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Late Barremian–early Aptian climate of the northern middle latitudes: Stable isotope evidence from bivalve and cephalopod molluscs of the Russian Platform

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ABSTRACT

Palaeotemperatures during the late Barremian–early Aptian (Early Cretaceous) on the Russian Platform have been determined on the basis of oxygen isotope analysis of aragonitic bivalve molluscan and ammonoid shells and belemnite rostra with well-preserved microstructure from the Ulyanovsk area. Those obtained from the planispiral and heteromorph ammonoid shells from the lower Aptian Volgensis–Schilovkensis, Deshayesi–Tuberculatum, and Deshayesi–Renauxianum zones range from 26.7 to 33.2 °C, from 29.2 to 33.1 °C, and from 27.0 to 29.5 °C, respectively. A heteromorph *Helicancylus*? cf. *philadelphius* shell from the uppermost lower Aptian Bowerbanki Zone was secreted in highest temperature conditions (32.8–35.2 °C). In contrast, upper Barremian molluscs (bivalve *Cyprina* sp. and belemnite *Oxyteuthis* sp.) of the Ulyanovsk area show significantly lower palaeotemperatures: 16.9–18.5 °C and 7.9–17.8 °C, respectively, which is in accordance with known palaeogeographic and palaeobotanical evidences, showing that a distinct climatic optimum seems to have occurred during the late early Aptian, when warm Tethyan water penetrated into the basin. Marked changes in calculated growth temperatures for investigated molluscs from the Russian Platform were most likely connected with both the general warming trend during the late Barremian–early Aptian and local palaeonvironmental conditions. New data from the Bowerbanki Zone of the Russian Platform provide evidence on existence of the positive carbon isotope anomaly (2.4–6‰) at the end of the lower Aptian. There were apparently the three positive C-isotope anomalies during the late Barremian–early Aptian. The onset of mid early Aptian Oceanic Anoxic Event (OAE) 1a seems to coincide with both the beginning of significant warm conditions (followed by short-term cooling) and the abrupt decline in heavy carbon isotope concentrations in marine carbonates, which partly were the likely consequences of the intensive release of CO_2 (biased by volcanic activity) and/or dissociation of methane gas hydrate.

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1. Introduction

Available information on Barremian–Aptian isotopic palaeotemperatures is very restricted. Bowen and Fontes (1963), and Teiss and Naidin (1973) were first, who have provided evidences of rather low (14.6–20.5 °C) Barremian water temperatures for France and Crimea based upon isotopic data on belemnite rostra and ammonoid jaws *Lamellaptychus*, associated with belemnites. Higher palaeotemperature (23.7 °C) was calculated from an Aptian belemnite rostrum of France (Bowen, 1961). Additional information on this topic during some years has been obtained from (1) lower upper Barremian belemnites of Yorkshire, England (McArthur et al., 2004), (2) lower-middle Barremian–Aptian belemnites from Hungary (Price et al., 2011) and Southern Ocean (Jenkyns et al., 2011), (3) lower Barremian and upper Aptian fish teeth from France and Switzerland (Pucéat et al., 2003), (4) upper Barremian–lower Aptian apatite phosphate of reptile remains from China, Thailand and Japan (Amiot et al., 2011), (5) middle Barremian and lower Aptian bivalves from the high latitude area of the Koryak Upland (Zakharov et al., 2004), (6) Aptian belemnites of Australia, and New Zealand (Dorman and Gill, 1959; Clayton and Stevens, 1968; Stevens and Clayton, 1971), and Mosambic (Bowen, 1963),

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(7) early Aptian membrane lepids of caenarchaeota from proto-North Atlantic (Schouten et al., 2003), (8) lower upper Aptian foraminifera from the subtropical North Atlantic (Huber et al., 2011) and Pacific (Huber et al., 1995), and (9) upper Aptian ammonoids from north Caucasus (Zakharov et al., 2000). Early Cretaceous palaeobiogeography and climate have been discussed by many authors (e.g., Mutterlose and Kessels, 2000; Steuber et al., 2005).

Recently, restricted data on extremely high palaeotemperatures (25.4–33.2 °C) based on well-preserved ammonoids *Deshayesites*, *Sinzovia*, and "*Acanthohoplites*" from the lower Aptian of the Ulyanovsk area, Russian platform (T. Tanabe and Y. Shigeta coll.) have been published (Zakharov et al., 2006).

Since information on upper Barremian–lower Aptian isotopic palaeotemperatures is especially restricted, we focus in this paper on palaeotemperture fluctuations and carbon isotope anomalies on the basis of the data on isotopic composition of very well-preserved fossils just from the mentioned interval of the Ulyanovsk area, Russian Platform (Fig. 1).

The studied fossil collections are kept at the Far Eastern Geological Institute, Vladivostok (N. Mansurova's, O. Smyshlyaeva's and Y. Zakharov's coll.) and Moscow State University (I. Michailova's coll) under numbers 2009, U28, 852 and 96, respectively.

2. Geological setting and stratigraphy

The investigated area is situated in the northern part of the Ulyanovsk-Saratov syneclise of the eastern European Russian Platform. Upper Barremian–Aptian sediments and molluscs of the Ulyanovsk area (previously named as Simbirsk government) were first studied by Yazykov (1832). Recent investigations include those by Baraboshkin (1996a, 1996b, 1997a, 1997b, 1998, 2001, 2002, 2005), Baraboshkin and Michailova (2002), Baraboshkin et al. (1997, 1999, 2001, 2002, 2007), Michailova and Baraboshkin (2001, 2002), Gavrilov et al. (2002), Baraboshkin and Mutterlose (2004), Guzhikov and Baraboshkin (2004, 2006), and Baraboshkin and Blagoveschensky (2010).

