Palaeoenvironments and palaeoceanography changes across the Jurassic/Cretaceous boundary in the Arctic realm: case study of the Nordvik section (north Siberia, Russia)

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Abstract

The Jurassic/Cretaceous transition was accompanied by significant changes in palaeoceanography and palaeoenvironments in the Tethyan Realm, but outside the Tethys such data are very scarce. Here we present results of a study of the most complete section in the Panboreal Superrealm, the Nordvik section. Belemnite $\delta^{18}O$ data show an irregular decrease from values reaching up to $+1.6‰$ in the Middle Oxfordian and from $+0.8$ to $-1.7‰$ in the basal Ryazanian, indicating a prolonged warming. The biodiversity changes were strongly related to sea-level oscillations, showing a relatively low belemnite and high ammonite diversity during sea-level rise, accompanied by a decrease of the macrobenthos taxonomical richness. The most prominent sea-level rise is marked by the occurrence of open sea ammonites with Pacific affinities. Peak abundances of spores and prasinophytes correlate with a negative excursion in organic carbon $\delta^{13}C$ near the J/K boundary and could reflect blooms of green algae caused by disturbance of the marine ecosystem.

The J/K boundary interval was characterized by remarkable palaeoceanographic and palaeoenvironmental changes in Europe (Tremolada et al. 2006), but in contrast to other system boundaries it was not connected to a global extinction event. The decrease in marine family diversity at the J/K boundary was estimated to lie between 5.1 and 6.5% (Hallam & Wignall 1997), while the decrease in generic diversity of all marine animals was less than 10% (Rogov 2013). Moreover, even this extinction rate could be overestimated due to the incomplete databases used, high evolutionary rates in Tithonian ammonites, time-averaging (Rogov 2013) and taphonomic features (i.e., a presence of numerous Lagerstätten of Kimmeridgian–Tithonian age and a scarcity of earliest Cretaceous ones), along with well-known relations of faunal diversity and the surface area of sediments surviving at outcrops (Smith & McGowan 2007). This suggests a continual biotic turnover caused partly by palaeoceanographic changes and, especially, large palaeogeographic events (Raup & Sepkoski 1982; Sepkoski 2002; Keller 2008). In the Arctic Realm, the transition between the Jurassic and Cretaceous was connected with neither extinction nor a radical reorganization in marine biota (Zakharov et al. 1993). This view is supported by faunal analysis (Dzyuba 2013; Rogov 2013) that indicated an increase in ammonite and belemnite diversity. However, on a global scale, the tectonic movements at the end of the Jurassic led to closure of many seaways and further differentiation of the Panboreal and Tethys–Pantalassa superrealms (Gasiński 1997). Following proposals by Westermann (2000), names and ranges of these units were subsequently adjusted.

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In the Panboreal Superrealm, there is no section where sedimentation patterns and biostratigraphy of the J/K boundary interval are represented more completely than in a section on the Nordvik Peninsula (north-eastern Siberia; Fig. 1). On the Nordvik Peninsula, the Laptev Sea cliff exposes a continuous succession of silty mudstones spanning the Middle Oxfordian to Upper Valanginian. The boreal ammonite and buchiid successions are recognized in great detail from the Middle Oxfordian to the top of the section (Zaharov et al. 1983; Zakharov & Rogov 2008; Rogov & Wierzbowski 2009). A belemnite biostratigraphy is well developed for the Middle Oxfordian–Lower Ryazanian interval (Dzûba 2004; Dzyuba 2012). Foraminifers and marine palynomorphs from the Middle Volgian to the Lower Valanginian have been studied in detail by Nikitenko et al. (2008).

Here we present results of an integrated study that includes an analysis of changes in assemblages (including relative abundance) of all major fossil groups and an analysis of sea-level oscillations. An earlier investigation of stable isotope data derived from belemnite rostra (Žák et al. 2011; Dzyuba et al. 2013) was complemented by analysing the $\delta^{13}C$ values of bulk organic matter. Major aims of this integrated study include the determination of biodiversity changes across the J/K boundary and the identification of possible relationships between different environmental factors, including sea-level oscillations, palaeoclimate, oxygen level in the sea water and biodiversity changes.

The unique original high-latitude palaeogeographic position (see Houša et al. 2007) of the investigated section was quite far from the coastline. The complete sedimentary succession without major hiatii and the precise

stratigraphic framework make this profile most suitable for a palaeocological and palaeoceanographic investigation of the Arctic Realm.

Geological settings and palaeogeographic aspects

The Nordvik section is one of the most comprehensively studied Jurassic sections in the Russian Arctic. It has been studied in detail by sedimentologists, geochemists, physicists and biostratigraphers (Zaharov & Judovnyj 1974). The Oxfordian–Ryazanian part of this section has been subdivided biostratigraphically by means of ammonites (Zaharov et al. 1983; Zakharov & Rogov 2008; Rogov & Wierzbowski 2009), belemnites (Dzûba 2004; Dzyuba 2012), buchiid bivalves (Zaharov et al. 1983), foraminifers and dinoflagellate cysts (Nikitenko et al. 2008, 2011). A remarkable positive $\delta^{13}C$ excursion (carbonate in belemnite rostra), which is considered as a useful marker for the Panboreal and Boreal–Tethyan correlation of J/K boundary beds, has recently been recorded in the Nordvik section in the top part of the Taimyrensis Zone (Dzyuba et al. 2013).

The Nordvik Peninsula is located in the eastern part of the Yenisei–Khatanga basin (Fig. 2) which is a part of the Mesozoic depression extending from the Yenisei River mouth to the Lena River mouth along the northern margin of the Siberian platform (Saks et al. 1959). In the south, the Yenisei–Khatanga basin is bounded by the northern edge of the platform which is covered by Palaeozoic and Lower Triassic deposits. In the west, it is connected with the Ust–Yenisei basin. In the east, the Yenisei–Khatanga basin reaches the Lena–Anabar
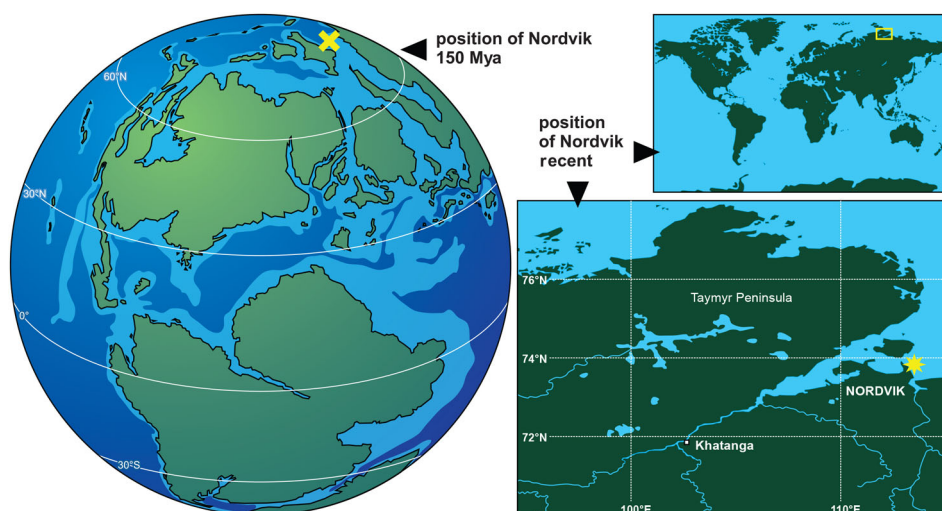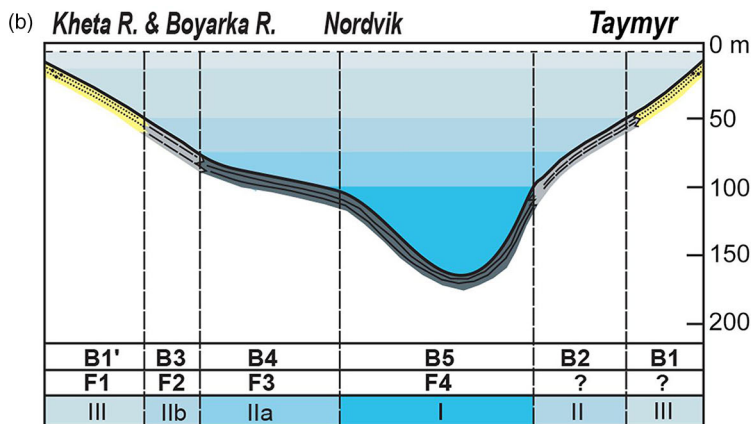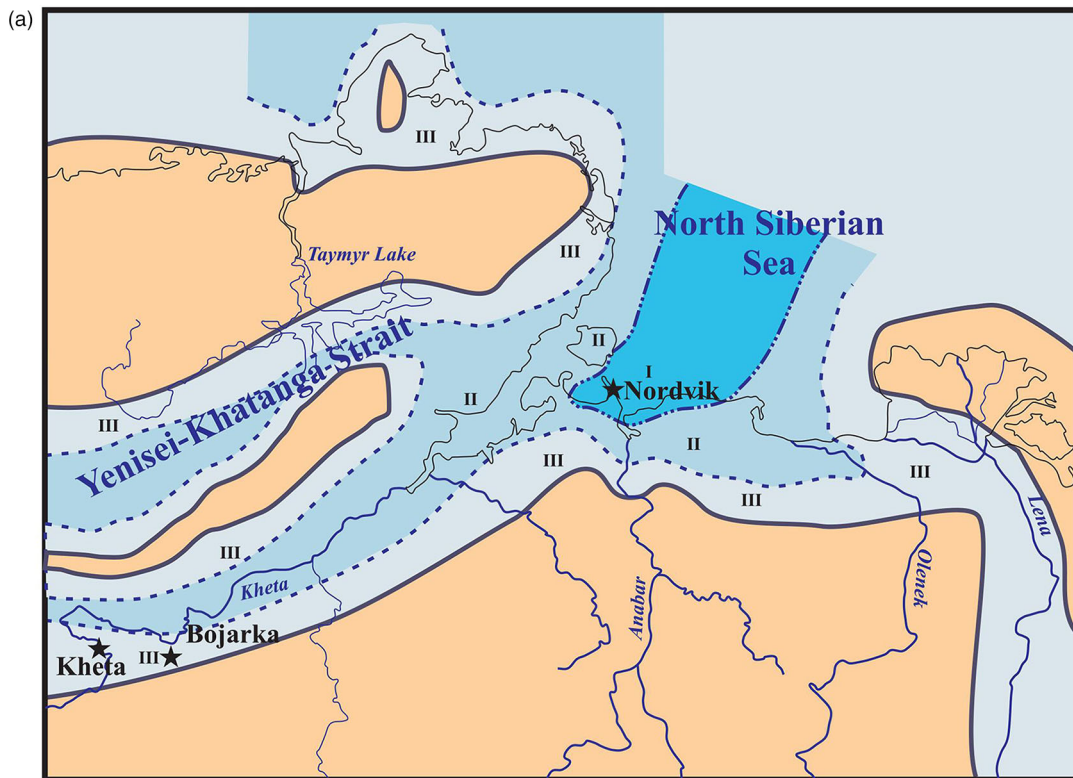

