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New stratigraphic and isotope data on the Kimmeridgian–Volgian boundary beds of the Subpolar Urals, Western Siberia

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A review and new data regarding the ammonite faunas and biostratigraphy of the uppermost Kimmeridgian–lowermost Volgian of the Subpolar Urals are presented. The combined ranges of almost all ammonite genera in the lowermost Volgian of the Subpolar Urals supports the traditional point of view regarding the equivalence of the *Magnum* Zone with the two lowermost Bolonian Zones and with the bulk of the *Klimovi* Zone. This stratigraphic interpretation permits the stable isotope data (carbon and oxygen) derived from associated belemnites to be presented in context. The isotopic records from the belemnites suggest that the lower Volgian sediments of the Yatria River, Subpolar Ural Mountains were deposited in a warm marine environment consistent with a warm high latitude scenario. If reduced salinites are invoked apparent temperatures are lowered by ~5°C, but still remain well above freezing and are relatively warm compared to some recent modelled estimates of Late Jurassic ocean temperatures.

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Key words: Kimmeridgian, Volgian, ammonite biostratigraphy, belemnites, oxygen isotopes.

INTRODUCTION

Sections of the Kimmeridgian–Volgian boundary beds situated on the eastern slope of the Subpolar Ural Mountains have been known for more than 100 years. Over the last few decades these deposits have been intensively studied at localities along the banks of the rivers Yatria, Lopsia and Tolja for the purpose of biostratigraphy (Mesezhnikov, 1963, 1977, 1984; Mikhailov, 1964; Zakharov and Mesezhnikov, 1974; Golbert *et al*., 1975; Lebedeva and Nikitenko, 1999) as well as palaeoclimate studies (e.g., Sahagian *et al*., 1996; Price and Mutterlose, 2004; Zakharov *et al*., 2005). Following Mesezhnikov's investigations, the Kimmeridgian–Volgian boundary was traced to the base of *Magnum* Zone (Zakharov and Mesezhnikov, 1974; Mesezhnikov, 1977, 1984; Zakharov *et al*., 1997, 2005). Its earliest Volgian age has been demonstrated by the occurrence of *Gravesia* (and also an absence of the Kimmeridgian *Aulacostephanus* fauna). The *Magnum* Zone has typically been considered by Russian authors as the equivalent of the two basal zones seen in north-west Europe (*Elegans* and *Scitulus*), the *Klimovi* Zone of the Volgian Stage of the Russian Platform as well as the *Hybonotum* Zone of Tithonian Stage. *Gravesia*, figured by Zakharov and Mesezhnikov (1974), was recently revised by Hantzpergue (1989) and Schweigert (1993) and partially ascribed to the Kimmeridgian species *G. lafaugiana* Hantzpergue. This data, in conjunction with records of ammonoids that resemble *Eosphinctoceras magnum* in the upper Kimmeridgian of Germany, led Schweigert (1993) to suggest a Kimmeridgian age of the *Magnum* Zone. On the other hand, it has been suggested that the *Magnum* Zone corresponds at least in part to the *Wheatleyensis* Zone (Callomon and Birkelund, 1982; Callomon, 1994). Hence correlative charts based upon *Eosphinctoceras* alone lead to some contradictions. This study presents new faunal descriptions from the classic section of the Kimmeridgian–Volgian boundary beds situated on the eastern slope of Subpolar Ural Mountains. Stable carbon and oxygen isotope data derived from associated belemnites are also presented. A number of studies (e.g., Ditchfield, 1997; Price and Mutterlose, 2004; Wierzbowski, 2004; Price *et al*., 2009) have demonstrated that, with appropriate constraints placed upon the isotopic composition of seawater, credible palaeotemperature trends can be derived from the isotopic analysis of belemnites. As the Late Jurassic and in particular the Kimmeridgian has been identified as a period of time when temperatures reached a maximum (e.g., Frakes, 1979) it is important that isotope data and consequent interpretations are placed in context. In addition to an assessment of the ammonite occurrence at the Kimmeridgian–Volgian boundary, it is the purpose of this contribution to provide robust, biostratigraphically constrained, oxygen and carbon isotopic data from high latitudes. These data will contribute to the debate on whether the Late Jurassic was at times characterized by sub-freezing or warm polar temperatures (e.g., Frakes, 1979; Ditchfield, 1997; Price, 1999; Dromart *et al*., 2003).

