. 2, 3) than those reported in the previous study (Houša et al., 2007). Of 83 samples analyzed, 72 have NRM values

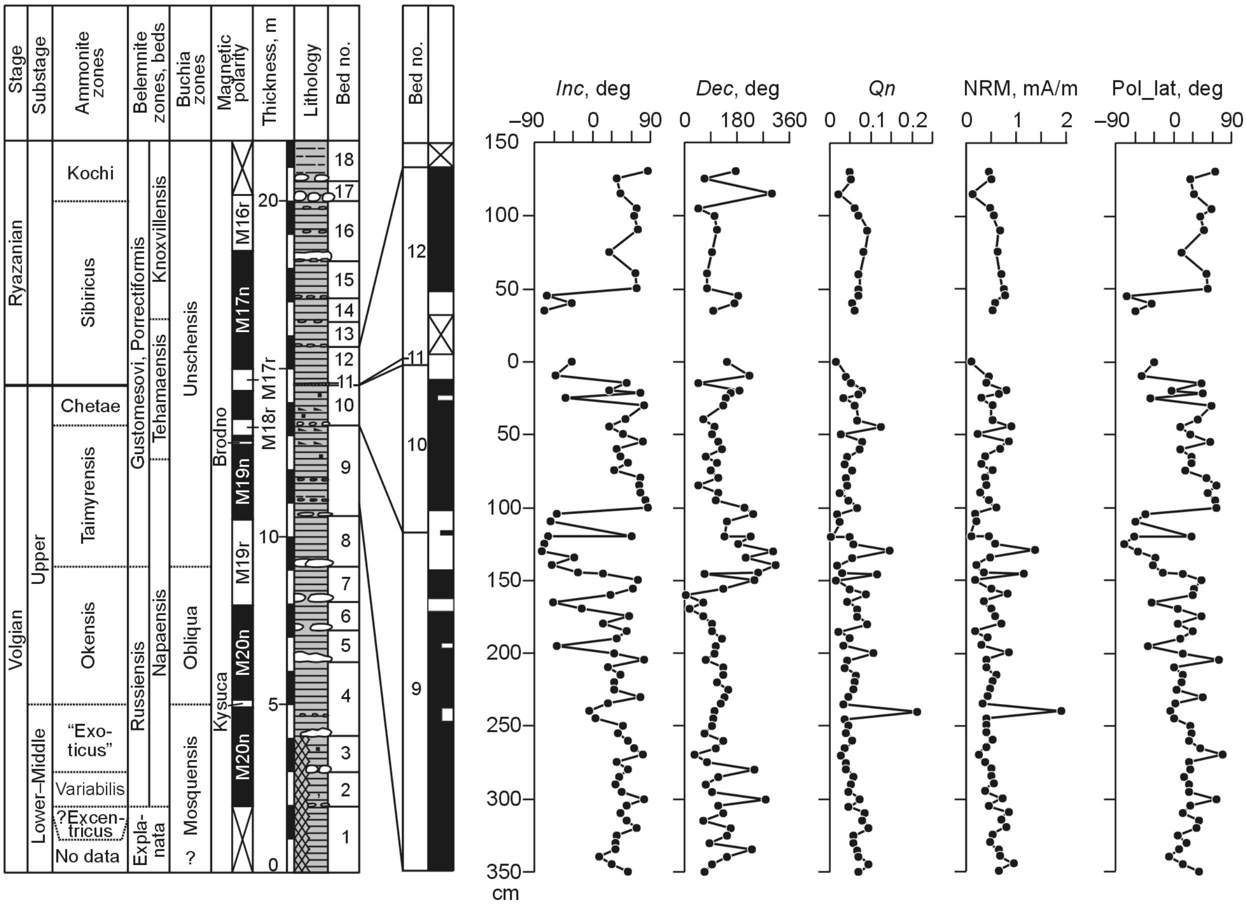

Fig. 2. Jurassic–Cretaceous boundary section at the Urdyuk-Khaya Cape, Nordvik Peninsula (outcrop 32). Lithology, biostratigraphy, magnetostratigraphy, and rock magnetic properties. *1*, clay; *2*, silty clay; *3*, organic-rich clay; *4*, fractured rock; *5*, condensed phosphatized limestone layer (PLL); *6*, carbonate concretions; *7*, pyrite (*a*), glauconite (*b*); *8*, normal polarity; *9*, reversed polarity (magnetozones defined by no adjacent specimens of the same polarity, are indicated by half bars); *10*, no sampling. Paleomagnetic and rock magnetic parameters: *Inc*, ChRM inclination; *Dec*, ChRM declination; NRM, natural remanent magnetization intensity; *Qn*, Koenigsberger ratio; Pol_lat, paleopole latitude calculated from a ChRM direction; k_{int}, initial magnetic susceptibility; k_{fer}, magnetic susceptibility of ferromagnetic minerals; J_r, saturation remanence; dJ_r/J_r, magnetic viscosity (drop of J_r in 50 ms after shutdown of direct magnetizing field); J_f, saturation magnetization (ferromagnetgic minerals); B_{cr}, coercivity of remanence; B_c, coercive force (ferromagnetic minerals); *S*, magnetic hardness ($S = -J_r\,(-300\ \text{mT}) / J_r(700\ \text{mT})$. Gray shading indicates samples collected from concretions and PLL. Lithology and biostratighraphic units after Zakharov et al. (1983) and Dzyuba (2012), magnetic polarity column modified after Houša et al. (2007).

ranging from 0.4 to 0.8 mA/m, eight samples from the concretionary lithologies have NRM values < 0.4 mA/m and only three sample display NRM in the range of 1.0 to 1.9 mA/m. Samples with extremely high NRM values (>5 mA/m), or very strongly magnetic samples, as described by Houša et al. (2007), were not detected. *Qn* values (the ratio of remanent to induced magnetization) generally range from 0.04 to 0.15, six samples have *Qn* < 0.03 and only one sample has *Qn* > 0.2 (Figs. 2, 3).

This behavior of magnetic parameter indicates that the criteria used for sample selection allowed us to collect samples which exhibit the uniformity of their magnetic properties and retain their primary magnetizations. A few weakly magnetic samples representing the concretionary lithologies differ markedly in other magnetic properties, and yield poor and unreliable paleomagnetic signal, as will be discussed below.

Hysteresis measurements suggest an extremely low concentration of ferromagnetic minerals. The contribution of the ferromagnetic fraction k_{fer} to the overall susceptibility k_{int} does not exceed 25% (Fig. 2). This is in good agreement with the conclusions of Chadima et al. (2006) that paramagnetic minerals dominate (~ 80 %) susceptibility. The only exceptions to this are samples collected from the PLL and concretions, which exhibit a dramatic decrease in either concentration dependent or grain-size dependent parameters (Fig. 2). It should be also noted that minor differences in the concentration of ferromagnetic minerals are recorded above and below the PLL. The mean k_{fer} values (except those for concretions and PLL) within the basal Ryazanian Stage are 1.2–1.3 times higher than those of the uppermost Volgian Stage.