Fig. 1 Palaeogeographic and geographic position of the Nordvik section.

Fig. 2 Palaeogeography and facial succession in the Yenisei–Khatanga Strait during the Jurassic/Cretaceous transitional time (modified after Zaharov & Šurygin 1983). (a) Detailed palaeogeography of the Yenisei–Khatanga Strait during the Ryazanian. Land area is indicated in beige. Bionomic marine zones are marked by Roman numerals: I, deep-water; II, moderately deep-water; III, shallow water. (b) Facies profile through the Yenisei–Khatanga Strait and changes in bivalve and foraminiferal assemblages.

basin, being separated from it by a buried uplift. The latter continues as a projection of the Siberian platform between the Popigai and Anabar rivers towards the Anabar Gulf.

The basement of the Yenisei–Khatanga basin is composed of Palaeozoic and volcanogenic Lower Triassic rocks. The basin is primarily filled by marine Jurassic to lowermost Hauterivian deposits, and in the west overlain

Fig. 3 (*Continued*)

by continental Lower Cretaceous deposits and marine Upper Cretaceous sediments. The Triassic deposits occur in the eastern part of the basin.

In Volgian and Ryazanian times, the Nordvik Peninsula was located in the middle part of the Yenisei–Khatanga Sea Strait (Fig. 2). Due to the great distance (about 200 km) from the source areas in the north and south, fine-grained sediments such as alternating clays, bituminous clays and clayey silts accumulated there (Fig. 3). The total thickness of the studied interval from the Middle Oxfordian to basal Ryazanian is slightly more than 50 m. As judged from relative thicknesses of the ammonite zones, sedimentation rates gradually decreased during the Volgian to reach a minimum at the J/K transition and began to increase again in the earliest Cretaceous (Zakharov et al. 1993). Sedimentation rates for the Nordvik section were recently calculated by Grabowski (2011) and Bragin et al. (2013) on the basis of durations of magnetochrons presented by Ogg (2004). Grabowski (2011) concluded that quite uniform sedimentation rates characterized chrons M20n1n and M19r (ca. 11–12 m/My), while sedimentation rates decreased drastically at the Taimyrensis–Chetae transition (M19n and M18r) to 1.5–2.0 m/My. Additional studies of the Nordvik section have shown that sedimentation tends to decrease in Chron M18n (about 1.7 m/My) and especially in M17r (0.5 m/My), embracing the Volgian/Ryazanian boundary, whereas M17n reveals a major increase in the sedimentation rate up to 12 m/My (Bragin et al. 2013). Sedimentation rates recalculated on the basis of work by Ogg et al. (2012) are similar to previous rates.

The lower part of the Upper Jurassic is represented by the uppermost Middle Oxfordian, Upper Oxfordian, Lower and Upper Kimmeridgian. In contrast to the same interval located 500 km to the west, the Nordvik section contains no representatives of Aulacostephanidae, i.e., no index species of the Kimmeridgian zones at the Boyarka

River (Kheta River basin; Saks 1969). Only cardioceratids *Amoeboceras* s.l. and oppeliids *Suboxydiscites* have been found in the studied section (Zaharov et al. 1983; Rogov & Wierzbowski 2009). Therefore, the Kimmeridgian ammonite zones of the Kheta River basin could only be tentatively correlated to those of the Nordvik Peninsula, but the entire Kimmeridgian belemnite succession of the Boyarka River section is recognized here (Dzûba 2004; Dzyuba et al. 2007). The Kimmeridgian/Volgian boundary in the Nordvik section is satisfactorily identified by using belemnite data. All Volgian ammonite zones are well correlated throughout the Arctic and the lower boreal regions of Europe and Canada. The Ryazanian sequences are also represented by Arctic ammonite and buchiid zones (Zakharov & Rogov 2008; Rogov & Zakharov 2009).

Comprehensive studies of the Mesozoic deposits of the Khatanga depression began in the 1930s. Oil exploration, including drilling and geophysical investigations, was carried out from 1933 to 1953 in the Nordvik and some other regions of the Yenisei–Khatanga basin. The data on the Mesozoic deposits were summarized by Saks et al. (1959).

Saks (1958) compiled palaeogeographic and palaeofacies schemes of the Yenisei–Khatanga basin and the whole Arctic separately for the Jurassic and Cretaceous. A significant contribution to the palaeobiogeographic studies of the boreal climatic belt was given by Saks et al. (1971), who established palaeozoogeographic realms and provinces for the Jurassic and Neocomian of the Arctic. In the early 1980s, the palaeogeographic and facies maps for the northern USSR for each of 11 ages of the Jurassic Period were prepared (Bogolepov 1983). According to these reconstructions, a deep-water strait connected to the North Pacific existed throughout the Jurassic Period in the eastern sector of the Arctic (Zakharov et al. 2002). In the Late Jurassic, the margin of the bay was near the New Siberian (Novosibirskie) Islands. In Volgian and Valanginian times, deep-water troughs of the bay