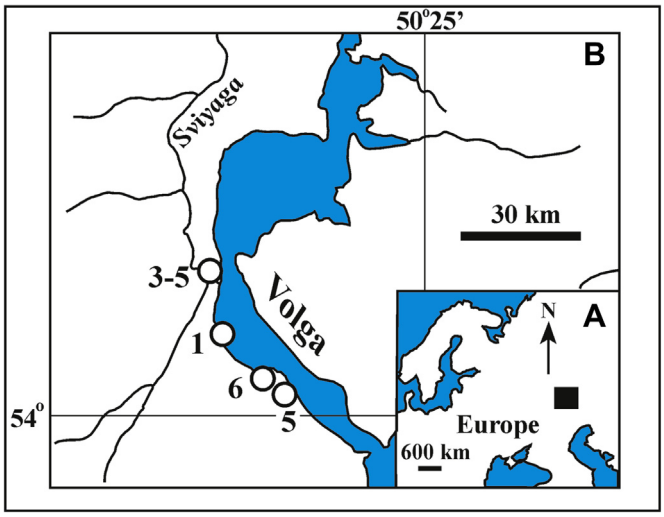

Fig. 1. Location map of Cretaceous outcrops in the Ulyanovsk area. A – location of the Ulyanovsk area in Europe; B – localities with upper Barremian and lower Aptian molluscs investigated: 1 – Novoulyanovsk (*Cyprina* sp., *Oxyteuthis* sp. – upper Barremian Germanica Zone); 2 – Shilovka (*Neocomiceramus volgensis*, *N.* cf. *borealis*, *Deshayesites volgensis*, *Sinzovia sazonovae* (Volgensis–Schilovkensis Zone), *?Acrioceras* sp. (Deshaesi–Renauxianum Zone); 3 – Ulyanovsk (*Deshayesites volgensis*, *Sinzovia sazonovae*, *Volgoceratoides schilovkensis* – Volgensis–Schilovkensis Zone); 4 – Solovyev ravine: *Proaustraliceras tuberculatum* (Deshaesi–Tuberculatum Zone); 5 – New Bridge (*Helicancylus*? cf. *philadelphius* – Bowerbanki Zone); *Neocomiceramus volgensis* – Schilovkensis Zone); 6 – Kriushi (*Deshayesites volgensis* – Volgensis–Schilovkensis Zone).

Belemnite- and bivalve-bearing sediments of the upper Barremian Germanica and the lower part of the Lahuseni zones of the Ulyanovsk area consist of dark-grey sandy clay with interbeds of greenish glauconitic muddy sand, 25–30 m thickness (Baraboshkin and Blagoveschensky, 2010).

The lower Aptian of the Ulyanovsk area, up to 39.5 m in thickness, is represented by the next members in descending order-details on lower Aptian cephalopods are shown in Fig. 2 (Baraboshkin and Blagoveschensky, 2010).

Member VII (Bowerbanki Zone) comprises the rhythmical alternation of grey muddy siltstone and mud sediments, including glauconitic ones, with large siderite concretions at the base. Its thickness is 1.6–1.8 m.

Member VI (Deshayesi–Renauxianum and Deshayesi–Tuberculatum zones) is dominated by dark-grey silty mud with rare lenses of glauconitic sand, carbonate and phosphorite concretions. It is of 4 m-thickness.

Member V (Volgensis–Matheronianum Zone) is composed of dark-grey mud with the shell detritus, it is of 3–3.2 m in thickness.

Member IV (Volgensis–Schilovkensis Zone), a 3.8–4-m-thick layer of black bituminous shales with carbonate concretions in the upper part and larger carbonate concretions ("Aptian Slab") near base.

Member III (the upper part of the Tenuicostatus Zone) is represented by the rhythmical alternation of glauconitic-quartz sandstone and dark-grey and grey mud (7.8 m in thickness) with siderite concretions.

Member II (the lower part of the Tenuicostatus Zone) is represented by the rhythmical alternation of dark-grey silty mud (with marcazite concretions) and glaconite–quartz sandsone (with carbonate concretions). It has a thickness of 22–23 m.

Member I is 10.2 m thick; it shows the rhythmical alternation of sandstone, dark-grey muddy silt and black mud with no ammonoids. Sandy layers contain marcazite concretions.

3. Material and methods

The macrofossil samples for the isotope analyses in this study were collected from the upper Barremian and lower Aptian of the Ulyanovsk area, Russian. The collections comprise mainly molluscs (normally coiled and heteromorph ammonoids, belemnites, and bivalves). In addition, well-preserved lower Ordovician and upper Berriasian brachiopods from Cincinnati, USA (Holland and Patzkowsky, 2009.) and South West England, and upper Aptian belemnite *Neohibolites*? sp. rostra from the Biyasalinskaya Formation (?*Aconeceras nisum* Zone) of Belaya mount, Crimea, and also upper Barremian belemnite rostra from the stratotype section of the Barreme locality (*Holcodiscus uhligi* Zone) in France (Table 1) were analysed for comparison.

Most material from the Ulyanovsk area used for isotopic analyses consisted of: (1) exceptionally well-preserved calcitic belemnite rostra *Oxyoteuthis* sp. and aragonitic bivalve *Cyprina* sp. from the upper Barremian Germanica Zone of the Novoulyanovsk area, (2) aragonitic bivalve *Neocomiceramus volgensis*, heteromorph ammonoid *Volgoceratoides schilovkensis* and planispiral ammonoids *Deshayesites volgensis* and *Sinzovia trautscholdi* from the lower Aptian Volgensis–Schilovkensis Zone of the Shilovka–Kriushi area, (3) aragonitic heteromorph ammonoid *Proaustraliceras tuberculatum* from the lower Aptian Deshaesi–Tuberculatum Zone of the Solovyev ravine area, (4) aragonitic heteromorph ammonoid *Acrioceras?* sp. from the lower Aptian Renauxianum Zone of the Ulyanovsk area, and (5) aragonitic bivalve *Neocomiceramus volgensis* and heteromorph ammonoid *Helicancylus*? cf. *philadelphius* from the lower Aptian Bowerbanki Zone of the Ulyanovsk area (New Bridge region).