MATERIAL AND METHODS

The Yatria River near to the Nia-Yu River mouth was examined in this study (Fig. 1). This section has been previously described by Mikhailov (1964), Zakharov and Mesezhnikov (1974) and Mesezhnikov (1984). From this section a number of key ammonite species have been identified (Fig. 2). Additionally a number of belemnite rostra (*Cylindroteuthis* sp.) were

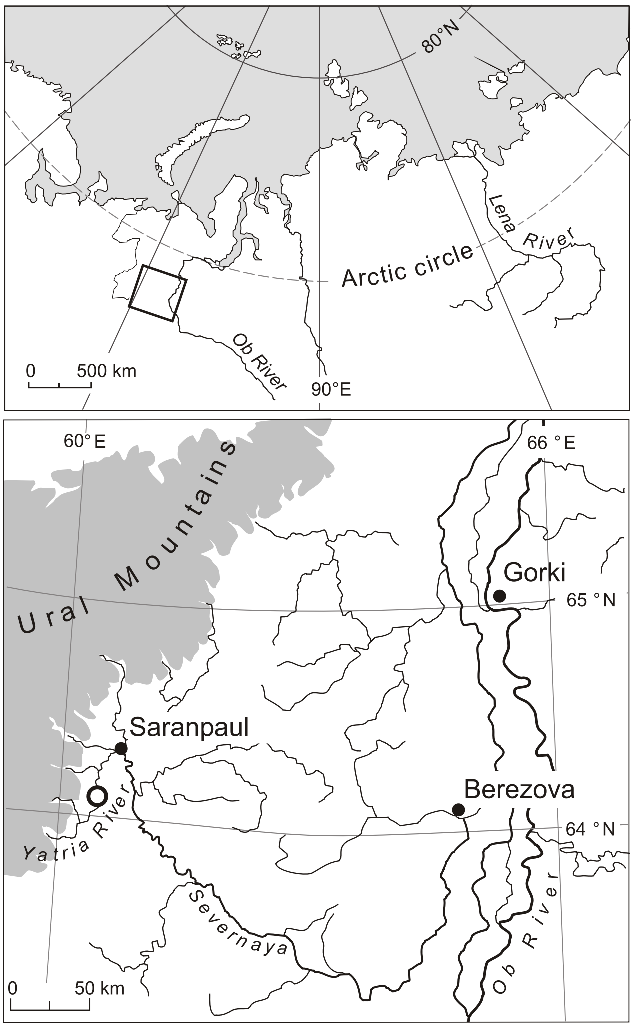

Fig. 1. Location of the studied section within the Subpolar Ural Mountains

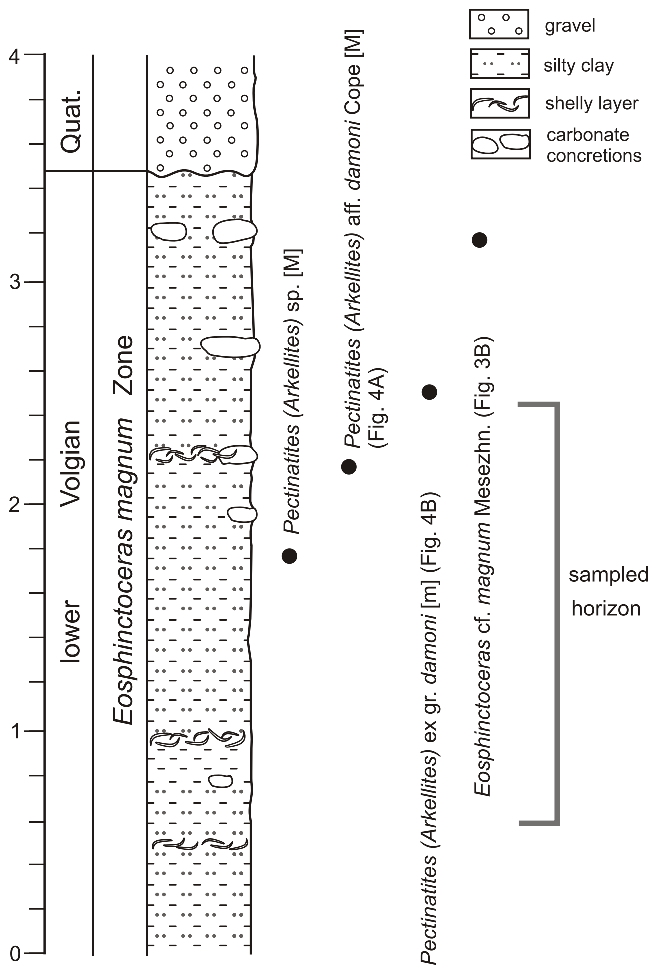

Fig. 2. Stratigraphic log with new ammonite records showing horizon from which belemnites were sampled

also collected. Oxygen and carbon isotopic compositions have been determined on these belemnite specimens. Carbonate staining (Dickson, 1966) revealed partial replacement by ferroan calcite preferentially along the outermost concentric growth bands and associated with the apical line. Areas such as these were either removed prior to or avoided during sub-sampling. The remains were fragmented (sub-mm), washed in ultrapure water, and dried in a clean environment for subsequent isotopic analysis. Carbon and oxygen isotopes have been determined on a *VG Instruments Optima Isotope Ratio Mass Spectrometer* with a *Multiprep Automated Carbonate System* (at the University of Plymouth) using 200 to 300 micrograms of carbonate. The $\delta^{13}C$ and $\delta^{18}O$ values obtained were calibrated against NBS-19. Analytical reproducibility of the measurements is ±0.2 permil based upon replicate analyses. The $\delta^{18}O$ and $\delta^{13}C$ data are reported in the conventional delta notation with respect to V-PDB. Diagenetic alteration of each of the belemnite samples was characterized by a combination of petrographic investigations and trace element geochemistry. All samples were analysed for trace element contents (Fe, Mn) on 50–100 mg subsamples using a *Perkin Elmer 3100 Atomic Absorption Spectrometer*. Based upon analysis of duplicate samples reproducibility was better than ±3% of the measured concentration of each element.