Fig. 3 Ammonite, belemnite and buchiid zonations in relation to litho- and magneto-stratigraphy and biodiversity of major taxonomic groups. Member 1 (section 33, beds 1–3) is Middle Oxfordian, with silty clay to silty mudstone, dark-grey to black, and an interband of sandy-silt at the middle part of the bed. Member 2 (section 33, beds 4–5) is Upper Oxfordian, with silty thin-bedded black clay. Member 3 (section 33, bed 6) is Upper Oxfordian–Lower Kimmeridgian, with silty dark-grey to greenish clay. The contents of the silt fraction decreases upwards and clay became well-sorted. Member 4 (section 33, bed 7) is Lower Kimmeridgian–Middle Volgian, with silty dark-grey glauconite–leptochlorite badly sorted clay and small addition of sandy grains. Member 5 (section 33, beds 8–9; section 32, beds 1–2) is Middle Volgian and belonging to the Epivirgatites variabilis Zone. The mudstone-like fractured dark-grey glauconite–leptochlorite clay within this member has a bluish tint. Member 6 (section 33, bed 10–14; section 32, bed 3–7) is Middle Volgian–Upper Volgian, with mudstone-like fractured clay consisting of alternating layers of dark-grey, brown and bluish-grey colour, and a glauconite-rich band at the base. Member 7 (section 33, beds 15, 16; section 32, beds 8, 9) is Upper Volgian. The mudstone-like clay is dark-grey, sometimes silty, bedded, with occasional bands of bluish-grey fractured clay and with high contents of organic matter and pyrite. Member 8 (section 33, bed 17; section 32, bed 10) is Upper Volgian and belonging to the Chetaites chetae Zone. The thin-bedded dark-grey brownish clay has fossil plant remains and pyrite globules. Member 9 (section 33, beds 18–23; section 32, beds 11–16) is Lower Ryazanian, and belonging to the Chetaites sibiricus Zone. The clay is sometimes mudstone-like and is dark-grey, thin-bedded, with interbeds of fractured bluish-grey clay. The lower part of member 10 (section 33, bed 24; section 32, beds 17–18) is Lower Ryazanian and belonging to the basal bed of the Hectoroceras kochi Zone. The clay is mudstone-like, partially silty, fractured, bluish-grey, with intercalations of thin-bedded dark-grey clay. 1C–2A, No of levels.

penetrated into the eastern part of the Laptev Sea. Flyschoid successions of terrigenous rocks, such as sandstones, siltstones and mudstones—over 1200 m in total thickness—were formed in these troughs (Kuz'michev et al. 2009). Apparently, the nearby water masses affected the environments of northern East Siberia by bringing about a climatic warming and consequent changes in biota. The diverse Late Jurassic biota of the North Siberian seas were formed under the influence of the northern European seas, starting with the Central Russian Sea (Saks & Nalnjaeva 1973; Bogolepov 1983; Dzûba et al. 2006; Rogov 2012).

Materials and methods

Macrofossils used for the present study were collected noting their position within the section to the nearest centimetre (cephalopods) or were collected separately from each member (bivalves). Data concerning the relative abundance of macrofossils were obtained from field observations using a semi-quantitative approach.

Palynological samples were collected every 0.2–1.0 m. A total of 72 rock samples, recovered from dark claystones, were processed for palynomorphs. After washing and drying, the standard processing involved chemical treatment of 10 g of the sample with HCl to remove the calcareous fraction and with HF to remove silicates, sieving through a 15-µm nylon mesh, and centrifuging to concentrate the residues. Oxidation was not used. Three microscope slides were made from each sample for palynofacies analysis and dinoflagellate cyst analysis. Whole slides of residues were investigated under a binocular transmitted light microscope to identify and count the palynomorphs and other organic materials. A total of 63 samples for foraminiferal analysis were collected within the Kimmeridgian—Lower Ryazanian, with a sample resolution of 1.2 m in the lowermost part of the section and 10–20 cm in the Upper Volgian—Ryazanian.

For the determination of the $\delta^{13}C$ values of organic carbon, sample aliquots were first boiled with HCl to remove any carbonates. Samples were then repeatedly washed by distilled water, dried and the $\delta^{13}C$ values determined through gas chromatography–isotope-ratio mass spectrometry (GC–IRMS), using a 1108 Elemental Analyzer (Fisons, Ipswich, UK) with a ConFlo (Thermo Finnigan, San Jose, CA, USA) interface and a MAT 251 mass spectrometer (Thermo Finnigan) at the Laboratories of the Czech Geological Survey in Prague. Overall, analytical uncertainty of the $\delta^{13}C$ values of the organic matter was $\pm 0.2‰$.

Palaeoecological changes: available data and environmental interpretation

Changes in bivalve communities

Analysis of benthic communities can provide detailed information on the environment and the character of sedimentation. The most promising approach is a trophic structural study by analysing the levels of feeding (Turpaeva 1953). Benthic molluscs can be divided into two large groups on the basis of the feeding method: deposit-feeders (detritophagous) and suspension-feeders (sestonophagous), both subdivided in two subgroups: high or low feeders.

The first subgroup of deposit-feeder bivalves feeds at the sediment surface. The second group gains its food below the sediment surface. Suspension-feeder bivalves feed near the sediment surface, or above it. The presence of detritophagous bivalves in the community always indicates quiet conditions with stable rates of sedimentation. If species feeding at the surface are dominant in the community, this shows that there is poor oxygenation at the bottom. The well-recognized "taxonomic stairs" are a good indicator of the stability of all environmental factors, showing the presence of few dominant, characteristic species and numerous rare species in the community (Odum 1971). A "mature community" is characterized by the presence of all groups in the "taxonomic stairs"; such biocoenoses are formed in stable environments. The absence of one or more "stairs" indicates an unstable environment and the influence of some kind of abnormality. On this basis, we conclude that mature communities are absent (Fig. 3). Only the first (Middle Oxfordian) and tenth (Kochi Chron) communities are characterized by the absence of strongly dominated taxa and can be considered to be rather uniform. The most noticeable characteristic in all cases is the absence of an obvious dominant species.

The predominance of *Aequipecten* in taphococenoses is not significant since this genus with thin-walled equilateral and equivalved shells seems to be pseudoplanktonic. Therefore, we can reasonably conclude that the influence of one or more environmental factors was anomalous during the Late Jurassic and in the very beginning of the Early Cretaceous. Among the most probable factors is an oxygen deficit of near-bottom water, with possible periodic anoxic events at the sediment surface. The trophic structure of the communities confirms this idea because epifaunal deposit-feeders represent a considerable fraction in most communities, sometimes accounting for more than half of all the bivalves (Fig. 3).

Another possible factor disturbing the development of benthic communities is a low temperature of near-bottom waters. Small size, thin, sometimes transparent shells in Kimmeridgian and Volgian bivalves can be a strong argument for this suggestion. Near-bottom waters could cool by the inflow of cold waters from the east where deep foredeeps were located. The proximity of an open ocean to the east is indicated by the presence of phylloceratids in the Nordvik section in Volgian and Ryazanian strata. These ammonites are absent in the Oxfordian and Kimmeridgian of this area. However, as inhabitants of open seas, phylloceratids are quite common in the Upper Jurassic of north-east Russia (Parakecov & Parakecova 1989). Possible paths of a phylloceratid invasion into the Yenisei–Khatanga Sea are deep-water troughs: flysh sediments, usually filling such troughs, were recently found at the New Siberian Islands (Kuz'michev et al. 2009).

Changes in ammonite diversity

As at other high-latitude sites (Rogov 2012), the ammonite assemblages of the Nordvik section are mainly characterized by very low taxonomic diversity, usually ranging between one and three at both genus and species level. All levels that are characterized by increased diversity coincide with immigration events of ocean-associated ammonites, with the exception of the Kimmeridgian, when the high diversity interval coincides with the appearance of *Suboxydiscites* (Fig. 4d), and the last cardioceratid diversification. One such high diversity level can be observed at the Middle–Late Volgian transition when, in addition to boreal ammonites, *Euphylloceras* occurs (Fig. 4e). The appearance of these phylloceratids in the studied area and in Svalbard (Rogov 2010) indicates the penetration of typical open sea ammonites from the northern Pacific. In contrast to the Middle Volgian the beginning of the Late Volgian is also characterized by the decrease of provincialism of boreal ammonites. Only the western part of the Panboreal Superrealm, westward of the Greenland–Norwegian Seaway, was inhabited by an endemic craspeditid lineage (*Swinnertonia–Subcraspedites–Volgidiscus*). Both a reduction in ammonite endemism and the occurrence of phylloceratids could be explained by a short-term sea-level rise in the Arctic. Such a sea-level rise is also reflected in the Russian Platform succession (Sahagian et al. 1996). Afterwards, the ammonite diversity quickly decreased, albeit ammonite faunas of the different parts of the Arctic became very similar in this time. Near to the Volgian–Ryazanian boundary, the ammonite diversity increased again. The Chetae Chron is characterized by the co-occurrence of boreal *Chetaites* and *Praechetaites*

as well as oceanic phylloceratids (Zaharov et al. 1983). An increase in ammonite diversity at the beginning of the Ryazanian is connected with a high diversity of boreal taxa belonging to three lineages: last *Craspedites* (*Taimyroceras*); first *Praetollia* derived from *Volgidiscus*; and the last Dorsoplanitid ammonites, the *Chetaites*. The most remarkable diversity increase at the beginning of the Kochi Chron again relates to the invasion of oceanic ammonites. These ammonites include at least one endemic Arctic taxon *Boreophylloceras,* while the typical oceanic *Biasaloceras* (Fig. 4b) and *Bochianites* cf. *glennensis* (Fig. 4c) resemble Californian occurrences which immigrated from the Pacific (Rogov & Igol'nikov 2009). Moreover, such open sea ammonites even penetrated the much more shallow seas of the Khatanga depression, and their records are also known from the basal Kochi Zone of the Bojarka section (Fig. 4a). This event also closely corresponds with a suggested sea-level rise leading to rapid spreading of the first *Hectoroceras* throughout the Arctic.