This rather uniform concentration of ferromagnetic minerals in the sampled section is indicated not only by the behavior of k_{int} and k_{fer} but also by the ratio of these parameters as well as a similar variation pattern of J_r/J_f, whose mean values in Ryazanian samples are 1.2–1.3 times higher than in Volgian samples. Although these parameters exhibit little variation throughout the sampled interval, they are extremely low in the

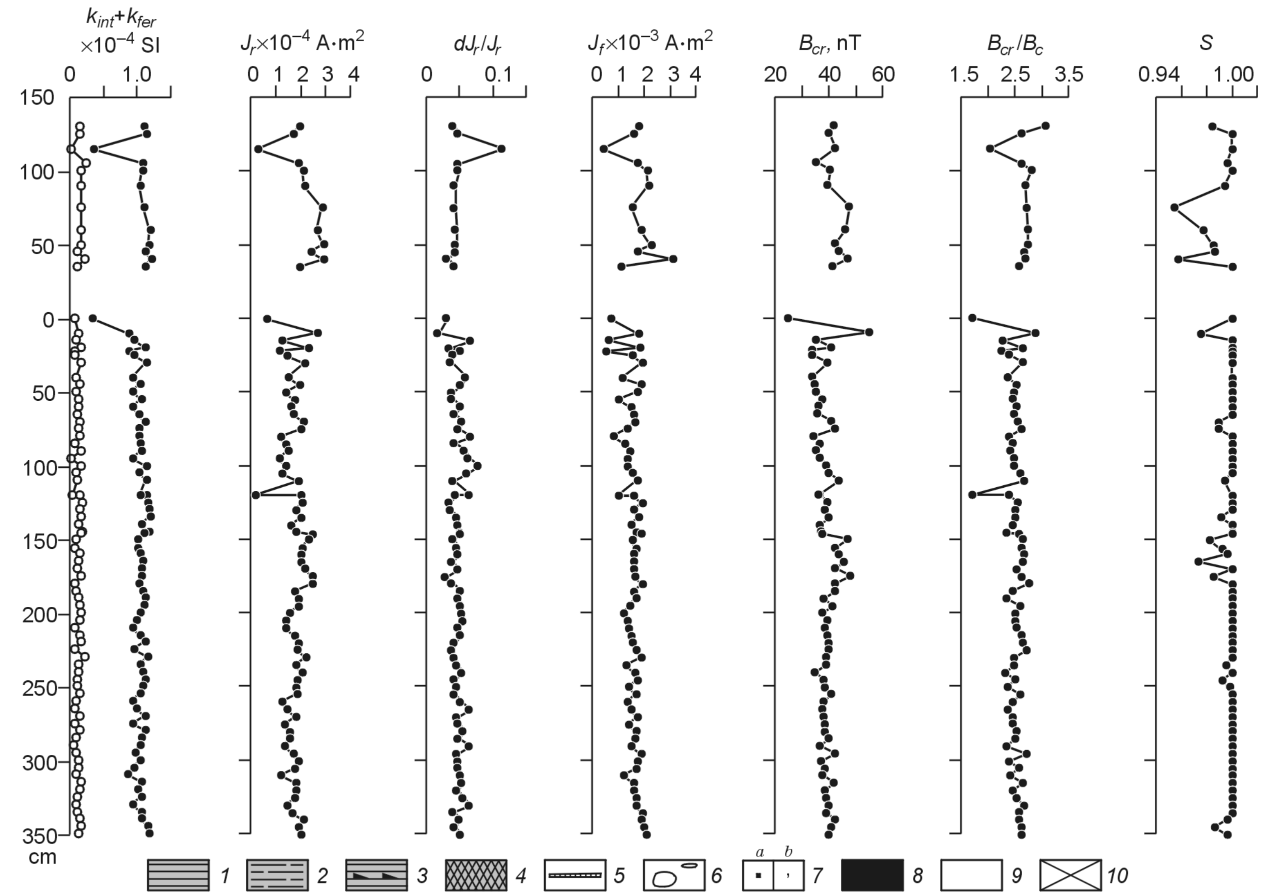

Fig. 2 (*continued*).

siderite-bearing and concretionary layers, exhibiting a decreasing trend similar to susceptibility values (Fig. 2).

Grain-size dependent rock magnetic parameters. Similar to concentration dependent parameters, grain-size dependent parameters derived for the sedimentary and concretionary lithologies parallel each other in their general trends. The concretions exhibit distinctly lower values of B_c, B_{cr} and decreasing magnetic grain sizes (B_{cr}/B_c), and sometimes higher magnetic viscosity (dJ_r/J_r), which is consistent with a ultrafine-grained magnetite (Houša et al., 2007), whereas the remainder of the sampled section demonstrates a rather uniform behavior of the above parameters (Fig. 2).

The Day–Dunlop plot was used to estimate the magnetic domain state of ferromagnetic grains (Day et al., 1977; Dunlop, 2002). Figure 4 shows a tight clustering of samples from the sedimentary interval within the pseudosingle domain (PSD) field. These grains are most likely 2–3 μm in size (Jackson et al., 1988). This group of points fits well a theoretical mixture curve of single domain (SD) and multidomain (MD) grains ranging from 40 to 20 % of the respective fraction, which is consistent with a magnetite–titanomagnetite carrier.

Samples collected from the concretions plot away from the theoretical mixing curve and the J_r/J_f ratio is significantly lower, which can be explained by extremely low ferromagnetic concentrations and, thus, the greater error in the measurements of J_r and J_f.

The *S*-ratio used to distinguish between magnetically soft (members of the magnetite–titanomagnetite series and maghemite) and hard (hematite and goethite) ferromagnets, indicates the dominance of a soft ferromagnetic phase in samples from the topmost Volgian Stage (Fig. 2), except a few samples with $0.97 < S < 1$, suggesting the presence of a minor hard magnetic phase.

Samples from the Cretaceous intervals directly above the PLL have lower *S*-ratios (0.95), suggesting higher concentrations of magnetically hard minerals. This can be attributed to the higher surface oxidation degree of ferromagnetic grains and the development of maghemite–martite crusts. The concentration of magnetically hard minerals decreases upwards, as indicated by $S \sim 1$. This suggests a lower oxidation degree of the magnetic grains.

Magnetic mineralogy. As indicated by thermomagnetic analysis, the magnetic grains carrying the ChRM component are represented by three minerals: (a) low-Ti magnetite with Curie points of 535–545 °C, probably in association with maghemite, as suggested by its irreversible thermomagnetic behavior at 180–200 °C (Burov and Yasonov, 1979); (b) titanomagnetite with Curie points of 360–420 °C; (c) titanomagnetite with Curie points of 270–290 °C (Fig. 5). This magnetic mineral assemblage exhibits a striking similarity in thermomagnetic curves throughout the sampled section, suggesting a complex, but stable source of magnetic minerals in sediments. Since low-Ti magnetite with Curie points of 500–550 °C and titanomagnetite with Curie points between 400 and 420 °C are known from Permo-Triassic traps of the Siberian Platform (Heunemann, 2003), it seems likely that the products of weathering of these Siberian traps were the possible source of magnetic minerals in the Late Jurassic–Early Cretaceous sedimentary basin.

The absence of ferrimagnetic sulfides with roughly similar Curie temperatures was determined by the ratios of J_r/k_{fer} and B_c, according to Peters and Thompson (1998). All samples correspond to magnetite–titanomagnetite.

The presence of hematite was not detected by the rock magnetic method due to its extremely low concentration in the oxidized grains.

These mineral magnetic data from the studied samples using a variety of magnetic methods agree well with the previous conclusion about the presence of low-Ti titanomagnetite and absence of magnetic sulfides in the section.

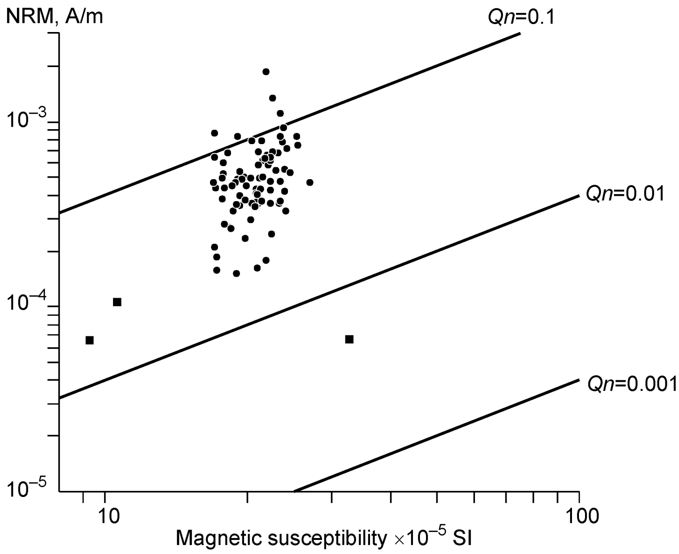

Fig. 3. Magnetic properties of rock samples from the Urdyuk-Khaya section. Squares denote samples from concretionary and condensed beds.