AMMONITE OCCURRENCE

Based upon the presence of *Eosphinctoceras* cf. *magnum* (Fig. 3A, B) recorded from near to the top of the section, it is possible to consider the *Magnum* Zone as the age of the upper part of section. Our described section would therefore include beds 1–2 of the locality no. 12 described by Mesezhnikov (1984). Both *in situ* ammonoids and ammonoids from fallen blocks resembling the English species *Pectinatites* (*Arkellites*) and *P.* (*Virgatosphinctoides*) were gathered. *P. (A.)* cf. *damoni* [m, M] (Fig. 4A1, 2 and B1, 2), were recorded *in situ*. These ammonoids are virtually the same as the typical English examples from the *Scitulus* Zone – which co-occur with the guide fossil *Gravesia gravesiana* in both England Cope (1967) and the Urals Zakharov and Mesezhnikov (1974), including a very characteristic feature, the horn in the aperture of microconchs. From the fallen blocks a suspected macroconch of the other typical Bolonian species (*Elegans* Zone), *P.* (*V.*) *elegans* (Fig. 3E), was also collected. All ammonites are housed in the geological Institute of RAS except Figure 3D (Oil Institute, St Petersburg) and Figure 4C. Of note is that the Tithonian is now internationally accepted as the primary standard terminal Jurassic Stage and thus the underlying Kimmeridgian Stage can only be used in its *sensu gallico* interpretation (Cope, 2006, but see also Zakharov and Rogov, 2008). Cope (1993, 1995) suggested because of the difficulties of correlating Tithonian ammonite faunas with those to the north of Tethys, a series of Secondary Standard Stages were required. Blakes's (1881) proposal for a Bolonian Stage, equivalent to the upper Kimmeridgian *sensu anglico* (Cope, 2006) and is used in this paper.

STABLE ISOTOPE AND GEOCHEMICAL DATA

The isotope data for the belemnites are presented in Table 1 and Figure 5. The belemnites sampled in this study were composed translucent calcite. Mn and Fe concentrations of the belemnites provide a means to further verify their state of preservation. The low Mn (<10 ppm) and Fe (<40 ppm) values, recorded, in conjunction with the petrographic evidence, are consistent minimal diagenetic alteration (see Marshall, 1992; Price and Page, 2008; Price and Rogov, 2009). The concentrations of Sr and Mg are also typical of well-preserved belemnites (e.g., Ditchfield, 1997; Price and Mutterlose, 2004). The oxygen and carbon isotope values of belemnites from range from –1.86 to –0.11‰ and 0.32 to 1.69‰ respectively. Calcite palaeotemperatures were calculated using the equation of Epstein *et al.* (1953) modified by Anderson and Arthur (1983):

$$T[°C] = 16.0–4.14\ (\delta c–\delta w) + 0.13\ (\delta c–\delta w)^2$$

where: δc equals the oxygen isotopic composition of the calcite with respect to the PDB international standard and δw equates to the oxygen isotopic composition of the water from which the calcite was precipitated with respect to the SMOW standard. In order to calculate palaeotemperatures, an assumption regarding the δw of the Jurassic ocean which is in part influenced by the presence or absence of polar ice during the Jurassic, must be made. Seawater on Earth during periods that were free from major icecaps would have been isotopically lighter than at present and a $\delta_{seawater}$ of –1.0‰ (SMOW), has been suggested as appropriate (Shackleton and Kennett, 1975).

DISCUSSION

Our interpretations of the belemnite isotope data (see below) rely upon a sound biostratigraphic framework. The correlation charts of the *Magnum* Zone with European successions, however, differ from each other (*cf.* Mesezhnikov, 1984; Schweigert, 1993; Callomon, 1994). Evidence for these correlations is based upon only limited amount of data which are sometimes contradictory. Each of these schemes are examined step by step (Fig. 6).

Mesezhnikov (1974, 1984) proposed the earliest correlation chart. Following Mesezhnikov (1984), the base of the *Magnum* Zone was considered to correspond to the base of the Volgian Stage of the central areas of Russian Platform, and the *Magnum* Zone equivalent of the *Klimovi* Zone and Bolonian *Scitulus* and *Elegans* zones. These correlations are demonstrated using the following reasoning:

1. Typical Kimmeridgian *Aulacostephanus* are entirely absent within the *Magnum* Zone and are uncommon in the underlying *Dividuum* Subzone of the *Autissiodorensis* Zone;

2. *Gravesia* encountered in the *Magnum* Zone are characteristic of the lowermost Tithonian, lowermost Bolonian and of the *Klimovi* Zone;

3. *Ilowaiskya* aff. *sokolovi* resembling the index species of the *Sokolovi* Zone of the Volgian Stage, occurs in the *Subcrassum* Zone.