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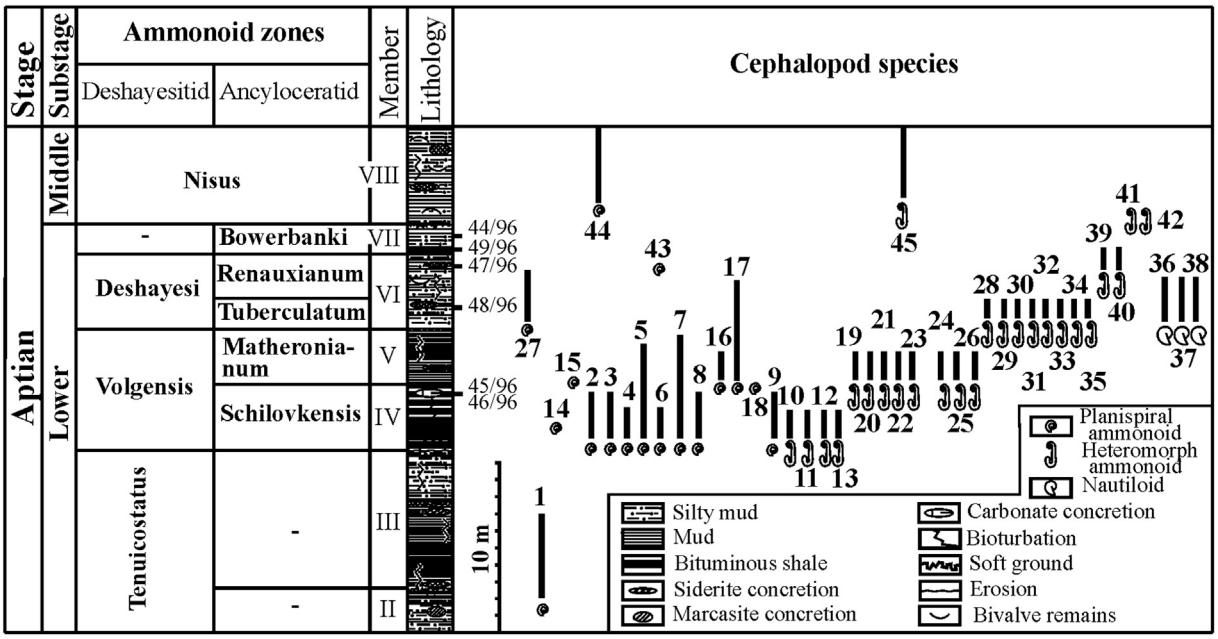

Fig. 2. The lower-middle Aptian column (Baraboshkin and Michailova, 2002, with modifications), and distribution of ammonoid taxa in the Aptian of the Ulyanovsk area. Cephalopod species: 1 – *Deshayesites* cf. *tenuicostatus* (Koenen), 2 – *D. volgensis* Sazonova, 3 – *D. forbesi* Casey, 4 – *D. gracilis* Casey, 5 – *D. consobrinoides* (Sinzow), 6 – *D. saxbyi* Casey, 7 – *Deshayesites* sp., 8 – *Paradeshayesites imitator* (Glasunova), 9 – *Sinzovia trautscholdi* (Sinzow), 10 – *Volgoceratoides schilovkensis* I. Michailova et Baraboshkin, 11 – *Koeneniceras tenuiplicatum* (Koenen), 12 – *K. rareplicatum* I. Michailova et Baraboshkin, 13 – *Koeneniceras* sp., 14 – *Obsoleticeras levigatum* (Bogdanova), 15 – *Deshayesites multicostatus* Swinnerton, 16 – *Paradeshayesites callidiscus* Casey, 17 – *P. ssengileyensis* (Sazonova), 18 – *P. similis* (Bogdanova), 19 – *Ancyloceras matheronianum* d'Orbigny, 20 – *A. mantelli* Casey, 21 – *Lithancylus grandis* (J. de C. Sowerby), 22 – *L. igori* I. Michailova et Baraboshkin, 23 – *L. glebi* I. Michailova et Baraboshkin, 24 – *L. russiensis* I. Michailova et Baraboshkin, 25 – *L. tirolensiformis* I. Michailova et Baraboshkin, 26 – *Pseudoanstraliceras pavlovi* (Vassilievsky), 27 – *Deshayesites* aff. rarecostatus Bogdanova, Kvantaliani et Scharikadze, 28 – *Toxoceratoides* sp., 29 – *Proaustraliceras rossicum* (Glasunova), 30 – *P. laticeps* (Sinzow), 31 – *P. tuberculatum* (Sinzow), 32 – *P. apticum* (Glasunova), 33 – *P. altum* (Glasunova), 34 – *P. solidum* (Glasunova), 35 – *P. jasykowi* (Glasunova), 36 – *Cymatoceras* cf. *karakaschi* Shimansky, 37 – *C.* karakashi Shimansky, 38 – *P.* aff. *bifurcatum* Ooster, 39 – *Audouliceras renauxianum* (d'Orbigny), 40 – *Toxoceratoides royerianus* (d'Orbigny), 41 – *Tropaeum* (*T.*) *bowerbanki* (J. de C. Sowerby), 42 – *Tropaeum* (*T.*) sp., 43 – *Cheloniceras* ex gr. *cornuelianum* (d'Orbigny), 44 – *Aconeceras nisum* (d'Orbigny), 45 – *Tonohamites* sp.

The following criteria were used in this study to determine diagenetic alteration: (1) macroscopic evidence; (2) percentage of aragonite in a skeleton, when the shells were originally represented by 100% aragonite, or presence of diagenetic admixture in both original aragonite or calcite (using X-ray analysis), (3) a degree of integrity of skeleton microstructure, determined under a scanning electron microscope (SEM) and (4) preliminary metallic-element measurements in belemnite rostra (using X-ray spectrometer coupled with a SEM to get energy-dispersion X-ray microanalytical (EDX) spectra).

We have usually recognised four stages in diagenetic alteration of aragonitic molluscs shells: 1st stage, where secondary calcite is absent (100% aragonite) or represented by a small portion, not more than 1–5%; 2nd stage, characterised by appearance of a larger portion (5–30%) secondary calcite, 3rd stage, where shell material consists of approximately 30–50% secondary calcite; 4th stage, characterised by presence of more than 50% secondary calcite and has very pronounced change in isotopic composition (Zakharov et al., 1975, 2006).

Selected belemnite rostra and ammonoid shell samples from our collection were broken into pieces and examined with a SEM (EVO 50 XVP) at the Institute of Marine Biology (IMB), Vladivostok, in order to obtain textural information and to ascertain the degree of diagenetic alteration. Cephalopod polished sections were also investigated with a SEM, after etching for 8–10 min with 1.0% HCl (with frequent interruptions for visual control – total treatment duration was about 3–6 min, as it was recommended by Sælen (1989), Podlaha et al. (1998), and Voigt et al. (2003)).

Samples for our isotopic analyses were carefully removed from the shells and rostra using a special method (Zakharov et al., 2005, 2007): material was taken by a scalpel mainly from narrow, small areas along growth striations on the external surface of bivalve and ammonoid shells, and from successive growth portions in the belemnite rostra, which enabled shell (rostrum) material, formed apparently during different seasons of the year to be identified. The same method has been used earlier by some other workers (e.g., Stevens and Clayton, 1971).

Oxygen and carbon isotope measurements were carried out using Finnigan MAT-252 mass spectrometer at Analytical Center of the Far Eastern Geological Institute (FEGI), Vladivostok. The laboratory gas standard used in the measurements was calibrated relatively to NBS-19 standard $\delta^{13}C = 1.93‰$ and $\delta^{18}O = -2.20‰$ (Coplen et al., 1983). Reproducibility of replicate standards was always better than ±0.1‰.