Changes in belemnite diversity

Belemnites (Cylindroteuthididae) in the Nordvik section as a whole are more abundant and higher in taxonomic diversity than ammonites. As has been observed (e.g., Zakharov et al. 2005; Rogov et al. 2006), there is an inverse relationship in diversity of these two cephalopod groups (see Fig. 3). In part, this is caused by competition between ammonites and belemnites and their different preferences concerning environmental conditions. Consequently, the highest levels of ammonite diversity are reached when the deepening of the North Siberian basin made the invasion of open sea ammonites possible. This is observed at the Middle–Late Volgian transition and at the beginning of the Ryazanian Kochi Chron. Belemnite diversity is notably reduced at these times, suggesting that cylindroteuthids were poorly adapted to deep-water environments.

Low diversity belemnite assemblages are recorded in the wide interval of the Upper Volgian and lowest Ryazanian beds. Only rare representatives of the genera *Arctoteuthis*, *Cylindroteuthis* and *Lagonibelus* with elongate rostra are distributed here (from one to five species). Taxa with shorter robust rostra (Pachyteuthidinae and Simobelinae) are absent; this indicates a deepening and broadening of the basin, especially during the Okensis Chron and most of the Taimyrensis Chron, which is confirmed by micropalaeontological and palynological evidence (Nikitenko et al. 2008). A slight diversity increase can be recognized at the top of the Taimyrensis Zone near
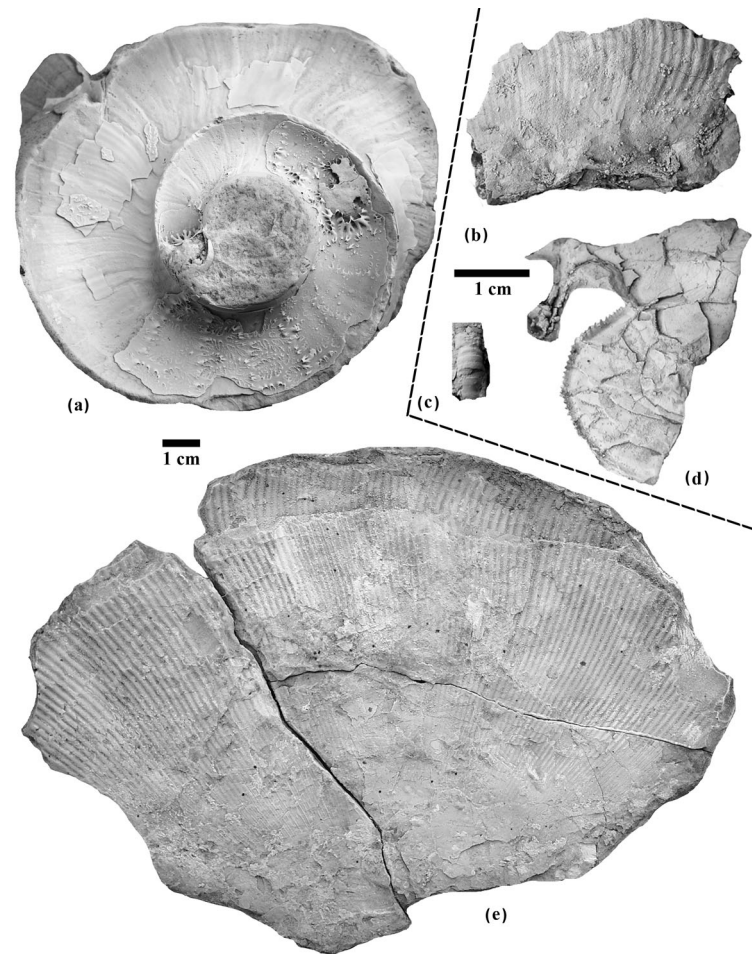
Fig. 4 Selected Upper Jurassic–Lower Cretaceous ammonites from the Nordvik and Bojarka sections. (a) *Biasaloceras* sp., no number, Bojarka river, Ryazanian, Kochi Zone; (b) *Biasaloceras* sp., MK1056, Nordvik, Ryazanian, Kochi Zone; 0.05 m above 1C; (c) *Bochianites* cf. *glennensis* And., MK 1094, Nordvik, Ryazanian, Kochi Zone; 0.05 m above 1C; (d) *Suboxydiscites* sp. [m]; MVI767; 0.3 m above 2G, Lower Kimmeridgian, Kitchini Zone, *subkitchini* horizon; (e) *Euphylloceras* cf. *knoxvillense* (Stanton); MK1082, 9.3 m below the base of the Ryazanian, Upper Volgian, Okensis Zone. Specimens were collected by M. Rogov during fieldwork in 2003 except (a), which was collected by M. Rogov in 2008. Specimens (a), (b), (c) and (e) are stored in the Trofimuk Institute of Petroleum Geology and Geophysics of the Siberian Branch of Russian Academy of Sciences, Novosibirsk, and specimen (d) is at the Geological Institute of Russian Academy of Sciences, Moscow.

the J/K boundary (as recently confirmed by magneto-stratigraphy; Houša et al. 2007), and just above the "Iridium bed" at the base of Member 9. At the same levels, the majority of the belemnites common for the Arctic and Northern Proto-Pacific (California) remains steady: *Cylindroteuthis knoxvillensis*, *C.* cf. *newvillensis*, *Arctoteuthis tehamaensis* and *A. porrectiformis*. In deposits from the Middle Oxfordian to the Kimmeridgian, among the belemnites many cosmopolitan taxa were observed, but all are common taxa for Arctic and subboreal European seas: *Cylindroteuthis puzosiana*, *C. obeliscoides*, *Pachyteuthis excentralis*, *P. panderiana*, *Boreioteuthis absoluta*, *Lagonibelus ingens*, *L. kostromensis*, *Simobelus breviaxis*. The interval between Kimmeridgian and Late Volgian time was characterized by an increase in belemnite endemism culmi-

nating in the Middle Volgian Variabilis Chron (up to 70% Arctic endemic belemnite assemblages).

The Kimmeridgian and Middle Volgian Variabilis chrons show both the highest taxonomic diversity (9–16 species from six to seven genera) and an abundance of belemnites. Both episodes of increasing belemnite diversity are typical features for the North Siberian seas and attributed to oceanographic (sea-level changes, expansion of sea connections) and probably climatic (warming) events (Saks & Nalnjaeva 1979; Dzûba et al. 2006; Dzyuba 2013).

Six major belemnite events, characterized by mass occurrences of belemnite rostra, have been recognized in the Upper Kimmeridgian through the lowest Ryazanian interval. The earliest one has been located at the top of the Septentrionalis belemnite Subzone (stratigraphic

equivalent of the uppermost Kimmeridgian Suboxydiscites taimyrensis ammonite Zone in Siberia).

While the high sea level reflected in the middle part of the Explanata belemnite Zone is not connected with a mass occurrence of belemnites, the sea-level variations between the upper part of the Explanata and lower part of the Russiensis belemnite zones are characterized by four, clearly distinguished belemnite events. Three of these are located in the Middle Volgian Variabilis ammonite Zone. The development of favourable conditions for a belemnite expansion (see above) and mass occurrences are predominantly associated with a shallowing. The belemnite dependence on changes in sea level and nutrient delivery are well recorded in the Upper Cretaceous taxa (Mitchell 2005; Wiese et al. 2009). However, the Cretaceous taxa are typical of shallow-water platform seas. The same mode of belemnite behaviour is reported here also from the Boreal–Arctic Basin. The depth of the sea bottom may represent an ecological limit for a mass expansion.

A sixth belemnite event is recorded at the base of the Sibiricus ammonite Zone. Its position shows a shallowing trend with an increasing input of terrigenous material.