Paleomagnetic study

The initial polarity pattern of the sampled section was determined by measuring the NRM intensities and directions of all samples with a 2G-Enterprises cryogenic magnetometer using stepwise AF demagnetization in a magnetic field of up to 120 mT at 10 mT increments. Demagnetization data were analyzed following the standard procedures (Kirschvink, 1980; McFadden and McElhinny, 1990; Zijderveld, 1967) using specialized software package (Enkin, 1994).

As seen on the orthogonal plots, two components can be recognized in most samples: a low-coercivity (LC) component that is removed by demagnetization at 5–15 mT and a high-coercivity (HC) component isolated by AF demagnetization at a peak field of 20 mT (Fig. 6). In most cases, the LC component plots close the present-day remagnetization direction and is, probably, a viscous overprint. The HC component represents the ChRM, which is used to determine polarity. About 90% of the samples yielded more or less consistent ChRM directions in the section, while the remaining 10% of the samples recorded the ChRM direction, which is strikingly different from that of the surrounding rocks (Fig. 2). These samples represent either weakly magnetic concretionary lithologies or are in contrast the most strongly magnetized rocks.

The ChRM directions determined by principal component analysis represent normal polarity directions (N) in the lower hemisphere and reverse polarity directions (R) in the upper hemisphere of the stereoplot (Fig. 7). In most cases, normal and reversed polarity components of the ChRM have shallower inclinations and are partially overlapped. This could be clearly the result of incomplete removal of the primary magnetization component, partial decay of primary remanence due to destruction of titanomagnetite and oxidation of magnetite to maghemite, shallowing of the ChRM inclination during compaction (Jackson, 1991), and rock deformation (Borradaile, 1993). Based on the degree of the magnetic anisotropy ellipsoid and the amount of the magnetic anisotropy (5–15%), compaction- and deformation-induced shallowing of the inclinations is reported from much of the sampled section (Chadima et al., 2006). In addition, this considerable scatter in the ChRM directions may be partially attributed to the weak magnetization of the samples, which approaches to the sensitivity threshold after being subjected to high demagnetizing fields. Mean directions of the high-coercivity ChRM

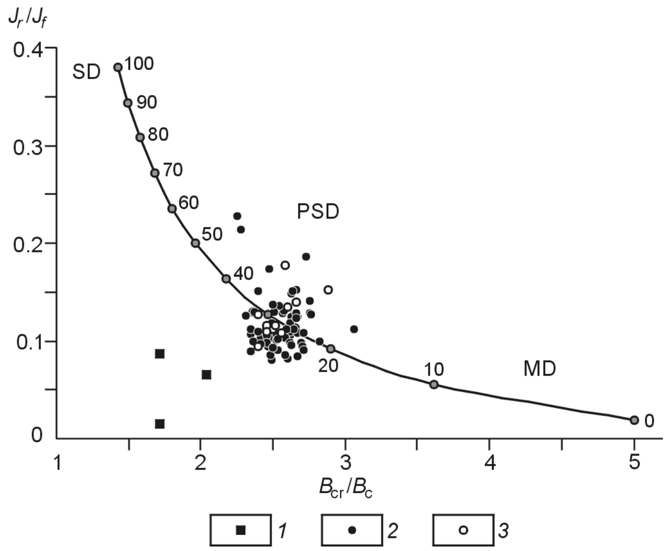

Fig. 4. Day–Dunlop plot (B_{cr}/B_c–J_r/J_f) for oriented samples from outcrop 32. SD, single-domain field; PSD, pseudosingle-domain field; MD, multidomain field. The theoretical SD–MD mixing curve for pure titanomagnetite is shown by line. Numbers along curve are percent fractions of SD grains. *1*, concretions, *2*, *3*, silty-clayey rocks with normal (*2*) and reversed (*3*) polarity.

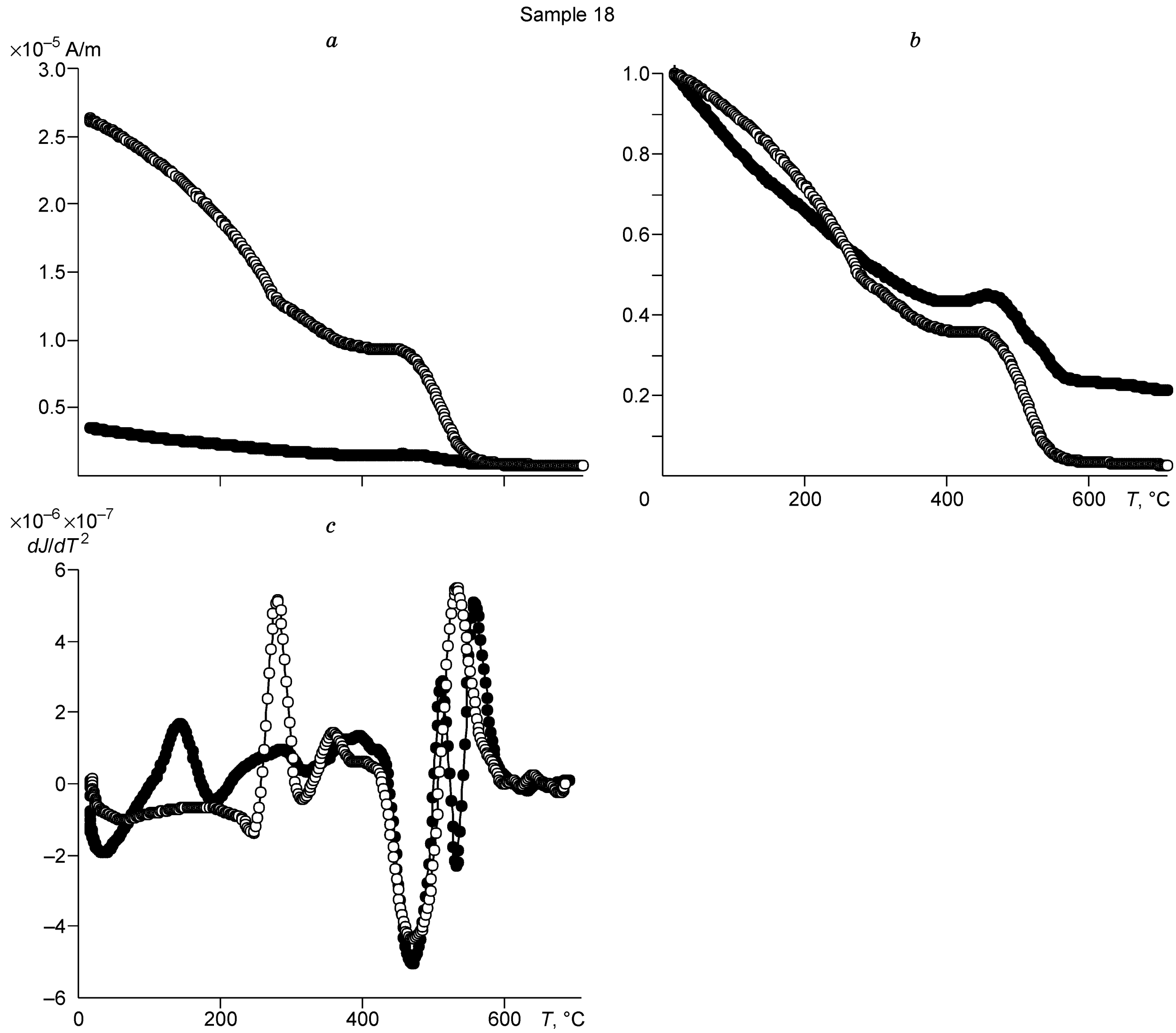

Fig. 5. Thermal demagnetization plots. *a*, TMA curves (solid circles are first heating step, open circles are second heating step); *b*, normalized TMA curve; *c*, second derivative of the heating curve.

component and associated paleomagnetic pole positions are given in Table 1. Note that the statistical parameters of the distribution of ChRM directional data for both the reversed and normal polarity groups, and for the entire population, are lower than those reported by Houša et al. (2007). Moreover, the study revealed paleopoles at low latitudes (Table 1), which can be probably explained by different selection criteria. Table 1 and Fig. 7 show all directions found in this study (83 ChRM directions for 83 hand samples), as compared to 209 ChRM directions for 317 samples used in the previous magnetostratigraphic study (Houša et al., 2007). The resulting data sets do not include 108 samples (~ 30% of the total number of samples), which are probably shallow inclination samples (compare Figs. 8 and 9 in Houša et al. (2007)).