Two equations were used for palaeotemperature calculation: those of (1) Anderson and Arthur (1983) for calcite, and (2) Grossman and Ku (1986) for aragonite:

$$T\,(^{\circ}C) = 16 - 4.14\left(\delta^{18}O_{calcite} - \delta w\right) + 0.13\left(\delta^{18}O_{calcite} - \delta w\right)^2 \quad (1)$$

$$T\,(^{\circ}C) = 20.6 - 4.34\left(\delta^{18}O_{aragonite} - \delta w\right) \quad (2)$$

In these equations T (°C) is the ambient temperature; $\delta^{18}O_{calcite}$ (‰), and $\delta^{18}O_{aragonite}$ (‰) are the measured oxygen-isotope values of calcite and aragonite (versus VPDB), and δ_w (‰) is the ambient water isotope ratio (versus VSMOW). A δ_w of −1.0‰ is often assumed to be appropriate for an ice-free world (e.g., Shackleton

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Table 1
Carbon and oxygen isotope analyses of late Barremian belemnite *Oxyteuthys* sp. rostra U28-B-4, U28-B-1 and U28-B-3 (O. Smyshlyaeva's coll.) from the Germanica Zone of the Ulyanovsk area, Russian Platform. With the purpose of comparison, information on late Barremian belemnite rostra 2009-1 and 2009-2 (N. Mansurova's coll.) from the Biyasalinskaya Formation of Belaya mouth, Crimea, and Bar-3 and Bar-3a from the base of the *Holcodiscus uhligi* Zone of the Barreme locality in France, as well as on brachiopod shells from the Lower Ordovician of the Cincinnati area, USA (Ord-3(11b) and Ord-3(5a); Y. Zakharov's coll.), and brachiopods from upper Berriasian Oyster Bed of the Durlston Fm. of South West England (3(6) and 3(7); Y. Zakharov's coll.) is provided (D – rostrum diameter, L – length of the brachiopod shell).

Sample	Belemnite rostrum/brachiopodshell/ Bivalve shell	Location (D, L and H, mm)	Diagenetic alteration			$\delta^{13}C$ (V-PDB) (‰)	$\delta^{18}O$ (V-PDB) (‰)	T°C
			Original calcite (%)	Admixture (α-SiO_2)	Colour			
U28-B-4-1	U28-B-4 (rostrum)	D = 12.0–12.3	100	No	Colourless	1.97	0.54	10.0
U28-B-4-2	Same rostrum	D = 11.8–12.0	100	No	Colourless	2.11	0.84	8.86
U28-B-4-3	Same rostrum	D = 11.4–11.8	100	No	Colourless	1.78	0.78	9.07
U28-B-4-4	Same rostrum	D = 11.0–11.4	100	No	Colourless	2.11	0.73	9.26
U28-B-4-5	Same rostrum	D = 10.8–11.0	100	No	Colourless	2.31	0.72	9.29
U28-B-4-6	Same rostrum	D = 10.3–10.8	100	No	Colourless	2.38	0.69	9.40
U28-B-4-7	Same rostrum	D = 10.0–10.3	100	No	Colourless	2.38	0.67	9.48
U28-B-4-8	Same rostrum	D = 9.5–10.0	100	No	Colourless	2.42	0.60	9.73
U28-B-4-9	Same rostrum	D = 9.0–9.5	100	No	Colourless	2.42	0.52	10.03
U28-B-4-10	Same rostrum	D = 8.5–9.0	100	No	Colourless	2.34	0.59	9.77
U28-B-4-11	Same rostrum	D = 8.0–8.5	100	No	Colourless	2.46	0.57	9.85
U28-B-4-12	Same rostrum	D = 7.8–8.0	100	No	Colourless	2.34	0.62	9.66
U28-B-4-13	Same rostrum	D = 7.2–7.8	100	No	Colourless	2.34	0.71	9.33
U28-B-4-14	Same rostrum	D = 6,8–7.2	100	No	Colourless	2.33	0.64	9.59
U28-B-4-15	Same rostrum	D = 6.5–6.8	100	No	Colourless	2.42	0.71	9.33
U28-B-4-16	Same rostrum	D = 5.8–6.5	100	No	Colourless	2.51	0.71	9.33
U28-B-4-17	Same rostrum	D = 5.5–5.8	100	No	Colourless	2.47	0.74	9.22
U28-B-4-18	Same rostrum	D = 5.2–5.5	100	No	Colourless	2.36	0.74	9.22
U28-B-4-19	Same rostrum	D = 5.0–5.2	100	No	Colourless	2.47	0.69	9.40
U28-B-4-20	Same rostrum	D = 4.8–5.0	100	No	Colourless	2.41	0.74	9.22
U28-B-4-21	Same rostrum	D = 4.5–4.8	100	No	Colourless	2.51	0.75	9.18
U28-B-4-22	Same rostrum	D = 4.2–4.5	100	No	Colourless	2.38	0.83	8.89
U28-B-4-23	Same rostrum	D = 4.0–4.2	100	No	Colourless	2.47	0.75	9.18
U28-B-4-24	Same rostrum	D = .8–4.0	100	No	Colourless	2.61	0.86	8.78
U28-B-4-25	Same rostrum	D = 3.5–3.8	100	No	Colourless	2.61	0.79	9.04
U28-B-4-26	Same rostrum	D = 3.3–3.5	100	No	Colourless	2.67	0.82	8.93
U28-B-4-27	Same rostrum	D = 3.0–3.3	100	No	Colourless	2.61	0.83	8.89
U28-B-4-28	Same rostrum	D = 2.5–3.0	100	No	Colourless	2.72	0.88	8.71
U28-B-4-29	Same rostrum	D = 2.2–2.5	100	No	Colourless	2.48	0.93	8.53
U28-B-4-30	Same rostrum	D = 1.8–2.2	100	No	Colourless	2.42	0.91	8.60
U28-B-4-31	Same rostrum	D = 1.0–1.8	100	No	Colourless	2.39	1.05	8.10
U28-B-4-32	Same rostrum	D = 0–1.0	100	No	Colourless	2.13	0.81	8.97
U28-B-1-1	U28-B-1 (rostrum)	D = 13.5–14.0	100	No	Colourless	−2.05	-1.44	17.85
U28-B-3-1	U28-B-3 (rostrum)	D = 10.5–11.0	100	No	Colourless	1.11	1.41	6.84
2009-1-1	2009-1	D = 5.0	100	SiO_2 (trace)	Colourless	0.71	−1.57	18.41
2009-21	2009-2	D = 4.6	100	No	Colourless	0.98	−0.53	14.09
Bar-3-1	Bar-3 (rostrum)	D = 8.0-8.6	100	No	Grey	0.92	−0.11	15.90
Bar-3a-1	Bar-3a (rostrum)	D = 10.0-10.6	100	No	Grey	0.78	−0.19	12.74
Ord-3(11b)-1	Ord-3(11b) (brachiopod shell)	L = 14.0	100	No	Silvery white	-0.23	−3.84	28.80
Ord-3(5a)-1	Ord-3(5a)-(brachiopod shell)	L = 15.0	100	No	Silvery white	0.03	−3.88	29.30
3(6)-1	3(6) (bivalve shell)	H = 10.0	100	No	Silvery white	0.27	−3.81	28.74
3(7)-1	3(7)	H = 10.0	100	No	Silvery white	0.46	−3.30	26.26