Eventually, the belemnite diversity shows a partial decrease in the J/K boundary interval. This corresponds to a time of sea-level rise and basin deepening.

Changes in palynological spectra

Our palynofacies analysis (counting up to 400 particles in each sample) was based on phytoclasts distinguished by Batten (1996): structural organic matter represented by black particles, brown woody particles and yellow material (cuticles); palynomorphs represented by bisaccate pollen, non-bisaccate pollen, spores, green algae (prasinophytes), dinoflagellate cysts and foraminiferal test linings. The quantitative study of the dinoflagellates and the analysis of their distribution has been published (Nikitenko et al. 2008). Three data sets were used to interpret palynological assemblage fluctuations in terms of environmental changes: (1) the ratio of terrestrial (pollen and spores) to marine palynomorphs (acritarchs, dinoflagellate cysts, foraminiferal linings, algae), known as the terrestrial/marine index (T/M index); (2) the changes in relative abundance of selected dinocyst genera; and (3) the diversity expressed as the number of genera or species found in each sample.

All samples contain rich palynological material. Overall, the studied samples display palynofacies variations through the section. Most residues are characterized by abundant structural organic matter, dominated by phytoclasts (brown woody particles and yellow particles). This material

dominates the section at the intervals of 34–39 and 45–49.5 m. Poorly preserved dinoflagellate cysts can be found in the same intervals (36–38.5 and 46–47.4 m). These are usually difficult to identify and carry marks of decay caused by crystallization of pyrite. This palynofacies is typical for anoxic conditions where deposition is slow. The studied parts of the section are also characterized by a low percentage of dinoflagellate cysts ($<10\%$) and a very low percentage of spores and pollen grains ($<15\%$).

Certain palynomorph assemblages contain a higher proportion of dinoflagellate cysts than found in the rest of the studied section. The increase in relative abundance of dinoflagellate cysts (Middle Volgian, Okensis ammonite zone of the Upper Volgian, Sibiricus and Kochi ammonite zones of the Ryazanian) is coinciding with an increased abundance of foraminiferal linings (typical of marine coastal and neritic environments) and green algae (Fig. 5). Foraminiferal test linings occur at 30 and 44 m. In the intervals from 42 to 45 m (Upper Volgian) and from 50 to 54 m (Lower Ryazanian), a distinct bloom of green algae (prasinophytes) is found (Fig. 5). Here dinoflagellate cysts comprise around 20–40% of the assemblage. Prasinophytes are known to appear in a wide range of environments, from marine to brackish, being most frequent in nearshore marine and anaerobic environments (e.g., Tappan 1980; Batten 1996). According to Prauss & Riegel (1989), prasinophycean algae might have favoured cold-water environments. Smelror et al. (2001) suggested that the algal bloom was possibly induced by the large amounts of nutrients released into the water column. High productivity and limited water circulation at the bottom with a marked eutrophication cause anoxic conditions of sedimentation (Below & Kirsch 1997). Prasinophytes are abundant in this type of facies (Skupien & Vašíček 2002; Nikitenko et al. 2008).

The changes in T/M index and the composition of palynofacies may aid in the interpretation of the depositional environments in terms of water depth, sea-level oscillations and terrigenous influx (Lister & Batten 1988; Smelror & Leereveld 1989; Batten 1996). A high fraction of terrestrial organic matter points to an intense supply of land-derived organic particles and/or shallowing marine conditions. An increased supply of continental material probably reflects higher precipitation on land, resulting in an enhanced nutrient supply to coastal waters and enhanced organic particle transport to the shelf margin. The T/M ratio decreases basin-ward and increases in a shallowing succession. The low amounts of amorphous organic matter in all samples may result from a high accumulation rate.

The diversity of dinoflagellates varies from eight to 25 genera and eight to 31 species in each sample.
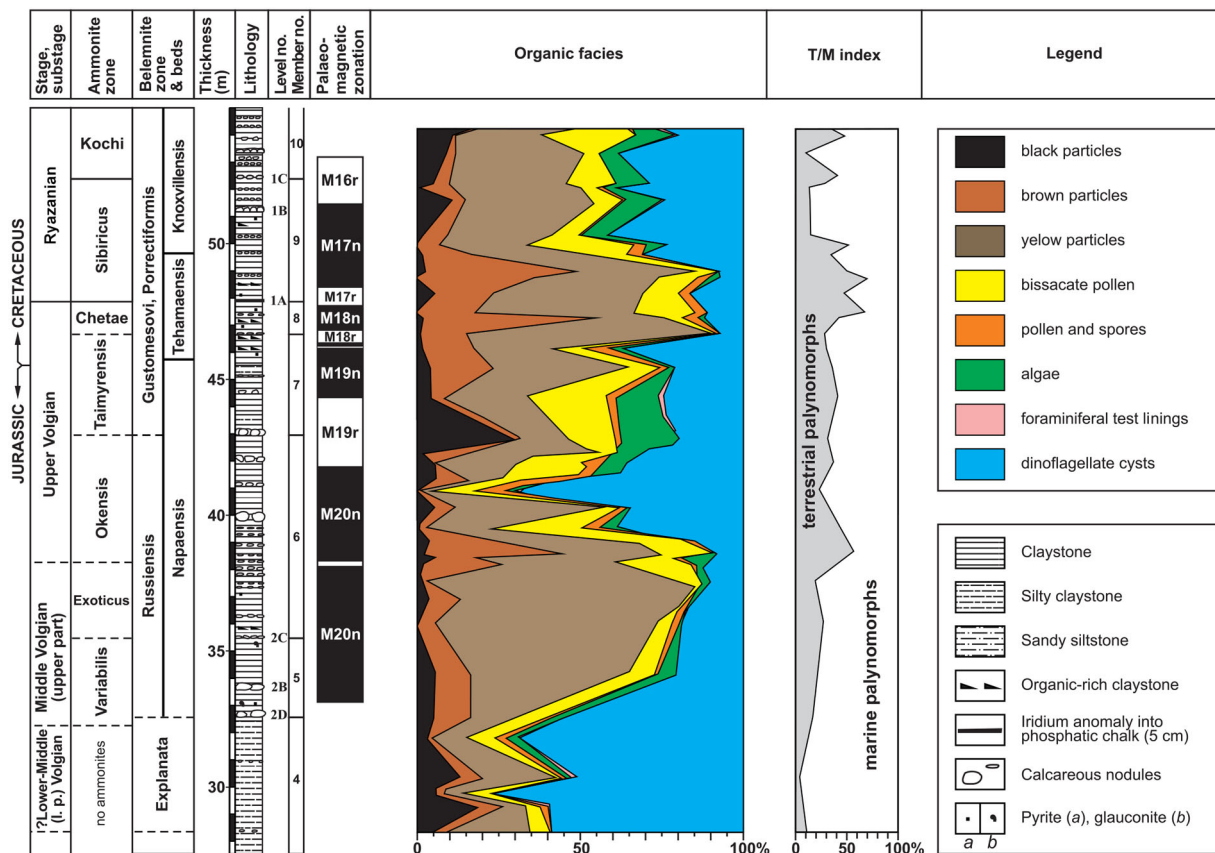
Fig. 5 Ammonite, belemnite and buchia zonations in relation to litho- and magneto-stratigraphy and relative abundance of micropalaeontologic data (palynomorphs, dinocysts and foraminiferal test linings). The T/M index is the relative abundance of terrestrial and marine palynomorphs.

The Lower–Middle Volgian Explanata belemnite zone, the Upper Volgian Okensis ammonite zone and the Lower Ryazanian Sibiricus ammonite zone show the highest diversity of dinoflagellates (Fig. 3). The samples with lower diversity also contain poorly preserved cysts. A low diversity of dinoflagellates has been interpreted to reflect dysoxic–anoxic palynofacies (Batten 1996).

The greatest changes in the taxonomic composition of dinocyst assemblages have been observed near the base of the Upper Volgian. Characteristic Upper Jurassic dinoflagellate cysts have their last occurrences in this position, while Volgian–Ryazanian taxa have their first occurrence slightly above (Nikitenko et al. 2008).