Variable success in removal of the ChRM component can lead to widely scattered directions in reversed polarity samples, but has little effect on the paleomagnetic statistics for normal polarity, because the normal polarity directions are rather close in both ancient and present geomegnatic field. This, in turn, yielded in a negative reversal test (McFadden and McElhinny, 1990), because the angle between normal and reversed means is less than 43.9, and exceeds the critical value of 23.8.

Nevertheless, despite the negative reversal test, the derived data sets meet 6 of 10 reliability criteria for paleomagnetic data in the magnetostratigraphy (Opdyke and Channell, 1996). This proves the data to be sufficiently reliable, at least, in terms of the sign of polarity. Rock magnetic data can provide another important argument for primary remanence preservation in all samples analyzed.

Rock magnetic evidence for the primary nature of the ChRM

1. Except for concretions and concretionary layers, the concentrations of ferromagnetic and paramagnetic minerals are very uniform throughout the section, suggesting steady-state sedimentary conditions, a permanent source area at the time

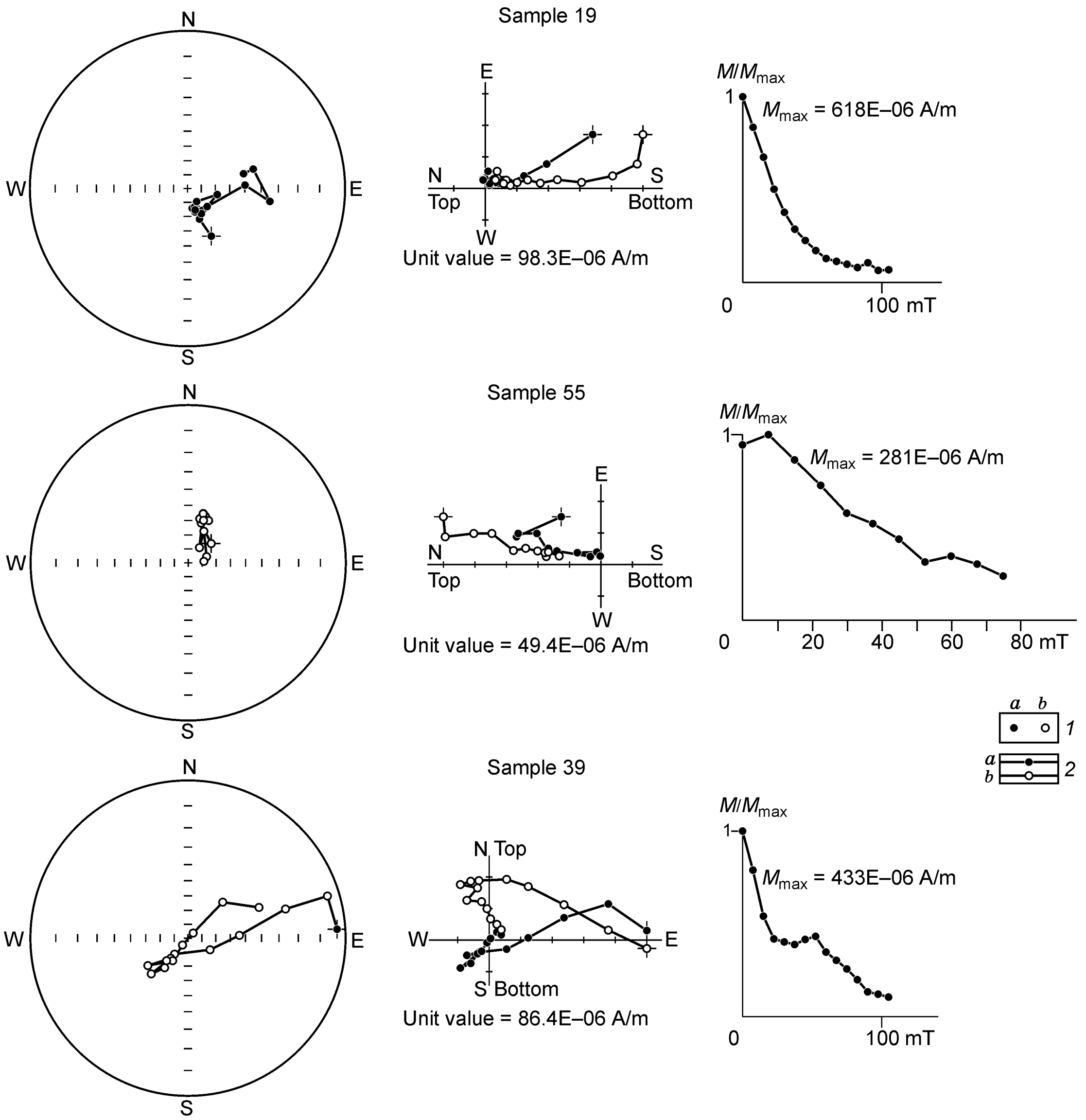

Fig. 6. Results of principal component analysis. From left to right: stereoplots of variation in the remanence directions during progressive AF demagnetization of samples, Zijderveld plots (stratigraphic coordinates), and intensity decay curves. *1*, hemispheres: *a*, lower, *b*, upper; *2*, planes: *a*, horizontal, *b*, vertical.

of deposition, and the lack of localized, chemical remagnetization of rocks.

2. Values of $Qn < 1$ in all samples indicate a detrital remanent magnetization. High Qn values, which were reported from Upper Cretaceous deposits of West Siberia (for the topmost Pokur Formation, Qn is well above 1.5), can then be interpreted as a record of both detrital and chemical magnetizations (Gnibidenko et al., 2012).

3. Variations in the rock magnetic properties across the section exhibit no correlation with the observed polarity zones, strongly suggesting that the ChRM direction is independent on the concentration, composition and structure of the magnetic minerals.

4. In most samples, the magnetic minerals and carriers of the ChRM are dominated by magnetite–titanomagnetite and have an almost identical PSD state. The PSD magnetite and titanomagnetite dominate the magnetization in marine sediments (Opdyke and Channell, 1996).

The above arguments strongly confirm the primary character of the isolated ChRM component and, therefore, the reliability of the magnetostratigraphic section derived from this component.