and Kennet, 1975; Hudson and Anderson, 1989; Pirrie and Marshall, 1990; Price and Hart, 2002; Huber et al., 2002). However, the isotopic composition of Cretaceous seawater may have varied considerably due to evaporation and/or freshwater input.

X-ray powder analyses were carried out using a DRON-3 diffractometer at FEGI, following the method of Davis and Hooper (1963), and desktop X-ray diffractometer MiniFlex II (Rigaku Firm) for control; elemental concentrations were determined by dispersion energy X-ray spectrometer INCA Energy 350 (Oxford) at IMB.

SEM, X-ray and trace element geochemical (EDX spectra) study of upper Barremian belemnite rostra and X-ray and SEM study of lower Aptian molluscs from the Ulyanovsk area suggest that all of them, apparently, retain their original texture and oxygen and carbon isotopic composition. X-ray diffraction analysis particularly shows the lack of secondary admixtures, including α-SiO_2, in the investigated calcitic belemnite rostra from the Ulyanovsk area and the analysed almost 100% aragonitic portions of the most part of bivalve and ammonoid shells from this region. Nevertheless, diagenetic alterations cannot be entirely excluded (e.g., in inner whorls of the *Proaustraliceras tuberculatum* shell, as suggested by the X-ray tests).

4. Stable isotope results

4.1. Upper Barremian Germanica Zone

From upper Barremian belemnites, one well-preserved *Oxyteuthys* sp. rostrum (U28-B-1) was investigated in detail on the basis of 32 samples taken from its different ontogenetic stages. SEM photographs of the one of *Oxyteuthys* sp. belemnite rostra (U28-B-4) (Figs. 3 and S1) show well-preserved micostructure. EDX spectra show the lack of secondary admixtures, indicating diagenetic alteration for it (Fig. 4). $\delta^{18}O$ values in this rostrum fluctuate from 0.5 to 1.15‰, which corresponds to palaeotemperatures of 8.1–10.0 °C (Fig. 5; Table 1), if a δ_w– value of −1‰ (Shackleton and Kennet, 1975; Hudson and Anderson, 1989; Pirrie and Marshall, 1990; Huber et al., 2002; Price and Hart, 2002) is chosen for the calculation of the temperature. All values of $\delta^{13}C$ in these samples are positive (1.8–2.6‰).

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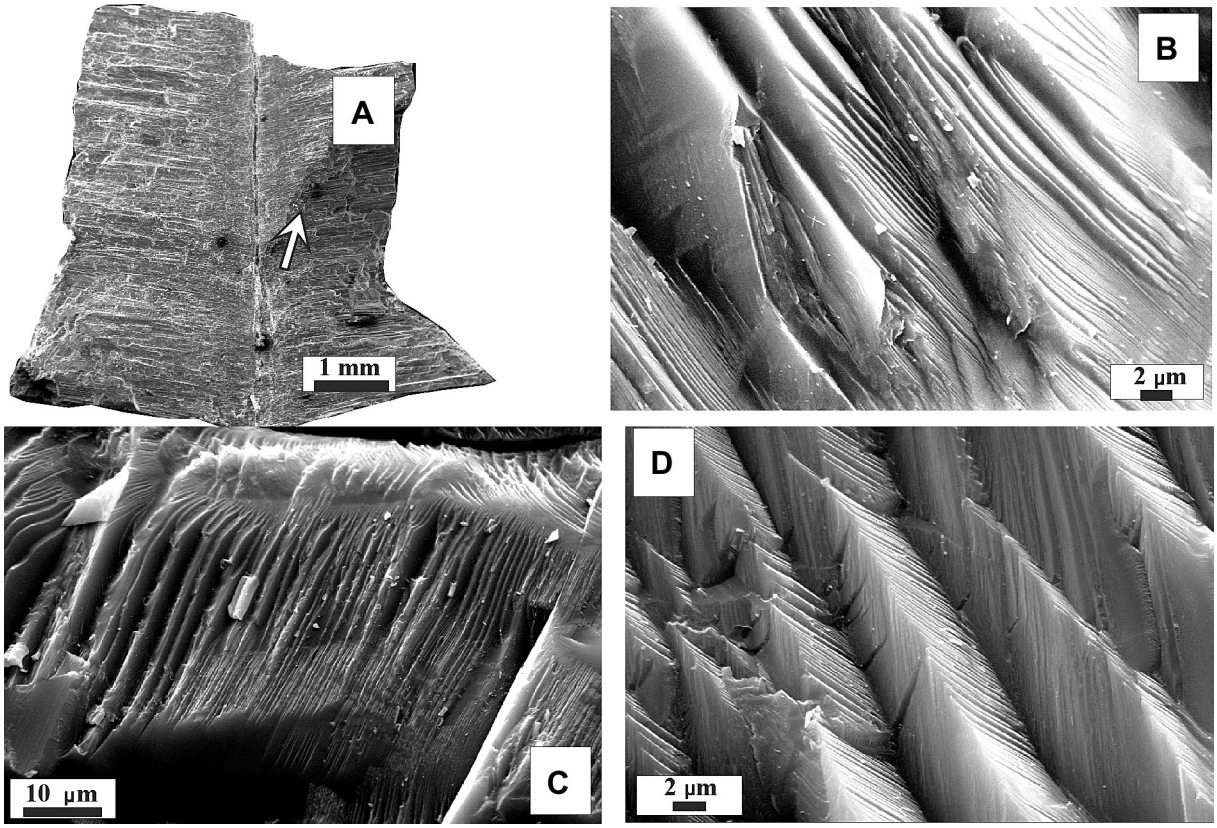

Fig. 3. SEM photomicrographs of the upper Barremian *Oxyteuthis* sp. rostrum-U28-B-4, longitudinal section (right side).