A more recent revision of the occurrence of *Gravesia* from the Subpolar Urals has been made by Hantzpergue (1989) and Schweigert (1993). One of the figured specimens, gathered from the isolated excavation near to Tolja village (Zakharov and Mesezhnikov, 1974, pl. 1, fig. 1), was assigned to the Kimmeridgian species *Gravesia lafauriana* (Hantzpergue, 1989; Schweigert, 1993), and another specimen, from the lower part of *Magnum* Zone of the locality no. 28, Tolja River (Zakharov and Mesezhnikov, 1974, pl. 1, fig. 2), was re-determined as *G. gravesiana* (Hantzpergue, 1989). Importantly, those *Gravesia* assigned to the upper Kimmeridgian were collected from a small excavation, from where other beds (and even other ammonites) are unknown. *Gravesia* from the *Magnum* Zone, figured by Mesezhnikov (1984, pl. XIV, fig. 2) perhaps belong to the Tithonian/Bolonian species *Tolvericeras* (*Pseudogravesia*) *hahni* (Schweigert pers. comm., January 2003). Ammonites from the *Subcrassum* Zone (all figured specimens were collected from the lowermost bed of the zone in locality no. 12, Yatria River), considered by Mesezhnikov (1984) as *Ilowaiskya* (Zakharov and Mesezhnikov, 1974, p. 86, pl. 4, figs. 2, 3, text-fig. 28), resemble microconchate *Pectinatites* (see Fig. 3D). Ammonites, figured as plate 4, fig. 3 by Zakharov and Mesezhnikov (1974), resemble *Pectinatites* (*Arkellites*) *hudlestoni* (Cope, 1967, pl. 2, fig. 3; pl. 5, fig. 2; Wignall, 1993, fig. 7f), whereas the specimen of figure 2 (of the same plate), is closer to *P.* (*Virgatosphinctoides*) cf. *donovani*