Paleomagnetic and biostratigraphic criteria for Tethyan–Boreal correlation

Paleomagnetic criteria

A magnetostratigraphic section compiled from the magnetic polarity of ChRM consists of four normal and three reversed polarity intervals (Fig. 2), apart from a number of the single sample-based short polarity events. Because of their poor

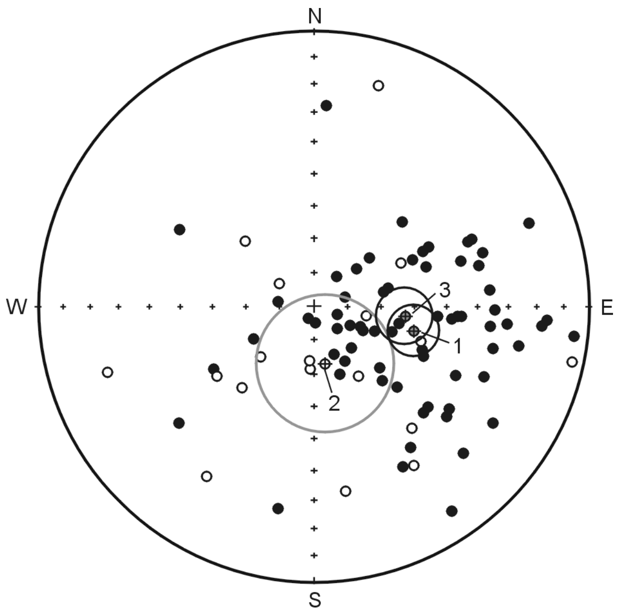

Fig. 7. Stereoplot showing the distribution of ChRM directions after AF demagnetization. Numbers show mean–site directions with confidence intervals for: 1, normal polarity sites; 2, reversed polarity sites; 3, entire population. Mean–site direction was calculated after rotation of all reversed directions by 180°. For symbols see Fig. 7.

reliability, these short events were ruled out from further interpretation.

The polarity pattern of the proposed section within the 50–350 cm interval below the PLL is broadly similar to that previously described by Houša et al. (2007). The fundamental difference from previous studies is the presence of an additional reversed polarity zone, which includes the PLL (Fig. 8). This zone has its lower boundary 10 cm below and its upper boundary 45 cm above the PLL (beds 10–12). Sediments at 45–130 cm above the phosphatized limestone represent the normal polarity interval, which is consistent with the previous data (Houša et al., 2007).

One likely explanation for the absence of a reversed polarity zone in beds 10–12 in the magnetostratigraphic section proposed by Houša et al. (2007) is that the interval above and below the PLL was not sampled properly due to the difficulties raised by cleaning up the surface of silty-clay rocks under conditions of permafrost. Poor preservation of the original rock texture may have caused difficulties in the sampling and isolation of a primary magnetization component.

A straightforward interpretation of our magnetic stratigraphy is that the basal part of the studied interval (beds 9, 10) shows the complete sequence of magnetozones, encompassing Chrons M19n, M19n.1r (Brodno), M18r, and M18n, which is consistent with those formerly described by Houša et al. (2007). In the upper part of this interval (the top of bed 10, beds 11 and 12), we recognized magnetozones assigned to Chrons M17r and M17n. Thus, the reversed polarity zone previously identified as M17r by Houša et al. (2007) must be reassigned in our interpretation to M16r.

These results provide an important constraint that allows correlation of Boreal and Tethyan biostratigraphies around the Jurassic–Cretaceous boundary (Fig. 9). According to the current understanding (Gradstein et al., 2004; Ogg and Ogg, 2008), the base of the Tethyan Tirnovella occitanica Ammonite Zone corresponds to the lower part of magnetozone M17r. A detailed paleomagnetic resampling of the Nordvik section revealed that magnetozone M17r includes the base of the Boreal Chetaites sibiricus Ammonite Zone rather than the base of the Hectoroceras kochi Ammonite Zone, as originally proposed by Houša et al. (2007). The C. sibiricus/H. kochi boundary falls within the reversed magnetozone (Houša et al., 2007) referred to as M16r in this paper, and appears to be stratigraphically closest to the Tirnovella occitanica/Fauriella boissieri zonal boundary of the Tethyan standard subdivision. These considerations could help resolve ambiguities in magnetostratigraphy of the Nordvik section arising from the absence of the equivalents of M17n within the C. sibiricus Zone. It became the basis for proposal of Guzhikov and Baraboshkin (2008) who postulate that part of this section

Table 1. Paleomagnetic directions and paleomagnetic pole positions from Jurassic–Cretaceous boundary interval at Nordvik (outcrop 32)

Polarity	n	Dec	Inc	k	α_{95}	Pol_lat	Pol_long	α_{95}
		deg			deg			
This study								
N	65	104.1	59.3	6.3	7.7	34.5	177.4	10.0
R	18	168.9	–72.5	3.8	20.6	–73.3	134.1	34.4
N + R	83	96.1	62.7	3.8	8.3	40.3	182.7	11.5
Houša et al. (2007)								
N	174	44.9	80.8	31.7	2.1	77	170.9	4.0
R	35	281.1	–75.6	6.7	10.1	–56.1	346.6	17.8
N + R	209	48.3	81.7	16.3	2.5	76.9	179.3	4.7

Note. Stratigraphic coordinates; n is number of samples; Dec and Inc, are declination and inclination; k, paleomagnetic clustering; α_{95} is the radius of the 95% confidence oval; Pol_lat and Pol_long are the latitude and logitude of the paleopole, respectively. Mean-site direction was calculated after rotation of all reversed directions by 180º.

seems to be either missing or is condensed. This assumption, in turn, was derived from conflicting magneto- and biostratigraphic results. If M17n corresponds to the overlying H. kochi Zone, then the base of this Boreal ammonite zone seems to be older than the base of the Dalmasiceras dalmasi Subzone of the Tethyan Tirnovella occitanica Zone, which is inconsistent with one of the biostratigraphic criteria as discussed below.

It should be noted that indications of the condensation were, however, detected in the Volgian–Ryazanian interval close to the boundary. Sedimentation rates as calculated by Grabowski (2011) for Chrons M20n, M19r and M18n in the Nordvik section vary from 8 to 12 m/m.y. Chrons M19n and M18r reveal apparently lower sedimentation rates comparable to those from ammonitico rosso facies (up to 1.5–2.0 m/m.y.). More precise age assignment to magnetozones in the upper part of the section shows that sedimentation tends to decrease in Chron M18n (about 1.7 m/ m.y.), and especially in M17r (0.5 m/m.y.), embracing the Volgian–Ryazanian boundary (thus, the timing of the PLL deposition), whereas M17n reveals a major increase in the sedimentation rate up to 12 m/m.y. This agrees with the sedimentation rates previously calculated for the Nordvik section on the basis of thickness data on the ammonite zones at the Volgian–Ryazanian boundary (Zakharov et al., 1993). The results confirm that the sedimentation tends to decrease dramatically from the beginning to the end of the Late Volgian, followed by increase since the early Ryazanian. The dramatic decrease in sedimentation rate at the Volgian–Ryazanian boundary was thought to correlate with the onset of the extremely condensed PLL with an anomalous enrichment of precious metals.

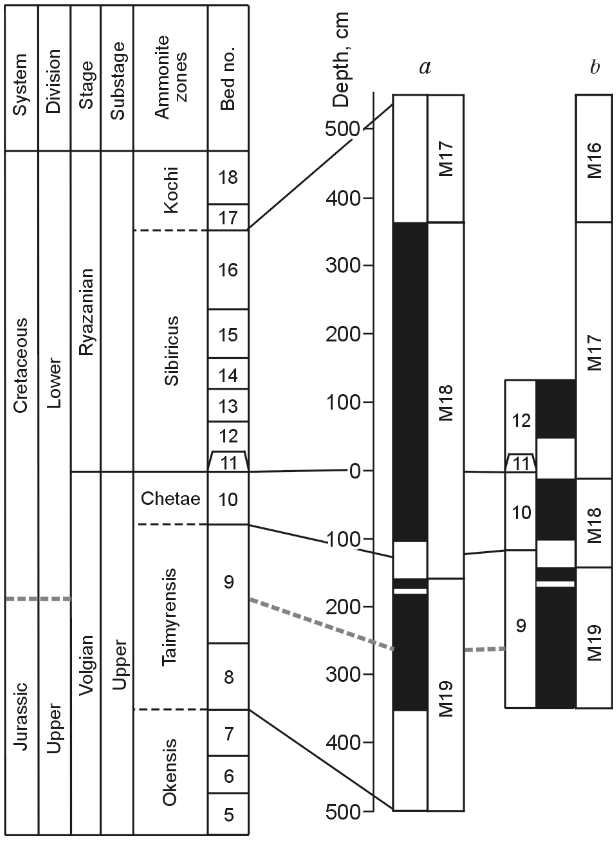

Fig. 8. Magnetostratigraphic calibration of Jurassic and Cretaceous boundary beds of the Nordvik section. *a*, Data from Houša et al. (2007), *b*, interpretation based on the data from this study and data from Houša et al. (2007). The inferred position of the Jurassic–Cretaceous boundary within magnetozone M19n (the base of the Tethyan Berriasella jacobi) is marked with a gray dashed line. For the remaining symbols see Fig. 2.