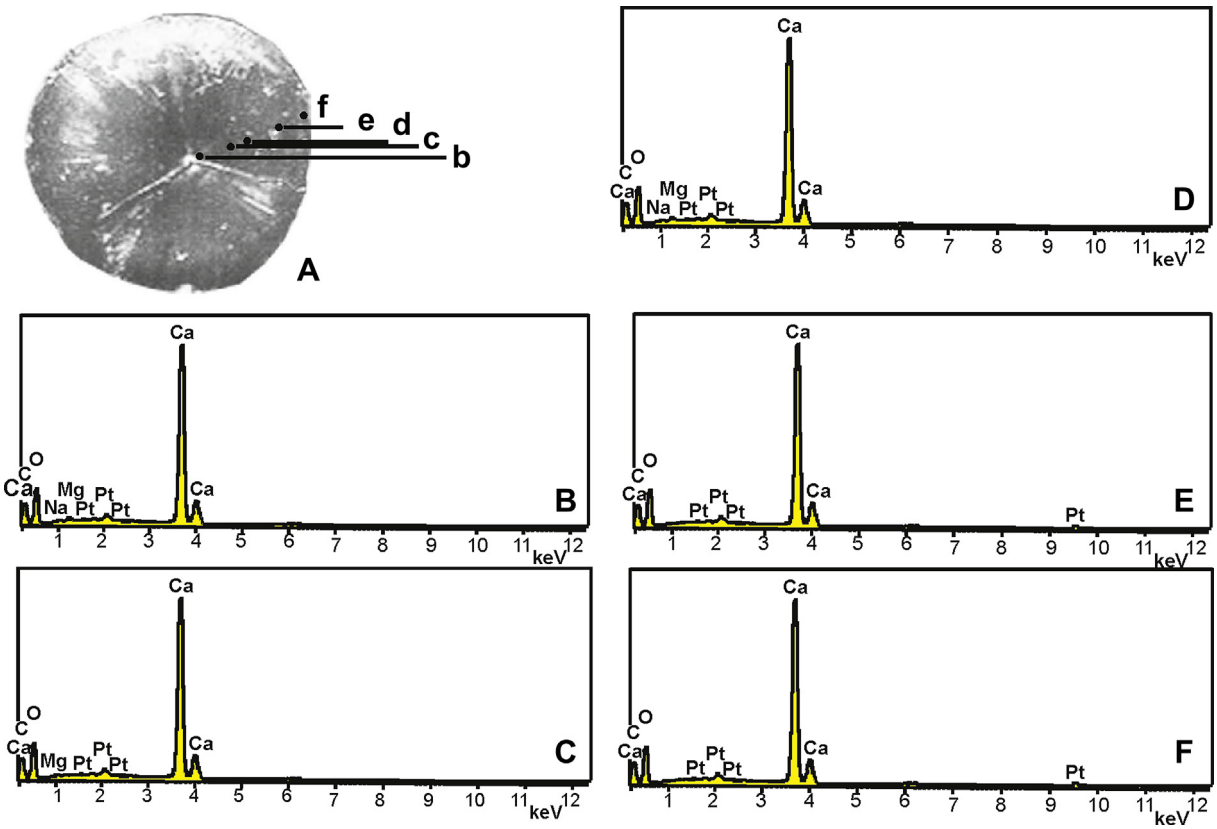

Fig. 4. Energy-dispersion X-ray microanalytical (EDX) spectra from the upper Barremian *Oxyteuthis* sp. Rostrum – U28-B-4a. Before metallic-element measurement the investigated surface was covered by Pt, therefore this element is also indicated.

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A heavier $\delta^{18}O$ value (1.4‰), corresponding to lower palaeotemperature (6.8 °C) (Fig. 5; Table 1) has been discovered in the rostrum *Oxyteuthys* sp.-U28-B-3. The $\delta^{13}C$ value in this sample is also positive (1.1‰).

A significantly lighter $\delta^{18}O$ value (−1.4‰) was recognised in the rostrum *Oxyteuthys* sp.-U28-B-1, corresponding to a palaeotemperature of 17.9 °C ($\delta^{13}C$=−2.1‰) (Fig. 5). Similar temperatures (15.8–18.3 °C) were calculated from oxygen-isotope composition of upper Barremian aragonitic (100%) bivalve *Cyprina* sp. shell ($\delta^{18}O$ values fluctuate from −0.65 to −0.1‰; $\delta^{13}C$ = 3.6–4.8‰) (Table 1).

4.2. Lower Aptian Volgensis–Schilovkensis Zone

Aragonitic shells of three ammonoid species were analysed (Fig. S2): planispiral ammonoids *Deshayesites volgensis* (80–100% aragonite), *Sinzovia trautscholdi* (100%), and small heteromorph ammonoid *Volgoceratoides schilovkensis* (83%), with absence of admixture. SEM photographs of *Deshayesites volgensis*-45/96 show well-preserved microstructures (Fig. 6). *Deshayesites volgensis*-50/96 (observation from 27 specimens) was investigated in detail (Fig. 7). $\delta^{18}O$ values in this ammonoid shell fluctuate from −3.6 to −2.6‰ (Table 2). In case of normal salinity these values correspond to palaeotemperature of 26.7–30.8 °C ($\delta^{13}C$ values fluctuate from −2.8 to −0.6‰). A similar palaeotemperature (30.4 °C) was calculated from a shell fragment of *Deshayesites volgensis* – U28-6a(2)-1 ($\delta^{18}O$ = −3.45‰; $\delta^{13}C$ = −2.29‰). This fragment was found in association with several *Sinzovia trautscholdi* shells, showing somewhat lower palaeotemperatures of 25.2–27.9 °C ($\delta^{18}O$ values fluctuate from −2.88 to −2.39‰, $\delta^{13}C$ values from −2.33 to +1.88‰) (Table 2). Somewhat lower palaeotemperatures (25.1–26.8 °C) were calculated also from the oxygen-isotope composition of *Deshayesites volgensis*-45/96 (Fig. S3). $\delta^{18}O$ values in this sample fluctuate from −2.59 to −2.24‰ ($\delta^{13}C$ values fluctuate from −3.8 to −1.97‰). All of these specimens were collected from the same zone.