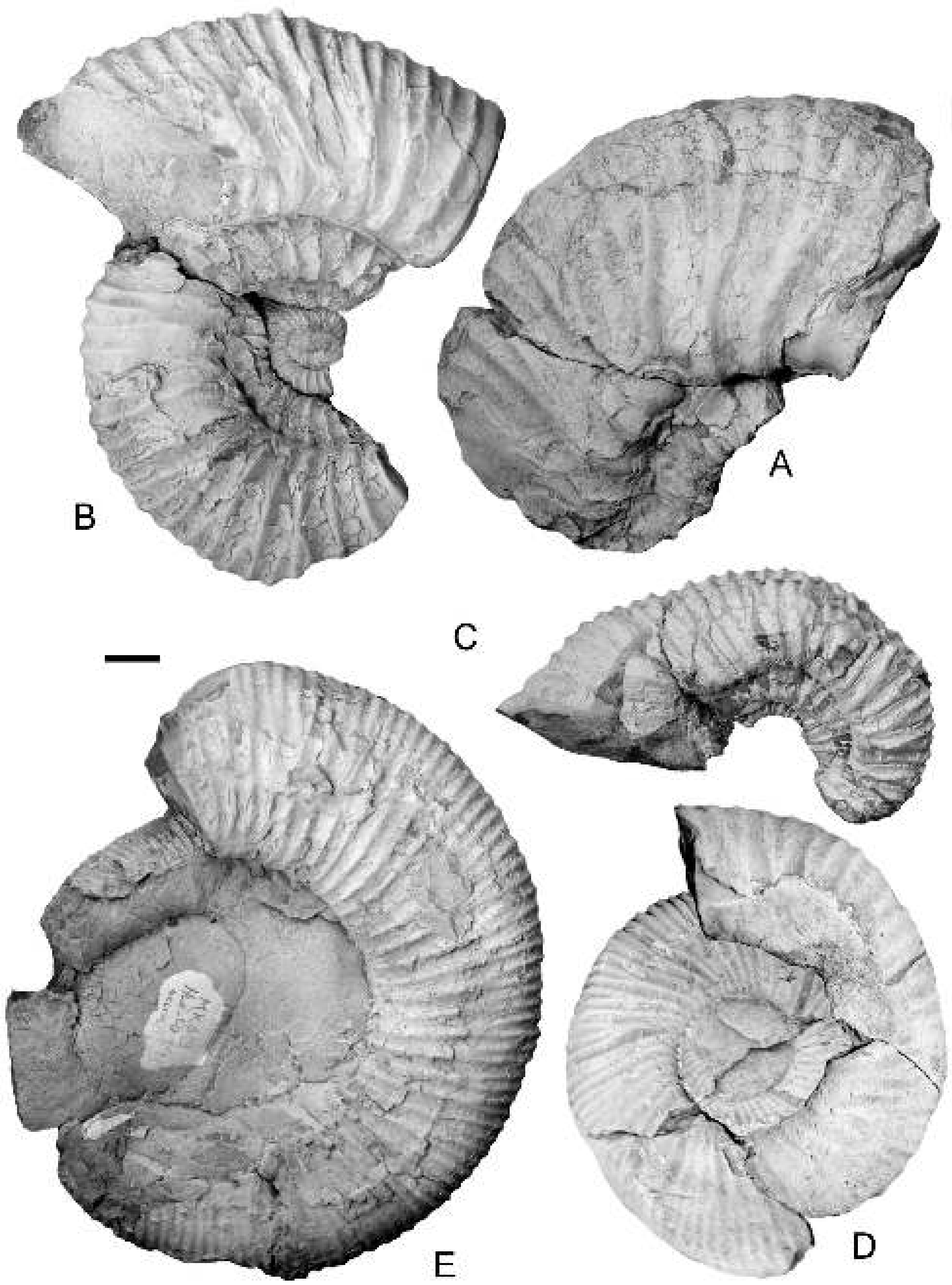

Fig. 3. Lower Volgian ammonoids from the Nia-Yu section

All ammonites are coated with ammonium chloride; **A**, **B** – *Eosphinctoceras magnum* Mesezhn.; A – GIN MK1835, presumable microconch, not *in situ*, *Magnum* Zone; B – GIN MK653, 330 cm above the base of the section, *Magnum* Zone; **C** – *Pectinatites* (*Arkellites*) aff. *arkelli* Cope, GIN MK620; microconch with horn preserved, not *in situ*, ?*Magnum* Zone; **D** – *Pectinatites* sp., VNIGRI 1640a-634, sample 131, locality 12, collected by Mesezhnikov (1963), *Subcrassum* Zone; **E** – *Pectinatites* (*Virgatosphinctoides*) cf. *elegans* Cope, GIN MK619, not *in situ*; scale bar = 1 cm

(Cope, 1967; Wignall, 1993, fig. 8a). Both species are characteristic of the *Hudlestoni* Zone.

Correlation of the *Magnum* Zone with the *Wheatleyensis* Zone (Callomon and Birkelund, 1982, fauna 25) is based on the records of *Eosphinctoceras* cf./aff. *magnum* Mesezhn. within the supposed *Wheatleyensis* Zone, as determined by Cope (1967, p. 73). English representatives of *Sphinctoceras* and *Eosphinctoceras* were described by Neaverson (1925) from the same zone, but his *Wheatleyensis* Zone corresponds to *Scitulus* Zone and basal beds of *Wheatleyensis* Zone sensu Cope (1967). In the Subpolar Urals the last *Eosphinctoceras* (including those with a high rib coefficient) occur in the *Subcrassum* Zone (Fig. 6), accompanied by some characteristic *Pectinatites* species. Additional (mentioned as *Subdichotomoceras* in Zakharov *et al*., 2005), tentatively ascribed to *P*. cf. *smedmorensis* and *P*. *groenlandicus* (Fig. 4C) were determined