Biostratigraphic criteria

Despite long-lasting attempts to evolve biostratigraphic criteria for Tethyan–Boreal correlation across the Jurassic–Cretaceous boundary, very few relatively narrow macrofauna-based biostratigraphic intervals allowing tentative correlation between the Boreal marine sections and Tethyan standard succession have been documented in the literature. The magnetic polarity zones identified within these intervals need to be calibrated in a manner that is consistent with the biostratigraphy.

All these intervals were identified in sections containing mixed faunas made up of both Boreal and Tethyan taxa. According to Hoedemaeker (1987, 1990), three of these intervals represent interprovincially (or interregionally, which seems like a more apt name in our opinion) correlatable horizons (ICH): (1) the upper part of the Buchia elderensis Subzone of the Californian B. piochii s.l. Zone containing *Kossmatia*; (2) the horizon with co-occurring *Proniceras* and *Spiticeras* (between the first appearance of *Spiticeras* and the last appearance of *Proniceras*), which corresponds to the upper part of the B. fischeriana Subzone of the B. piochii s.l. Zone and the lower part of the B. aff. okensis Zone in California; (3) the upper part of the B. okensis Zone containing ammonites "*Argentiniceras" noduliferum/bituberculatum* and the basal part of the overlying B. uncitoides Zone containing *Neocosmoceras* in British Columbia and California.

According to Hoedemaeker, the first ICH correlates with the Tethyan Durangites Zone or at least its lower part on the basis that in Mexico *Kossmatia* has never been found below beds with *Durangites*, and the acme of *Kossmatia* coincides with the acme of *Durangites*, whereas in the Mediterranean province, a diverse *Durangites* fauna is present even with the same species as in Mexico. However, tentative evidence by Pessagno et al. (2009) pointing to the probable presence of *Kossmatia* in beds that are older than the first *Durangites*-bearing beds in Mexico, throws doubt on a possible correlation of this ICH. The Californian Buchia elderensis Subzone either correlates with the Siberian B. russiensis–B. taimyrensis Zones (which occupy the interval from the base of the Pavlovia iatriensis Zone to the top of the Epivirgatites variabilis Zone in the ammonite zonal succession) (Rogov and Zakharov, 2009; Zakharov, 1981; Zeiss, 1986), or can only be equated with the B. taimyrensis Zone (Taimyrosphinctes excentricus–E. variabilis Ammonite Zones) (Hoedemaeker, 1987; Jeletzky, 1984; Sey and Kalacheva, 1993). In both cases, the stratigraphic position of the uppermost part of the Californian B. elderensis Subzone with *Kossmatia* (4000–5000 feet above the base) (Imlay and Jones, 1970) should be similar to

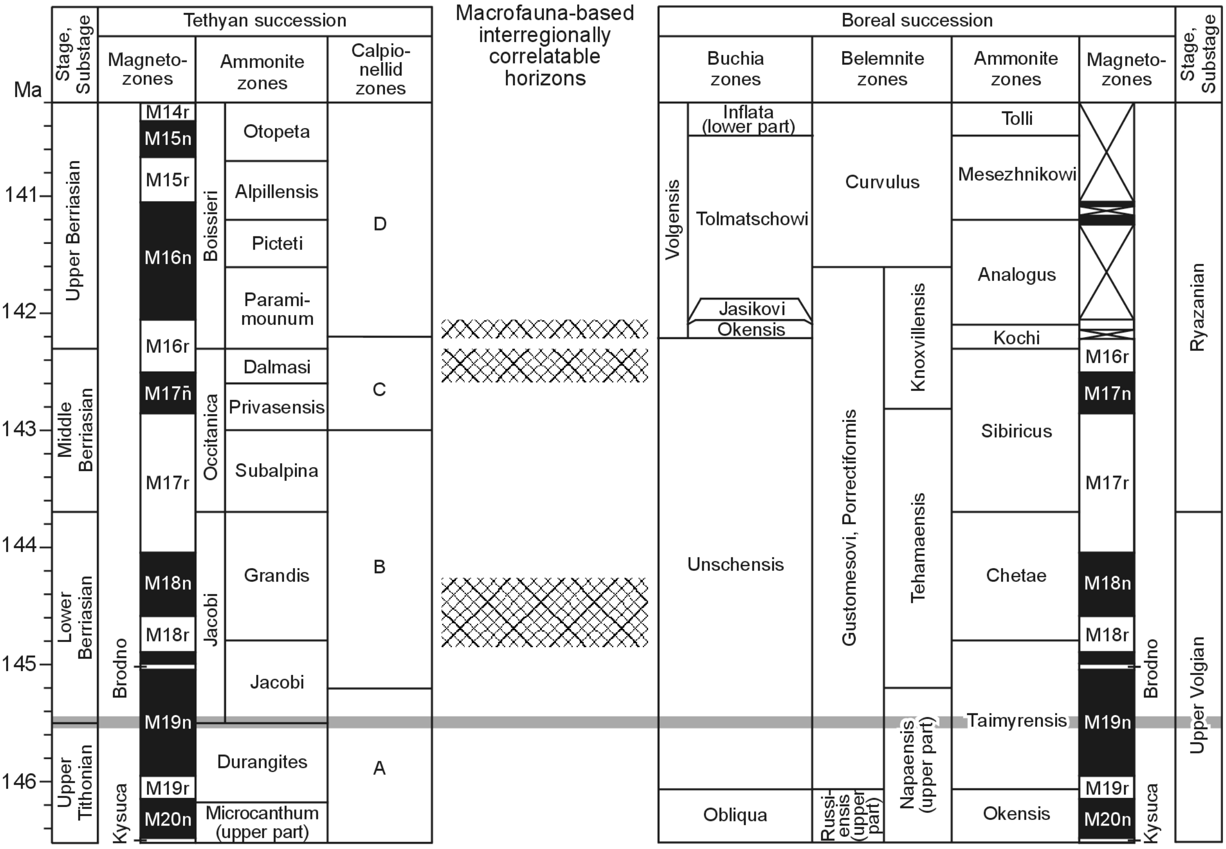

Fig. 9. Tehthyan–Boreal correlation around the Jurassic–Cretaceous boundary based on magneto- and biostratigraphic data. Boreal (northern Siberia) magnetostratigraphy is modified after Houša et al. (2007); Guzhikov and Baraboshkin (2008); biostratigraphy is after Zakharov et al. (1997); Shurygin et al. (2011); Dzyuba (2012); Tethyan standard subdivision is after Gradstein et al. (2004); with modifications after Pruner et al. (2010); Guzhikov et al. (2012). The Berriasian is conventionally accepted in three substages after Hoedemaeker et al. (2003). For symbols see Fig. 2.

that of the Boreal Epivirgatites variabilis Zone. This correlation would seem to be in accord with the paleomagnetic data by Houša et al. (2007) only under assumption that the first *Kossmatia* are older than the first *Durangites* and that the top of the Californian B. elderensis Subzone is similarly older than the Durangites Zone of the standard subdivision. The stratigraphic distribution of belemnites in California shows that beds with *Kossmatia* and *Durangites*(?) occur between beds containing belemnites *Lagonibelus californicus, L. tomsensis*, which are correlated with the base of the Siberian L. napaensis Zone (the base of the Epivirgatites variabilis ammonite Zone) and beds with *Arctoteuthis tehamaensis*, which correspond to the Siberian belemnite zone of the same name (whose base is placed within the Craspedites taimyrensis Ammonite Zone) (Dzyuba, 2010, 2012). Therefore, based on the belemnite data the upper part of the Buchia elderensis Subzone of the B. piochii s.l. Zone in California can be correlated with an interval from the upper part of the E. variabilis Zone to the lower part of the C. taimyrensis Zone of the Siberian ammonite zonation, which is equally consistent with the Buchia biostratigraphy and with magnetostraigraphy (Fig. 9). It has to be admitted, however, that the uncertainties in the ICH under consideration still remain large.