The $\delta^{18}O$ value in the diagenetically altered *Volgoceratoides schilovkensis* shell-46/96 (84% aragonite; $\delta^{13}C$ = −7.86‰) is −2.69‰, which corresponds to an elevated palaeotemperature of 27.1 °C (in case of normal salinity) (Fig. S4).

4.3. Lower Aptian Deshayesi–Tuberculatum Zone

$\delta^{18}O$ values in the aragonitic heteromorph ammonoid *Proaustraliceras tuberculatum* shell-48/96, investigated in detail, are also significantly lighter than those obtained from upper Barremian fossils: values measured in 22 samples vary between −4.08 and −3.19‰. These samples are all characterised by an elevated aragonite content (72–98%). These numbers correspond to palaeotemperatures of 29.2–33.1 °C (in case of normal salinity) (Fig. 8; Table 2). $\delta^{13}C$ values in these samples are mainly positive, fluctuating from −2.54 to +4.12‰. However, some portions, taken from the early ontogenetic stages are diagenetically significantly altered (with 33% aragonite). The sample measured shows a higher $\delta^{18}O$ value (−1.5‰), but lower $\delta^{13}C$ value (−8.0‰). These values have not been used for palaeotemperature calculation.

4.4. Lower Aptian Deshayesi–Renauxianum Zone

Only one single aragonite-preserved (70–82%) heteromorph ammonoid *Acrioceras*? sp. shell-47/96, found in the Deshayesi–Renauxianum Zone, was investigated. Its $\delta^{18}O$ values are also low. They fluctuate from −3.5‰ to −2.67‰, corresponding to palaeotemperatures of 27.0–29.5 °C (Fig. S4; Table 2). Low $\delta^{13}C$ values, fluctuating from −9.42 to −3.67‰, suggest that these samples were affected by diagenesis and that, therefore, the paleotemperatures calculated may be too high..

4.5. Lower Aptian Bowerbanki Zone

Aragonitic (100%) bivalve shells *Neocomiceramus volgensiis* Glasunova-49/96 and 49a/96 and heteromorph ammonoid *Helicancylus*? cf. *philadelphius* shell-44/96 (100% aragonite), collected in the Bowerbanki Zone, were investigated (Fig. S5). Bivalves show palaeotemperatures of 30.4–30.8 °C (in case of normal salinity;

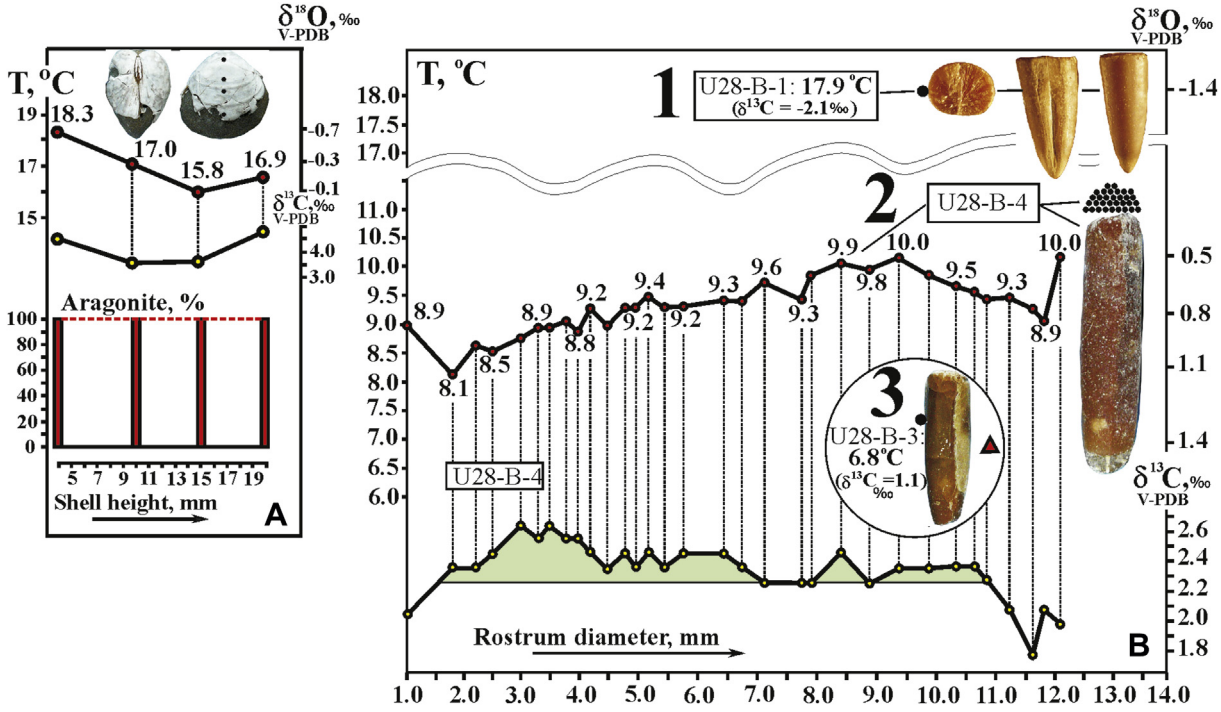

Fig. 5. Upper Barremian Germanica Zone: growth temperatures for aragonitic (A – bivalve *Cyprina* sp.) and calcitic (B – belemnite *Oxyteuthis* sp.) fossils.

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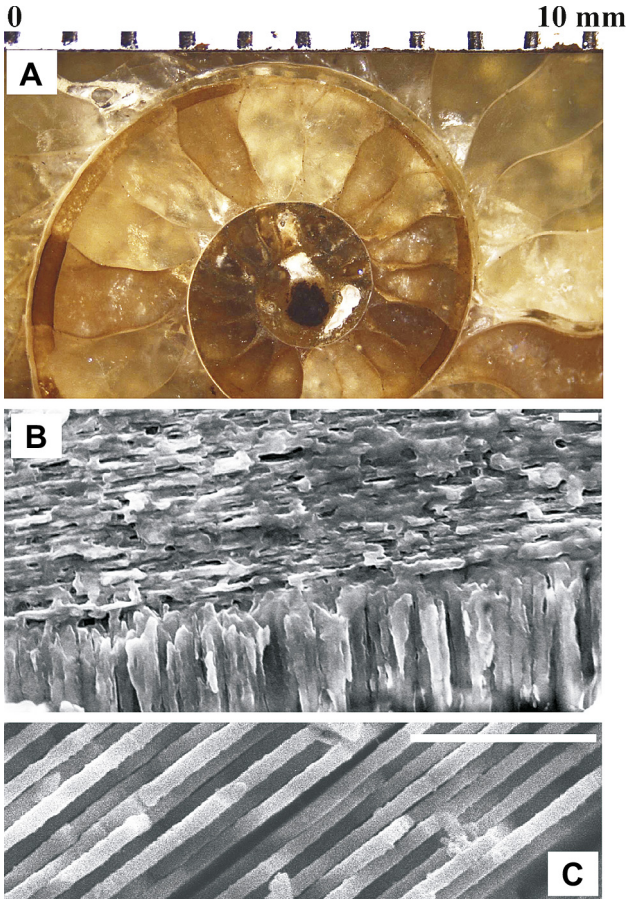