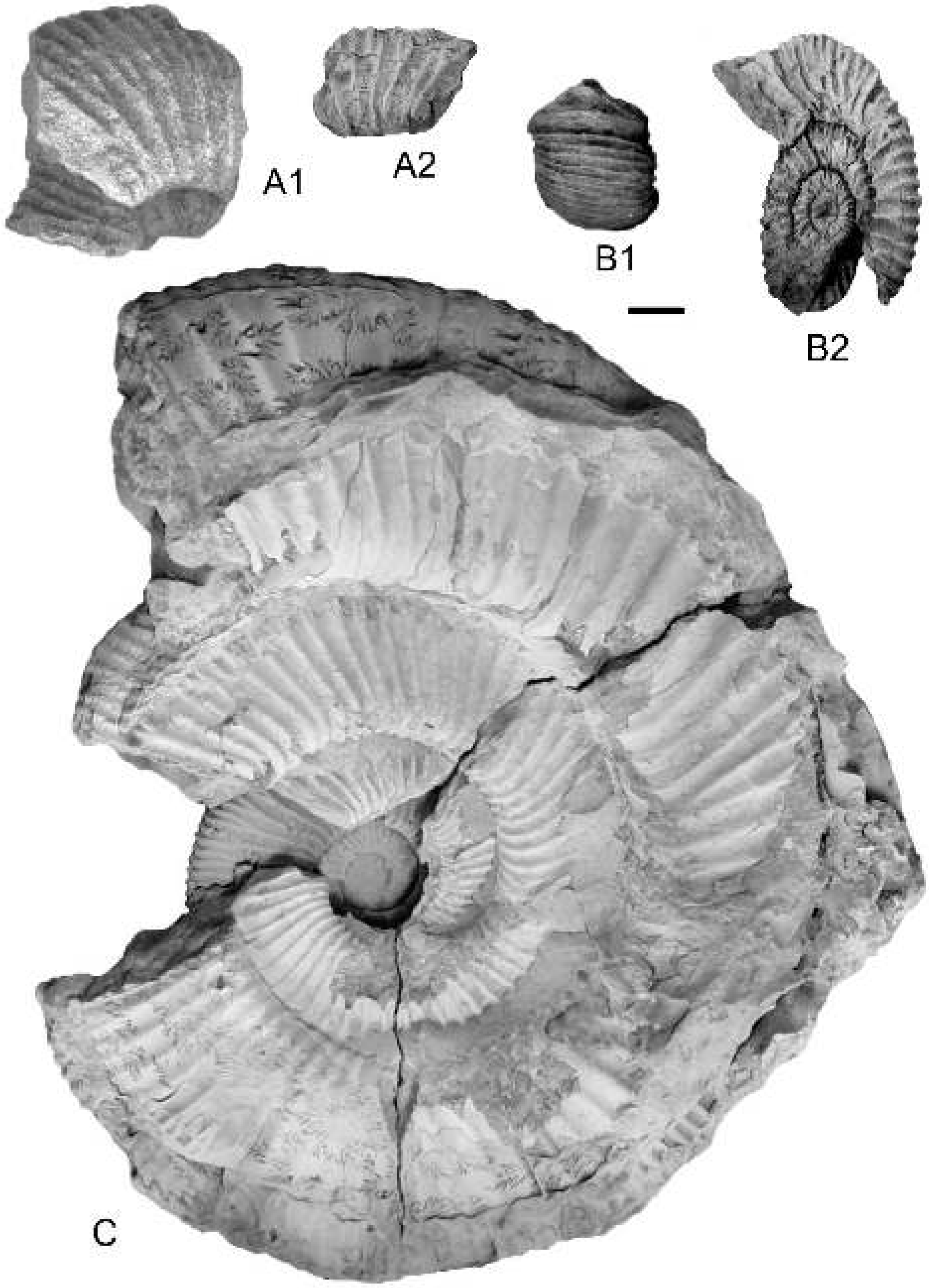

Fig. 4. Lower Volgian ammonites from Subpolar Ural

All ammonites are coated with ammonium chloride; **A1**, **A2** – *Pectinatites* (*Arkellites*) *damoni* Cope, MK 721, supposed macroconch, 200 cm above the base of the section Nia-Yu; **B1**, **B2** – *Pectinatites* (*Arkellites*) cf. *damoni* Cope, MK 622, supposed macroconch, 280 cm above the base of the section Nia-Yu; **C** – *Pectinatites groenlandicus* Spath, INGG, macroconch, Lopsia, locality 41, bed 10, *Subcrassum* Zone, collected by Bogomolov, 1997 (see Zakharov *et al*., 2005); scale bar = 1 cm

from the *Subcrassum* Zone of the Lopsia River. This allows us to suppose, that the *Magnum* Zone should be correlated with the lowermost Bolonian, whereas *Wheatleyensis* Zone records of *Eosphinctoceras* and *Subdichotomoceras* correspond to the same from the *Subcrassum* Zone. This point of view was also supported by recently collected early *Pectinatites* jointly with *Eosphinctoceras magnum*.

A comparison of the zonal successions of the Subpolar Urals and the Middle Volga area was undertaken by Zakharov and Mesezhnikov (1974) who noted *Gravesia* within both the *Magnum* and *Klimovi* zones and the disappearance of Aulacostephanids in the underlying strata (an isochronous event, traced throughout in the Panboreal Super realm, from England to Siberia). Unfortunately, *Gravesia* from the Middle Volga area have never been figured or described, and our careful search did not provide any *Gravesia*. It is probable, that these ammonites could be misidentified and confused with coarsely ribbed *Eosphinctoceras* and *Subdichotomoceras*, known from the *Klimovi* Zone (Rogov, 2005). Some coarse-ribbed *Eosphinctoceras* have been confused with *Gravesia* by one of us

Table 1

Isotopic and elemental compositions of belemnite rostra from the study site

Sample	$\delta^{13}C$	$\delta^{18}O$	T [°C]	Fe [ppm]	Sr [ppm]	Mn [ppm]	Mg [ppm]
NY 1-28	1.43	–1.09	16.4	5	2017	8	802
NY 1-67	1.29	–0.11	12.4	33	2015	2	650
NY 1-80	0.81	–1.00	16.0	6	1657	2	740
NY 1-83	1.69	–0.63	14.5	2	1737	2	588
NY 1-105	1.00	–0.44	13.7	21	1904	6	1143
NY 1-105 2	0.45	–1.14	16.6	17	1824	5	742
NY 1-110	1.42	–0.11	12.4	5	1558	2	615
NY 1-115	1.04	–0.83	15.3	5	1883	2	910
NY 1-200	0.32	–1.86	19.7	5	2015	2	1403
NY 1-250	0.68	–0.69	14.7	2	1502	2	624