The second ICH in the sense of Hoedemaeker is correlatable with at least a part of the Tethyan Berriasella jacobi Zone, because it is bounded by the first *Spiticeras* and the last *Proniceras*. When correlated with the Siberian Buchia zonal scale, these ammonite-bearing beds at the Buchia piochii/B. aff. okensis zonal transition of California (Imlay and Jones, 1970) were compared with the beds at the B. unschensis/B. okensis zonal transition (Zakharov, 1981), B. oblique/B. unschensis zonal transition (Hoedemaeker, 1987; Jeletzky, 1984), and with the middle part of the B. unschensis Zone (Sey and Kalacheva, 1993; Zakharov, 2004). The latter is supported by the belemnite data (Dzyuba, 2010, 2012). The upper part of the B. fischeriana Subzone (the top of the B. piochii s.l. Zone) in California contains *Cylindroteuthis newvillensis* And., whose range on Nordvik Peninsula begins at the top of the Craspedites taimyrensis ammonite Zone and ends within the Chetaites chetae Zone (Dzyuba, 2012). The composition of the belemnite assemblage at the base of the Californian B. aff. okensis Buchia Zone is not clear. It is only known that a diverse belemnite fauna was reported somewhere in this Buchia Zone (Anderson, 1945; Imlay and Jones, 1970), including a zonal species *Cylindroteuthis knoxvillensis* And., which replaces the species *C. newvillensis* in Siberia (e.g., at Nordvik) directly above the base of the Chetaites sibiricus ammonite Zone (Dzyuba, 2012). So it can safely be assumed that the upper part of the Californian B. fischeriana Subzone correlatable with a part of the Tethyan Berriasella Jacobi ammonite Zone could be equated with the top of the Boreal Craspedites taimyrensis Zone and at least the basal part of the Chetaites chetae Zone. This correlation does not contradict the latest paleomagnetic results from the Nordvik Peninsula (Fig. 9).

The third ICH proposed by Hoedemaeker was considered as a correlatable with the Malbosiceras paramimounum Subzone, starting at the base of the Tethyan Fauriella boissieri Zone, for two reasons: (1) the restriction of ammonites referred to as *Argentiniceras* of the *noduliferum/bituberculatum* group to the Argentiniceras noduliferum Zone in Argentina, which yielded also representatives of *Groebericeras* and *Pomeliceras* that only occur together in the M. paramimounum Subzone; and (2) the last appearance of *Neocosmoceras* in the M. paramimounum Subzone. This implies that the M. paramimounum Subzone can be equated with the upper part of the Buchia okensis Zone and the lower part of the B. uncitoides Zone in British Columbia and California (the latter Buchia zone is an equivalent of the B. jasikovi Zone of Siberia), i.e., the interval corresponding to the upper Hectoroceras kochi-basal part of the Surites analogus Zones of the Boreal ammonite succession. However, the Argentiniceras noduliferum Zone of Argentina is now correlatable with the Tirnovella occitanica Zone (Vennari et al., 2012). According to Rogov (personal communication), the ammonites from British Columbia (Jeletsky, 1984) cannot belong to the genus *Argentiniceras* or be considered close to the species *A. noduliferum* and *A. bituberculatum*. In Bulgaria, Poland, and France, representatives of *Neocosmoceras* were reported from a higher level of the Berriasian, including the Berriasella callisto Subzone (Arkadiev and Bogdanova, 2009).

Nevertheless, the ICH can readily be distinguished within the Malbosiceras paramimounum Subzone, which is supported by the results from the Northern Caucasus, Russian Far East and the Russian Platform. Of particular interest in this respect is the finding of *Buchia* cf. *fischeriana* (Orb.), *B. volgensis* (Lah.), *B. okensis* (Pavl.), *B. uncitoides* (Pavl.) in the Fauriella boissieri Ammonite Zone along the Urukh River in the Northern Caucasus. On account of this find, I.I. Sey has recognized the *Buchia okensis–B. uncitoides* Beds (Kolpenskaya et al., 2000). The above buchias were reported from the interval starting from the Riasanites rjasanensis–Spiticeras cautleyi Subzone to at least the lower portion of the *Jabronella* cf. *paquieri–Berriasella callisto* Beds, which according to the most recent data is equivalent to the M. paramimounum and Berriasella picteti Subzones of the Tethyan standard succession (Arkadiev et al., 2008). However, the entire buchia assemblage can be found only in the R. rjasanensis–S. cautleyi and Euthymiceras euthymi Subzones of the Northern Caucasus, which are correlatable with the lower and upper halves of the M. paramimounum Subzone, respectively. The only disadvantage of the Urukh River section is the absence of Buchias above and below the *B. okensis–B. uncitoides* Beds.

An additional support for the recognition of the ICH under consideration is the co-occurrence of the Tethyan ammonite *Spiticeras* (*Spiticeras*) *multiforme* Djanelidze and the Boreal *Buchia okensis* and *B. volgensis* reported from the Anyuy River basin in the Russia Far East (Sey and Kalacheva, 1999a). In the Northern Caucasus, *S.* (*S.*) cf. *multiforme* was sampled from the Riasanites rjasanensis–Spiticeras cautleyi Subzone (Kolpenskaya et al., 2000). The species *B. okensis* in Siberia is restricted to the B. okensis and B. jasikovi Zones (Zakharov, 1987). Of more weight in this respect is the other Tethyan ammonite, a *Transcaspiites transfigurabilis* (Bogosl.), from the upper part of the Riasanites rjasanensis Ammonite Zone of the Ryazanian Stage in Central Russia (Mesezhnikov et al., 1979; Mitta, 2007), where it has been found together with *Buchia volgensis* and the last representatives of *B. uncitoides* and *B. fischeriana.* This ammonite species is characteristic of the Euthymiceras euthymi Subzone in the Northern Caucasus (Kolpenskaya et al., 2000). The Buchia assemblage found together with ammonite most likely corresponds to the B. uncitoides Zone (correlatable with the Siberian B. jasikovi Zone).

Recent paleomagnetic data from the section along the Boyarka River (northern East Siberia) revealed an interval dominated by reversed polarity in the Hectoroceras kochi/Surites analogus boundary beds (= Buchia okensis/B. jasikovi boundary beds) (Guzhikov and Baraboshkin, 2008). This interval could be equated with either magnetozone M16r or M15r. The former should be a more realistic choice, based on the third ICH (Fig. 9).

Detailed studies that were carried out during several last years on the Jurassic–Cretaceous boundary interval provided the new factual evidence for another possible ICH. It should comprise the basal part of the Riasanites rjasanensis Ammonite Zone (R. swistowianus faunal horizon) that yielded *Dalmasiceras crassicostatum* Djan. in Central Russia. The R. swistowianus faunal horizon at quarry site 12-2 of Lopatinsky mine, according to Mitta (2007, 2009, 2011a,b), contains the abundant Tethyan ammonite fauna of *Riasanites*, *Riasanella*, *Subalpinites*, *Mazenoticeras*, and *Malbosiceras*, which is, however, represented by mainly endemic species. This locality also yielded one specimen of *Dalmasiceras crassicostatum* previously mentioned in SE France at the level with *D. dalmasi* (Pictet) and *D. punctatum* Djan. (Djanélidzé, 1922; Mazenot, 1939), which are characteristic for the Dalmasiceras dalmasi Subzone of the Tirnovella occitanica Zone. The absence of *Hectoroceras kochi* Spath in the R. swistowianus faunal horizon and undoubtful presence of *Hectoroceras* in a continuously deposited sequence (near Kuzminskoye) above the first *Riasanites* (Mesezhnikov et al., 1979) indicate that the index species of the widespread Boreal H. kochi Zone starts its range above beds with *D. crassicostatum*, and, consequently, the base of the H. kochi Zone could not be older than the base of the D. dalmasi Subzone. The previous paleomagnetic results from the Nordvik Peninsula (Houša et al., 2007) were contradicted by this biostratigraphic criterion.