The dinoflagellate cyst associations are dominated by numerous gonyaulacaceans that indicate rather deep-water palaeoenvironments. Among the dinoflagellate cysts, proximate (e.g., genera *Cribroperidinium, Gonyaulacysta, Paragonyaulacysta*) and cavate groups (e.g., genera *Dingodinium, Endoscrinium, Sirmiodinium, Tubotuberella*) are the most abundant and diverse. These types reflect a middle shelf environment (Nikitenko et al. 2008; Skupien & Smaržová 2011). The characteristic features of dino-

flagellate cyst assemblages are a low abundance and a low diversity of chorate (*Achomosphaera, Cleistosphaeridium*) and proximochorate (*Circulodinium, Sentusidinium*) types. Their abundance indicates a deepening of the depositional environment in the interval of the Taimyrensis—Sibiricus ammonite zones.

The quantity of cavate forms (*Sirmiodinium*) in the Upper Volgian (Taimyrensis ammonite Zone) correlates with a high percentage of prasinophytes and a low diversity of dinoflagellates, suggesting that these dinoflagellates may be less sensitive to anaerobic conditions and/or more tolerant of reduced salinities (Nikitenko et al. 2008).

Stable isotope records and their interpretation

The analytical methods used to obtain inorganic carbon (C) and oxygen (O) isotope data from the belemnite rostra (genera *Cylindroteuthis* and *Arctoteuthis* [76% of the analysed samples] *Lagonibelus* [10%], *Pachyteuthis* [6%], *Simobelus* [2%] and unidentified genera [6%]) as well as detailed stable isotope data and sample chemical composition from Nordvik are described by Žák et al. (2011) and

Dzyuba et al. (2013) and are not repeated here. It should be noted that *Arctoteuthis* is not mentioned in Žák et al. (2011) because this taxon was considered as a sub-genus of the genus *Cylindroteuthis*. In the present work, the belemnite taxonomy used to identify taxa to the genus level follows Dzûba (2011). The sampled interval covers a period from the Middle Oxfordian to the basal Ryazanian. Two positive excursions in the lower part of the section (in the Middle Oxfordian and in the basal part of the Upper Kimmeridgian) were recorded, with carbonate δ^{13}C values reaching up to of $+3\%_0$ (Vienna Pee Dee Belemnite [VPDB] scale; Fig. 6). These peaks are located at similar positions as positive δ^{13}C excursions in the belemnite record of the Russian Platform described by Riboulleau et al. (1998) and Price & Rogov (2009). Similar Middle Oxfordian positive carbon isotope excursions have been observed by Wierzbowski (2004) in the Western Carpathians. A stratigraphically useful carbon isotope signal has recently been recorded in the Nordvik section slightly above the J/K boundary, where the δ^{13}C values increase from 0.0–0.2 to $+0.9\%_0$ and then decrease to pre-excursion values. According to Dzyuba et al. (2013), this positive excursion is most distinctively observed in the Maurynya section of western Siberia and is less obvious in the Marievka section of central Russia and in pelagic limestones of the Tethyan Guppen–Heuberge section of Switzerland.

The whole Upper Jurassic is characterized by an irregular carbonate δ^{13}C decrease upward throughout the Nordvik section. This is a trend which has been detected at many other sections, both on the Russian Platform and in the Tethyan Realm (e.g., Weissert & Channell 1989; Podlaha et al. 1998; Savary et al. 2003; Price & Rogov 2009). Such a decrease in δ^{13}C could be connected with a gradual increase of the carbon dioxide contents in the atmosphere–ocean system, leading to warming, as reflected by coeval changes in the belemnite oxygen isotope record (see below). On the other hand, carbon isotopes in belemnite rostra are reported to not be in equilibrium with ambient seawater due to vital effects (Wierzbowski & Joachimski 2009). Thus, changes in carbon isotope records could be partially connected with changes of belemnite assemblages within the section, as vital effects could be different in different taxa. For example, the average carbon isotope values of the Nordvik *Pachyteuthis* belemnites are notably higher throughout the Upper Jurassic and lowermost Cretaceous than those in other belemnite genera. The values attain 2.29$\%_0$ in the Middle Oxfordian–Kimmeridgian and 0.99$\%_0$ in the Volgian-basal Ryazanian. The average δ^{13}C values of *Lagonibelus* change from 1.41 to 0.14$\%_0$ between the same stratigraphic intervals, and for

Cylindroteuthis they show a similar range from 1.33 to 0.32$\%_0$. However, a general trend of decreasing δ^{13}C is seen within the data derived from all belemnite genera: Volgian-basal Ryazanian average δ^{13}C values recorded by different genera are lower than those observed for the Middle Oxfordian–Kimmeridgian. Here, we interpret the results of stable isotope analyses taking into account the mode of life and habitat of different belemnite taxa and their possible influence on the stable oxygen isotope values. For this purpose cylindroteuthid belemnites (those which inhabited the Siberian seas) were classified based on morphological, palaeoecological and distributional data (Gustomesov 1976; Saks & Nalnjaeva 1979; Dzyuba 2004). In accordance with this classification, they were arranged in three groups characterized by common features of the rostral morphology that reflect a similar style of life and habitat depth.

Group I is characterized by short robust rostra and includes the genera *Simobelus*, *Liobelus*, *Acroteuthis*, *Microbelus* and—the most robust—*Pachyteuthis* and *Lagonibelus*. These relatively less active swimmers preferred shallow near-shore water and are most common in the upper sublittoral zone deposits. It cannot be excluded that all these genera, or only the dorso-ventrally depressed taxa (*Liobelus*, *Microbelus*, and *Acroteuthis*), were nekto-benthic organisms. Isotope ratios have been analysed from belemnites *Simobelus* sp. (position in profile see table 3 in Žák et al. 2011).

Belemnites in Group II have elongate to moderately elongate rostra with a well-defined ventral groove; transverse sections are circular to dorso-ventrally depressed. *Arctoteuthis*, *Holcobeloides*, *Eulagonibelus*, *Boreioteuthis*, some of *Cylindroteuthis* and *Lagonibelus* were moderately active epipelagic swimmers living not far from the shore. They are most common in the middle sublittoral zone deposits. Taxa characterized by a moderately elongate rostrum with a strongly depressed transverse section and a long and wide ventral groove (*Holcobeloides*, *Eulagonibelus* and many *Boreioteuthis*) probably lived in near-bottom waters. Isotope ratios have been analysed from belemnites belonging to the taxa *Arctoteuthis porrectiformis*, *A.* aff. *porrectiformis*, *A.* cf. *sachsi*, *A. urdjukhaensis*, *Cylindroteuthis* cf. *comes*, *C.* cf. *jacutica*, *Lagonibelus strigatus*, *L. parvulus* and *L. sibiricus*.