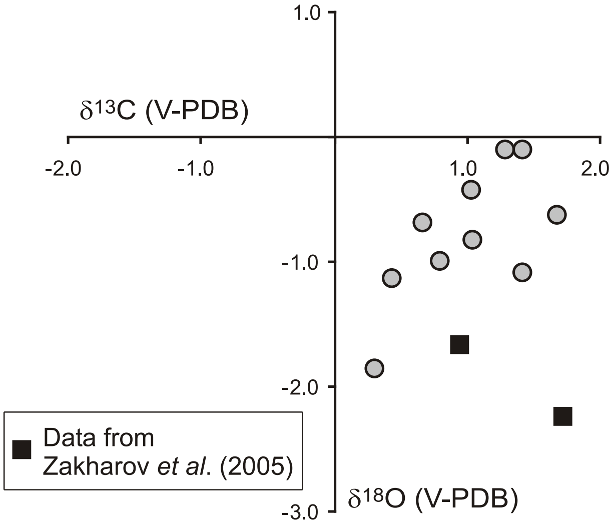

Fig. 5. Cross-plot of $\delta^{18}O$ and $\delta^{13}C$ values derived from belemnite samples of the Yatria River near to the Nia-Yu River mouth (this study, grey circles), with additional data from Zakharov *et al*. (2005)

(Rogov, 2004). Preservation of the bulk of the *Eosphinctoceras* and *Subdichotomoceras* gathered in the Middle Volga area chiefly is unsatisfactory and precise species determination difficult. Nevertheless the succession of *Eosphinctoceras* and *Subdichotomoceras* records in the two lower zones of the Volgian as a whole support the traditional correlation of the Volgian of the Subpolar Urals and Central Russia with the exception of the fact that the *Magnum*/*Subcrassum* boundary possibly lies within *Klimovi* Zone (Fig. 6).

Schweigert (1993, 1994) proposed a new correlation chart for the Kimmeridgian–Volgian boundary beds of the Subpolar Urals with Kimmeridgian–Tithonian of south-west Germany. This correlation was based on records of ammonoids of supposed Boreal affinities. The *Magnum* Zone was considered by Schweigert (1993, 1994) as equivalent of the uppermost Kimmeridgian based on the following points:

1. The *Autissiodorensis* Zone of south-west Germany yields *Gravesia lafauriana* and *Eosphinctoceras magnum*;

2. Ammonites resembling *Sarmatisphinctes dividuum* are present within the underlying strata of south-west Germany;

3. Geyer (1962) notes the presence of *Sphinctoceras crassum* in the *Gigas* Subzone of the *Hybonotum* Zone.

This correlation chart contradicts the suggested position of the *Magnum* Zone within the base of the Volgian, noted above. Ammonites thought by Schweigert (1993, 1994) as belonging to *E. magnum*, have some importance. Trifurcate and polygyrate ribs, which are very characteristic for *Eosphinctoceras*, are entirely absent in the German ammonites and its determination even as the genus *Eosphinctoceras* appears to be unproven. At that time records of *Sphinctoceras* and *Sarmatisphinctes* do not conflict with a lower Volgian age of *Magnum* Zone and corresponds to the recent data obtained from the *Klimovi* Zone. The German examples of *Sphinctoceras* could possibly be comparable with the Russian ammonites derived from the *Klimovi* Zone (Fig. 6).

Hence the proposition that the *Magnum* Zone corresponds to the base of the Volgian permits climate proxy data to be placed in context. The belemnite oxygen isotopes show only modest variability ranging from –1.86 to –0.11‰. Increasingly negative $\delta^{18}O_{carb}$ values can be related to elevated temperatures in environmental settings where continental ice volume is at a minimum and evaporation or freshwater input are minor factors. Assuming that these conditions apply, palaeotemperatures range from ~12 to 20°C. Hence the isotopic records from the belemnites suggest that the lower Volgian sediments of the Yatria River, Subpolar Ural Mountains were deposited in a warm marine environment. These Late Jurassic temperatures agree with the accepted warm high latitude scenario (see Frakes, 1979). Incidentally, such temperature interpretations rival high latitude temperatures associated with the mid-Cretaceous thermal maximum (e.g., Huber, 1998). Price and Mutterlose (2004) and Zakharov *et al*. (2005) also present belemnite derived stable isotope data from the Kimmeridgian and Volgian of the Subpolar Urals. The data of Zakharov *et al*. (2005) are consistent with the data presented here for the *Magnum* Zone (Fig. 5). The isotope data are also comparable with Late Jurassic belemnite isotope data from Submediterranean provinces of Central Poland and Southern Germany (Wierzbowski, 2004) and the Moscow Basin (Riboulleau *et al*., 1998). Zakharov *et al*. (2005) noted that palaeotemperatures calculated from the isotope composition of belemnite rostra derived from the Yatria River Basin may have been over estimated due to freshwater runoff. A reduced salinity of 30 PSU (but still above the tolerance of modern cuttlefish) reduces apparent temperatures by ~5°C (see Price and Mutterlose, 2004). Although these latter temperatures are certainly cooler – they still remain well above freezing and are relatively warm compared to some recent modelled estimates of Late Jurassic ocean temperatures (e.g., Sellwood and Valdes, 2008). A coincident sea level highstand in the mid-Bolonian (*Wheatleyensis* to *Pectinatus* zones) (e.g., Hallam, 1992; Sahagian *et al*., 1996; Taylor *et al*., 2001) during this postulated warm episode may reflect a lack of polar ice. Furthermore, during this episode practically the same ammonite assemblages inhabited the Boreal seas from England to Northern Siberia. Such a widespread distribution of fauna across Boreal seas may reflect high sea levels resulting in a more open seaways and reduced barriers to migration. Our new *Pectinatites* records as well as revision of the previously collected faunas suggest wide faunal exchange within