Riasanites swistowianus (Nikitin) has been recently reported from the *Riasanites*, *Himalayites* and *Picteticeras* Beds of the Berriasian in Poland (Mitta and Ploch, 2012), which are correlatable with the Tethyan Tirnovella occitanica Zone and the lower part of the Fauriella boissieri Zone (Marek and Shulgina, 1996). This find also provisionally points to the correlation of the base of the *Riasanites, Himalayites* and *Picteticeras* Beds with the R. swistowianus faunal horizon recognized by Mitta (2007) and Mitta and Sha (2011) in the lowermost part of the R. rjasanensis Zone of Central Russia on the basis of the acme of the index species. At the same time, the co-occurrence of *Chetaites sibiricus* Schulgina an index species of the basal ammonite zone of the Boreal Berriasian in Siberia, with numerous *R. swistowianus*, was reported near Kuznimskoye in Central Russia (Mitta and Sha, 2011). The above evidence, therefore, seems to establish a strong correlative link from the Tirnovella occitanica Zone to the lowermost *Riasanites*, *Himalayites* and *Picteticeras* Beds through the R. swistowianus faunal horizon to the Chetaites sibiricus Zone. Moreover, this correlation is strongly supported by the presence of reversed polarity magnetozone M17r identified in this study within the C. chetae/C. sibiricus boundary beds (Fig. 9).

With respect to the above results it should be noted that a revision of the ammonite genus *Riasanites* presented by Mitta (2008) and Mitta and Ploch (2012) made it clear that the Northern Caucasus can no longer be viewed as the dispersal center for *Riasanites*. Nevertheless this assumption, coupled with the known ranges of *Riasanites* and *Euthymiceras* in the Northern Caucasus and Russian Platform, served as a basis for correlation between the base of the Riasanites rjasanensis Zone and the base of the Fauriella boissieri Zone (Kolpenskaya et al., 2000; and others). Mitta (2008), in our opinion, suggested a more reliable hypothesis about the origin of *Riasanites* from Submediterranean Himalayatidae that have migrated from the western Tethys via the Polish Passage to the Central Russian basin and from there to Mangyshlak, Northern Caucasus, and the Crimea. However, the assumption of Mitta (2007) about the distribution (or at least the acme) of *Hectoroceras kochi* on the Russian Platform that predated the first *Riasanites* and, consequently, the first *Chetaites sibiricus* appears to be inconsistent with the data available on the Russian Platform (Mesezhnikov et al., 1979) and conflicts with previously held concept of the Boreal succession of *Chetaites* to *Hectoroceras*, as was described with certainty in Siberia (Zakharov et al., 1997) and Eastern Greenland (Surlyk et al., 1973). Therefore, this assumption is not considered in the correlations attempted here.

In the Russian Far East, the Volgian and Ryzanian sections are of special interest for Tethyan–Boreal correlation, because of the co-occurrence of ammonites of Tethyan affinity and buchias of Boreal affinity (Konovalov and Konovalova, 1997; Sey and Kalacheva, 1993, 1995, 1999a,b; Urman et al., 2011; and others). The structural complexity of these sections, the lack of continuous Volgian–Ryzanian boundary beds in some areas (especially, in southern Primorye), etc. (for details see Zakharov (2011)), and the consequent problems with intercalibration and conclusive interpretation of the fossil record, hinder identification of the reliable interregionally correlatable horizons around the Jurassic–Cretaceous boundary in the Russian Far East.

Conclusions

Paleomagnetic studies from the Jurassic–Cretaceous boundary sections in the Nordvik Peninsula provide new data on the magnetic mineralogy, which can be used to support and augment the conclusions of previous studies (Chadima et al., 2006) about the presence of low-Ti titanomagnetite and absence of magnetic sulfide in the section. The magnetostratigraphic section derived for the interval from the upper part of the Craspedites taimyrensis Ammonite Zone to the lower part of the Chetaites sibiricus Zone consists of the alternating succession of normal (four) and reversed (three) polarities corresponding to Chrons from M19n to M17n.

The combined paleomagnetic and biostrtaigraphic data show that the boundary between the Volgian and Ryazanian stages, which is coincident in Siberia with the Chetaites chetae/C. sibiricus zonal boundary, should be situated in magnetozone M17r rather than M18n, as previously proposed by Houša et al. (2007). This boundary is placed within the same magnetozone as the Lower/Middle Berriasian boundary (Berriasella jacobi/Tirnovella occitanica zonal boundary). The reversed polarity magnetozone, formerly referred to as M17r, may therefore be interpreted as corresponding to M16r. This proves that the C. sibiricus/Hectoroceras kochi zonal boundary lies within the same magnetozone as the base of the Upper Berriasian (T. occitanica/Fauriella boissieri zonal boundary).

Correlation of the Tethyan and Boreal biostratigraphic scales calibrated against magnetostratigraphy is best supported by paleontological data at the Middle–Upper Berriasian boundary interval.

We came to the conclusion that there is clear evidence for the base of the Boreal Hectoroceras kochi Zone not being older than the base of the Dalmasiceras dalmasi Subzone of the Tethyan Tirnovella occitanica Zone, as suggested by the following facts: (a) the finding of the ammonite *Dalmasiceras crassicostatum* Djan. within the Riasanites swistowianus faunal horizon in the R. rjasanensis ammonite Zone of Central Russia; (b) the first true *Hectoroceras kochi* Spath reported from beds overlying an interval with *D. crassicostatum*, above the R. swistowianus faunal horizon. The paleomagnetic evidence allows us to narrow down the correlation interval between the D. dalmasi Subzone and Chetaites sibiricus Zone (underlying the H. kochi Zone in Boreal sections) to the upper part of the latter zone. The correspondence of the C. sibiricus and T. occitanica Zones can be supported, on the one hand, by the occurrence of *R. swistowianus* (Nikitin) in the beds with *Riasanites*, *Himalayites* and *Picteticeras* in Poland and, on the other hand, by the co-occurrence of *C. sibiricus* Schulgina and numerous *R. swistowianus* in Central Russia.

The correspondence of the Buchia okensis and B. jasikovi (= B. uncitoides) Zones (the middle and upper parts of the Hectoroceras kochi Zone and the lower part of the Surites analogus Zone of the Boreal ammonite succession) to the Malbosiceras paramimounum Subzone of the Fauriella boissieri Zone of the Tethyan standard is supported by the buchia assemblage comprising *Buchia* cf. *fischeriana* (Orb.), *B. volgensis* (Lah.), *B. okensis* (Pavl.), *B. uncitoides* (Pavl.), which was reported from the Riasanites rjasanensis–Spiticeras cautleyi and Euthymiceras euthymi Subzones of the Northern Caucasus; by the co-occurrence of the ammonite *Spiticeras* (*Spiticeras*) *multiforme* Djanelidze (characteristic for the Riasanites rjasanensis–Spiticeras cautleyi Subzone of the Northern Caucasus) with *Buchia okensis* and *B. volgensis* in the sections within the Anyuy River basin of the Russian Far East; by the co-occurrence of the ammonite *Transcaspiites transfigurabilis* (Bogosl.) (characteristic for the Euthymiceras euthymi Subzone of the Northern Caucasus) with *Buchia volgensis*, *B. uncitoides*, and *B. fischeriana* in the Riasanites rjasanensis ammonite Zone of Central Russia.

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