In Group III, rostra are elongate to moderately elongate and slender, with a weak ventral groove; transverse sections are usually laterally compressed. Most of *Cylindroteuthis* and *Communicobelus*, as well as some of *Lagonibelus* and *Pachyteuthis*, belong to this group of active epipelagic swimmers. They are most common in the middle–lower sublittoral zone deposits. Isotope ratios have been analysed from belemnites belonging to the
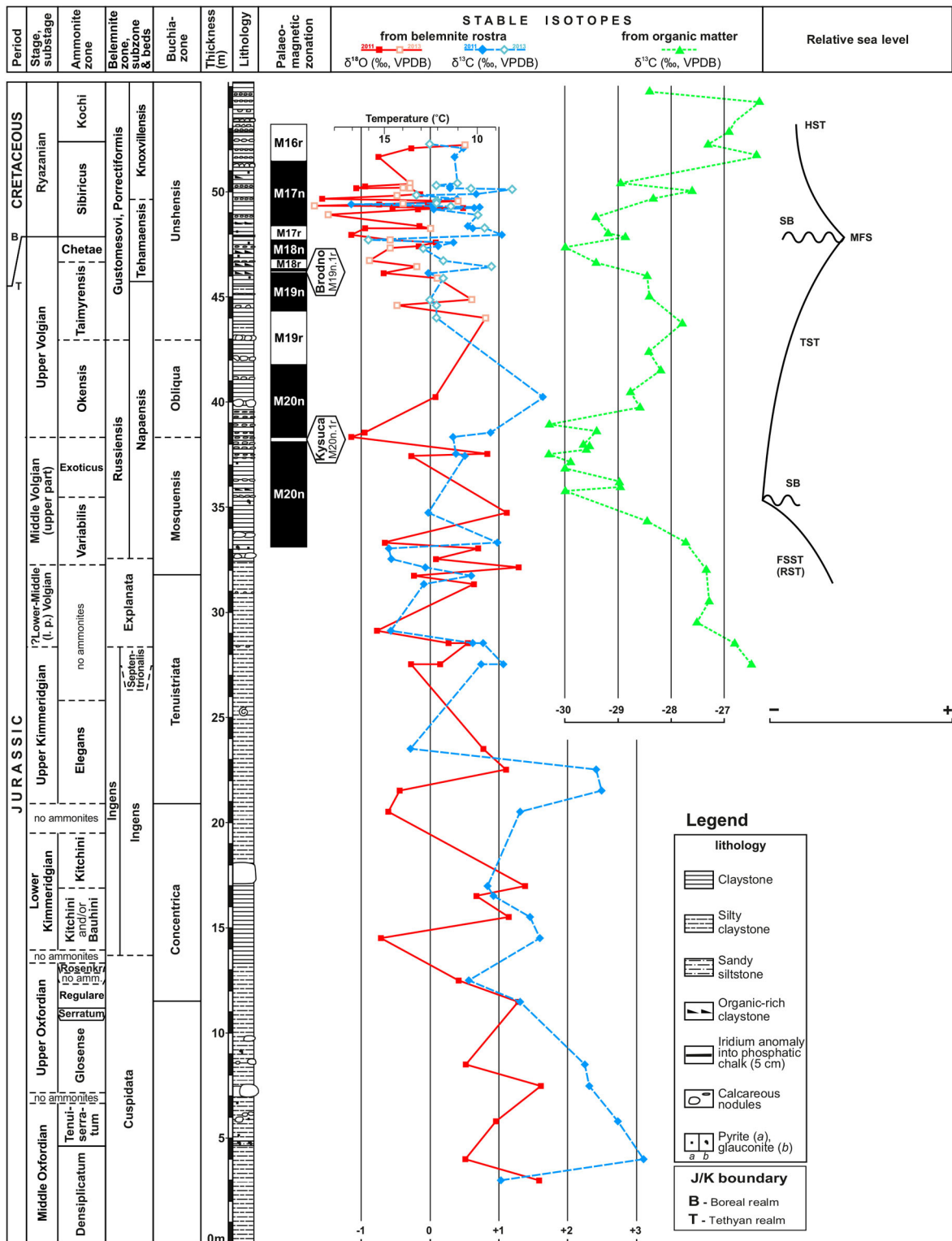
Fig. 6 Ammonite, belemnite and buchiid zonations in relation to litho- and magneto-stratigraphy, stable isotope curves based on the carbonate δ^{13}C and δ^{18}O record obtained from belemnite rostra and δ^{13}C of organic matter, and relative sea-level curve. The following terms are abbreviated: falling stage system tract (regressive system tract; FSST [RST]); sequence boundary (SB); transgressive system tract (TST); maximum flooded surface (MFS); and highstand system tract (HST).

taxa *Cylindroteuthis knoxvillensis*, *C. lenaensis*, *C. obeliscoides*, *Lagonibelus* cf. *nordvikensis*, *Pachyteuthis* cf. *excentralis* and *P.* cf. *panderiana*.

Several authors (Anderson et al. 1994; Price & Page 2008; Wierzbowski & Rogov 2011) consider belemnites as bottom-dwellers (with the ability of short vertical migration) on the basis of a comparison of their oxygen isotope records with those of ammonites and the similarity of oxygen isotope values to those of co-occurring bivalves. However, it is possible that the difference in $\delta^{18}O$ palaeo-temperatures recorded by different groups of cephalopods is due to the fact that belemnites are endocochleate (having an inner shell) whereas ammonites are ecto-cochleate (having an external shell). In any case, the morphological diversity among belemnites is too great to assume only a nektobenthic mode of life. Belemnite finds are known from black shales that lack any benthic organisms due to anoxic bottom waters (Mutterlose 1983; Seilacher et al. 1985; Oschmann et al. 1999). Rexfort & Mutterlose (2009) consider such findings as clear support for the view that belemnites (all or at least certain genera) had a nektonic mode of life.

Belemnite $\delta^{18}O$ data show an irregular decrease from values reaching up to $+1.6‰$ in the Middle Oxfordian to values between $+0.8$ and $-1.7‰$ in the Upper Volgian and basal Ryazanian. This trend is similar to that of the belemnite $\delta^{18}O$ in the Upper Jurassic of the Russian Platform (Riboulleau et al. 1998; Price & Rogov 2009) and Scotland (Nunn et al. 2009), possibly indicating a gradual warming during the Late Jurassic. Other explanations of such a trend include a gradual increase of freshwater input to the boreal seas during the Late Jurassic and a decrease in salinity. Nevertheless, there is no fossil evidence for any changes in salinity, as there are no fossils typical for brackish water from boreal marine deposits. Cephalopods, brachiopods and echinoderms are restricted to normal-salinity environments and occur in the same abundance during the end of the Jurassic and the beginning of the Cretaceous. Decreasing oxygen isotope values is a trend recognized from the *Arctoteuthis, Cylindroteuthis* and *Pachyteuthis* records. The *Lagonibelus* oxygen isotope data are scattered. According to the adopted classification (see above), samples analysed here belong to the cylindro-teuthid belemnites of the second and third group, combining moderately to very active epipelagic swimmers that were able to live in (or migrate into) relatively deep water (down to 200 m). Exceptions are two samples of *Simobelus* sp. (position 28.56 and 29.16 m in the profile) from the first, most "shallow-water" group and two samples of *Pachyteuthis* sp. (height 38.36 and 40.26 m in profile) of an uncertain group affiliation. Suppositional nekto-benthic forms among them are not established. In many cases, if the belemnite samples could not be identified to the species level, we could not determine whether the samples should be ascribed to the second or the third group. All these samples are attributed to the genera *Cylindroteuthis* and *Arctoteuthis* (Žák et al. 2011; Dzyuba et al. 2013) for which a nektobenthic mode of life is unlikely (Gustomesov 1976; Saks & Nalnjaeva 1979). The absence of bottom-dwellers probably explains why, despite the deepening of the studied area during the Late Jurassic, the belemnite $\delta^{18}O$ data could record a climatic warming. However, many aspects of the ecology of belemnites remain unclear, complicating interpretations of isotope data.

The $\delta^{13}C$ values of organic matter in sediments of the upper part of the Nordvik section range from -26.3 to $-30.3‰$ (VPDB; see Fig. 6). The values negatively correlate with the content of organic carbon in the sediments. Higher contents of organic carbon are accompanied by lower $\delta^{13}C$ data and vice versa. The variability of organic carbon isotope data is about twice as large as the variability of the isotopic composition of inorganic carbon. The differences between $\delta^{13}C$ values of the organic matter and of carbonate (belemnite rostra) Δ values ($\Delta^{13}C = \delta^{13}C_{carbonate} - \delta^{13}C_{organic\ matter}$) range from 26.76 to 30.81‰.

Oscillations of carbonate and organic matter $\delta^{13}C$ values are not parallel in the studied part of the section. Positive peaks in $\delta^{13}C$ values of organic matter are locally accompanied by negative peaks in $\delta^{13}C$ of belemnite rostra, but the degree of this negative correlation is again weak, like in the case of the relations between organic matter contents and $\delta^{13}C$ values.

Relative sea-level changes

During the Late Jurassic, the Yenisei–Khatanga strait experienced a gradual deepening, indicated by the change of sedimentation from sands and silts in the Oxfordian to mudstones and oil-shales in the Volgian (Fig. 3). Only after the beginning of the Ryazanian *Hectoroceras kochi* Chron silt deposition begin to increase and silts became dominant sediments in Nordvik during the Valanginian (Zaharov et al. 1983). These changes in grain size through the section were accompanied by an oscillation in sedimentation rates, recognized by significant differences in the thicknesses of stages and zones. The lowest sedimentation rate and thickness of ammonite zones is found close to the J/K boundary, coinciding with palaeomagnetic evidence for a slow sedimentation (Grabowski 2011). Above the J/K boundary the thickness of each ammonite zone gradually increased.