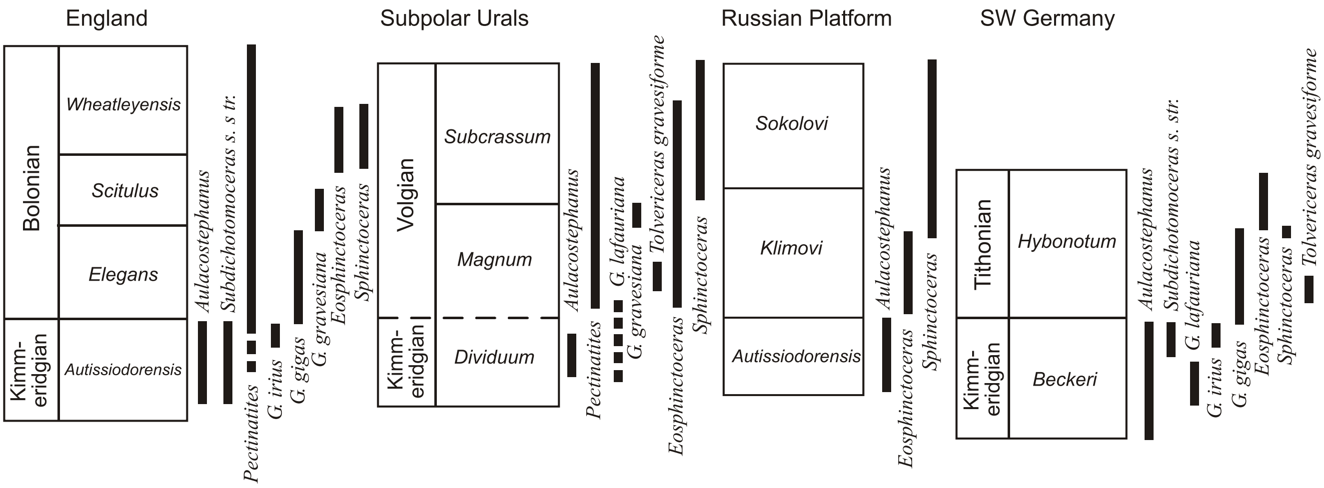

Fig. 6. Correlation chart of the beds around the Kimmeridgian–Volgian boundary and its equivalents through Europe

the Boreal basin during the early Volgian. Possibly, some of the *Ilowaiskya* of Zakharov and Mesezhnikov (1974, pl. 4, figs. 2, 3) also belong to *Pectinatites*. Unfigured *Ilowaiskya* from the Lena Basin, Yakutia (Djinoridze and Meledina, 1965) may also be the most easterly records of *Pectinatites* (Rogov, 2004).

CONCLUSIONS

The combined ranges of almost all ammonite genera in the lowermost Volgian of the Subpolar Urals supports the traditional point of view (Mesezhnikov, 1984) regarding the equivalence of the *Magnum* Zone with the two lowermost Bolonian Zones and with the bulk of the *Klimovi* Zone. New *Pectinatites* records testify that connections between ammonite faunas of England and the Subpolar Urals existed permanently during the early Volgian. The Magnum Chron is characterized by the isolated eastwards straying (Rawson, 1973) of *Pectinatites*, whilst mutual penetrations of the typical Uralian ammonoids are unknown. The *Wheatleyensis* to *Pectinatus* zones interval sees a rise in sea level, coincident with warm palaeotemperatures as derived from the isotopic composition of the belemnites (this study and Zakharov *et al*., 2005). Furthermore, practically the same ammonite assemblages inhabited the Boreal seas from England to Northern Siberia. The eudemic *Eosphinctoceras-Subdichotomoceras* lineage of the Subpolar Urals became extinct near to *Subcrassum*/*Pectinatum* boundary. The isotopic records from the belemnites further suggest a warm high latitude scenario comparable with warmth envisaged for times during the middle Cretaceous and incompatible with the extensive development of ice sheets during this time. Reduced salinities in the area need to be invoked to lower apparent temperatures.

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