Our record of relative sea-level variations is based especially on lithological changes and the T/M index. The sea-level rise interpretation (TST in Fig. 6) towards the boreal J/K boundary is supported by micro- and macropalaeontological, geochemical, lithological and—especially—stable isotopic data. Sea-level variations were related to climatic cooling and warming phases corresponding to positive and negative excursions in $\delta^{18}O$ values, respectively. Three positive peaks in $\delta^{18}O$ values within the Explanata belemnite zone, Variabilis ammonite zone (Middle Volgian), and ca. 1 m below the base of the Okensis ammonite zone, are related to a relative sea-level decrease. The marked negative peak of $\delta^{18}O$ just above the Kysuca M20n.1r. magneto-subzone is stratigraphically very important. Similar $\delta^{18}O$ values are well known from the boreal J/K boundary and they may represent a rising sea level. The relative sea-level fall partly corresponds to negative $\delta^{13}C$ values of organic matter and the T/M index (Fig. 5). However, the Okensis ammonite zone and lower part of the Taimyrensis ammonite zone lack relevant $\delta^{18}O$ data from belemnite rostra. Several peaks of the T/M index may indicate specific trangressive/regressive pulses (probably fourth or fifth order sea-level changes; Fig. 6). The major eustatic excursions should represent third order sea-level variations during greenhouse phases (Tucker 1993). A long-term (first order) rise in sea level through the Jurassic and Cretaceous (Hallam 1988; Haq et al. 1988, Surlyk 1991) is well documented in stable isotopes in the Nordvik section and is well correlated worldwide.

In the critical J/K boundary interval, the two major sequence boundaries are clearly distinguished. The base of Member 6 (15–20 cm) shows a marked shallowing event as indicated by high glauconite concentration, marked ichnofabric, bottom communities and lithologic changes. Over- and underlying beds contain rich *Chondrites* ichnofabrics, while the base of Member 6 includes typical *Planolites* assemblages. Deposit-feeders are absent in the bottom communities and only high-level suspension-feeders could exist there. This indicates a shallowing event and/or a better oxidation of the sea bottom. The conclusion on a low sea level during the Variabilis zone is also supported by macropalaeontological data including bivalve assemblages and a rich belemnite fauna (Fig. 3). Another shallowing event, probably connected to a regression, has been identified at the top of the Exoticus zone. This event, clearly recorded by a positive excursion of $\delta^{18}O$ (see Žák et al. 2011), corresponds to the regression observed on the Russian Platform (Price & Rogov 2009). In contrast, the base of the Okensis zone is marked by the appearance of ammonites with a Pacific affinity (*Euphylloceras*), reflecting a sea-level rise. The

sea level apparently increased during the Okensis and Taimyrensis Chrons, which caused the influx of marine waters with new ammonite assemblages and a sharply decreasing belemnite faunal diversity. High-level detrito-phagous bivalves appear once again in the bottom communities, supporting the existence of dysoxic bottom environments.

The base of Member 9 ("Iridium bed") originated during the time of maximum eustatic sea level and represents a highstand systems tract in relation to the maximum flooded surface. The occurrence of anomalous levels of iridium and other platinum group elements has been reported and explained by the presence of diagenetically sulphidized iron particles of cosmic dust deposited under conditions of a drastically reduced clastic sedimentation rate (Zakharov et al. 1993; Mizera et al. 2010; Dypvik & Zakharov 2012). However, limited basaltic components from a source in the Siberian Traps (Permian–Triassic) containing also rare elements cannot be excluded (Dypvik & Zakharov 2012). The sea-level rise at the Sibiricus and Kochi zones boundary was also accompanied by the immigration of open sea ammonite taxa.

The Nordvik section demonstrates a clear trend of a strongly decreasing depositional rate upwards from the Okensis Zone to the base of the Ryazanian, with estimated changes up to 7–10 times, from ca. 11–12 m/ My to 1.5–2 to 11–12 m/My (Zakharov et al. 1993; Grabowski 2011). This decrease of terrestrial matter input was quickly reversed to higher rates of sedimentation after the deposition of the phosphate-rich band in the base of Ryazanian (Zakharov et al. 1993; Bragin et al. 2013). A strongly reduced sedimentation at the beginning of the Cretaceous led to the deposition of the iridium-rich band. The same trend of decreasing sedimentary rates, succeeded by its rise, has been recently recognized in many Tethyan sections around the J/K boundary (Grabowski et al. 2010; Lukeneder et al. 2010; Pruner et al. 2010). Such a phenomenon could be explained by climatic changes, especially by a progressive aridization (Abbink et al. 2001) and a decrease of rainfall and weathering at the J/K boundary.

Concluding remarks: the Nordvik section in a supraregional context

The biodiversity changes recorded at Nordvik are strongly related to sea-level oscillations. Macro-faunal data show a relatively high ammonite and low belemnite diversity when the sea level was high. The most prominent sea-level rise is marked by the occurrence of sea ammonites with Pacific affinities (*Euphylloceras, Bochianites*, etc.). Sea-level changes from the Oxfordian to the J/K boundary

were also accompanied by significant turnovers in the bottom community structure. The relatively high taxonomical richness of bivalves during the Oxfordian and Kimmeridgian (up to 18 genera in the Oxfordian) was substituted by a low diversity during the Volgian, especially the Late Volgian (four genera). These changes in bivalve diversity were accompanied by a simplification of the trophical structure of bivalve communities. Late Kimmeridgian bivalve communities hold up to six detritophagous genera, including four high-level deposit-feeders, while in the Late Volgian only two detritophagous genera were encountered, and both were uncommon. Sestonophagous bivalves are represented by a single genus (*Buchia*) only, which is sometimes found in abundance. These data suggest an anomaly in some environmental factors. Following sedimentological, mineralogical and geochemical analyses, we conclude that these changes in benthic communities were caused by low oxygen contents in the near-bottom water layer and an oxygen deficit in the sediment due to the deepening of the sea during sea-level rise.

The most striking feature of the Nordvik succession is a synchronous peak abundance in spores, corresponding to the $\delta^{13}C$ negative excursion in organic matter, and in prasinophytes near the J/K boundary (Nikitenko et al. 2008). Götz et al. (2009) reported a high abundance of prasinophytes from near the Triassic/Jurassic boundary in the Tethyan Realm, corresponding to the interval of the positive peak and an initial negative carbon isotope excursion, which they interpret as representing a bloom of green algae that flourished as a result of a disturbance in the marine ecosystem. A bloom of organic walled green algae is also known from the Triassic/Jurassic boundary interval of the St. Audrie's Bay section in Somerset, UK (van de Schootbrugge et al. 2007), which led to the suggestion that the proliferation of green algal phytoplankton may have been triggered by elevated carbon dioxide levels in the atmosphere.

During the Late Jurassic and Early Cretaceous, the Nordvik area was also affected by significant influences of cold water masses. The deep South Anyuy ocean developed at that time, forming a long but narrow bay from the northern Pacific. Oscillations in the relative diversity of different groups of molluscs could also be connected to fluctuations caused by local tectonics and sea-level changes rather than to changes in palaeotemperature. The Nordvik section is also important because information and data can be obtained time-equivalent to those of the oil-bearing Bazhenovo Formation of western Siberia. Our study makes it possible to recognize depositional conditions of the Bazhenovo Formation more precisely.

Two patterns are observed in the relationship between the Nordvik faunal diversity and the general trend of decreasing $\delta^{18}O$: an inverse correlation for the Oxfordian–Middle Volgian and a direct correlation for the Late Volgian–earliest Ryazanian. The mid-Oxfordian to Middle Volgian decrease of $\delta^{18}O$ values corresponds to an irregular but consistent increase in the taxonomic diversity in all faunal groups. The subsequent warming events in the Yenisei–Khatanga Sea (Žák et al. 2011) apparently did not favour Nordvik belemnites, bivalves and foraminifers. Their diversity was considerably reduced. In contrast, the ammonite diversity increased twice during the Late Jurassic to earliest Cretaceous, at the Middle–Late Volgian transition and at the beginning of the Ryazanian Kochi Chron. The highest levels of ammonite diversity were reached when a deepening of the North Siberian basin enabled the invasion of open sea ammonites. The water depths in the Nordvik area of the Late Volgian–earliest Ryazanian Yenisei-Khatanga Sea were evidently too great not only for benthos, but also for belemnites.

The belemnite $\delta^{18}O$ data show an irregular decrease from values reaching up to $+1.6‰$ in the Middle Oxfordian to values between $+0.8$ and $-1.7‰$ in the Upper Volgian and basal Ryazanian. They could be interpreted as reflecting a gradual warming (Fig. 6). This trend is similar to that of belemnite $\delta^{18}O$ in the Upper Jurassic of the Russian Platform (Riboulleau et al. 1998; Price & Rogov 2009) and Scotland (Nunn et al. 2009). These oxygen isotopic data indicate a prolonged episode of gradual warming in boreal and subboreal areas. In contrast to this Late Jurassic warming, Tethyan data suggests a cooling in the latest Jurassic (Tremolada et al. 2006; Dera et al. 2011). Such a dichotomy may point to a weaker latitudinal temperature gradient during this time.

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