Fig. 6. Steriomicroscope (Discovery V12, Zeiss) and SEM photomicrographs of the lower Aptian *Deshayesites volgensis* shell-50/96, median section. Bar = 3 μm. A – view in median section; B – outer prismatic and nacreous layers in medial section (polished and etched surface); C – nacreous layer, found in medial break (no. 45/96, at H = 30 mm).

$\delta^{18}O$ values fluctuate from −3.56 to −3.45‰); $\delta^{13}C$ values are high: 5.47–5.98‰ (Fig. S6; Table 2). Somewhat higher palaeotemperatures (32.8–35.2 °C) were calculated from the heteromorph ammonoid shell. In this shell $\delta^{18}O$ values fluctuate between −4.56 to −4.02‰ and corresponding $\delta^{13}C$ values vary between 3.0–4.86‰ (Table 2).

5. Discussion

5.1. The fossil cephalopod habitat

The palaeodepth habitat of belemnite species is still debated (Naidin, 1969; Spaeth, 1971a, 1971b, 1973; Stevens and Clayton, 1971; Teiss and Naidin, 1973; Westermann, 1973; Tays et al., 1978; Bandel et al., 1984; Doyle and MacDonald, 1993; Anderson et al., 1994; Price and Selwood, 1997; Huber et al., 1995; Huber and Hodell, 1996; Monks et al., 1996; Price et al., 1996; Hewitt, 2000; Van de Schootbrugge et al., 2000; Pirrie et al., 2004; Wierzbowski, 2004; Zakharov et al., 2006, 2007, 2010; Dutton et al., 2007; Dauphin et al., 2007; Wierzbowski and Joachimski, 2007; Price and Page, 2008).

Data on the high $\delta^{18}O$ values in the uppermost Cretaceous belemnites from the Magellan Seamounts, showing relatively cool palaeotemperatures for the tropical area of the Pacific (9.0–17.1 °C) (Zakharov et al., 2007, 2010, 2012c), confirm that belemnites would have behaved in a way more like that of *Spirula*, which migrates vertically down to maximal depths of >950 m.

However, according to the calculations by many authors (e.g., Naidin, 1969; Westermann, 1973; Hewitt, 2000; Wierzbowski, 2004), the depth limit of inhabitation of some Jurassic and Cretaceous belemnites was about 100–200 m mainly because they were found in shallow-water sediments. According to the data of Baraboshkin et al. (2007), the Cretaceous marine basin in the Ulyanovsk area was not deeper than 50–100 m. At the same time, analyses of the oxygen isotopic composition of Campanian–Maastrichtian belemnite rostra from the shallow-water basin of the Russian Platform demonstrate that $\delta^{18}O$ values in their adult stage are frequently lower than those in their juvenile stage (Teiss and Naidin, 1973), which corresponds to higher temperatures. Such regularity was also pointed out by us (Zakharov et al., 2006) in well-preserved middle and upper Albian belemnite rostra from the shallow-water basin *Pas de Calais* in north France: temperatures calculated from some adult and juvenile stages are 15.2–20.7 °C and 12.4–14.4 °C, respectively, but a co-occurring aragonite-preserved *Oxytropidoceras* ammonoid shell shows palaeotemperature of 21.9 °C.

High $\delta^{18}O$ values in the belemnite rostra of late Barremian marine basin in the Ulyanovsk area, having the only connection with the Boreal sea (Fig. S7), suggest that they calcified under cool conditions. Temperatures calculated from investigated *Oxyteuthis* rostra of the shallow-water marine sediments of this area are 6.8–10.0 °C (observation from 33 specimens), but a single rostrum from the same locality records a higher temperature in its adult stage (17.9 °C). This value is close to the ones calculated from co-occurring aragonite-preserved bivalve *Cyprina* shells (15.8–18.3 °C) (Figs. 9 and 10).

Taking into account that some portions of Cretaceous belemnite rostra found in shallow-water sediments are characterised by $\delta^{18}O$ values significantly higher than those calculated from other co-occurring benthic fossils, we hypothesise that these belemnites, including the ones sampled from the upper Barremian at Ulyanovsk, were mainly inhabitants of cooler, deeper waters: Similar to *Sepia* and *Nautilus* in modern oceans (e.g., Rexfort and Mutterlose, 2006; Zakharov et al., 2006) they prefer apparently warmer, shallow-water conditions, when they spawn, migrating from adjacent deeper marine basins. In addition, the lower palaeotemperatures, calculated from some upper Barremian belemnites of the Ulyanovsk area, likely illustrate a strong Boreal (lower temperature) impact on the water mass of the basin. This is not in disagreement with the interpretation of Baraboshkin et al. (2007). They proposed that the poor upper Barremian faunal assemblage with no ammonoids, indicates brackish-marine conditions in the late Barremian basin in the Ulyanovsk area. However, if this is correct, the oxygen-isotope value of seawater was lower than −1‰ and late Barremian temperatures in that area were actually lower than those, calculated from the oxygen-isotope composition of upper Barremian molluscs.

According to published data on Cretaceous molluscs from Far East and North America both aragonite-preserved planispiral and heteromorph ammonoid shells show optimal temperatures of their growth mainly comparable to those of their co-occurring benthos on the shelf (Smyshlyaeva et al., 2002; Moriya et al., 2003; Zakharov et al., 2003, 2004; Landman et al., 2012). Temperatures, however, were significantly lower than those calculated from contemporaneous planktic foraminifera (Moriya et al., 2003). New data on planispiral and heteromorph ammonoids and bivalve molluscs from the lower Aptian of the Ulyanovsk area are in agreement with these observations.

Both lower Aptian ammonoid and bivalve shells of the Ulyanovsk area are characterised by low $\delta^{18}O$ values, which seem to be unaltered according to our diagenetic control data. Fossil cephalopod-bearing facies are usually considered to record normal

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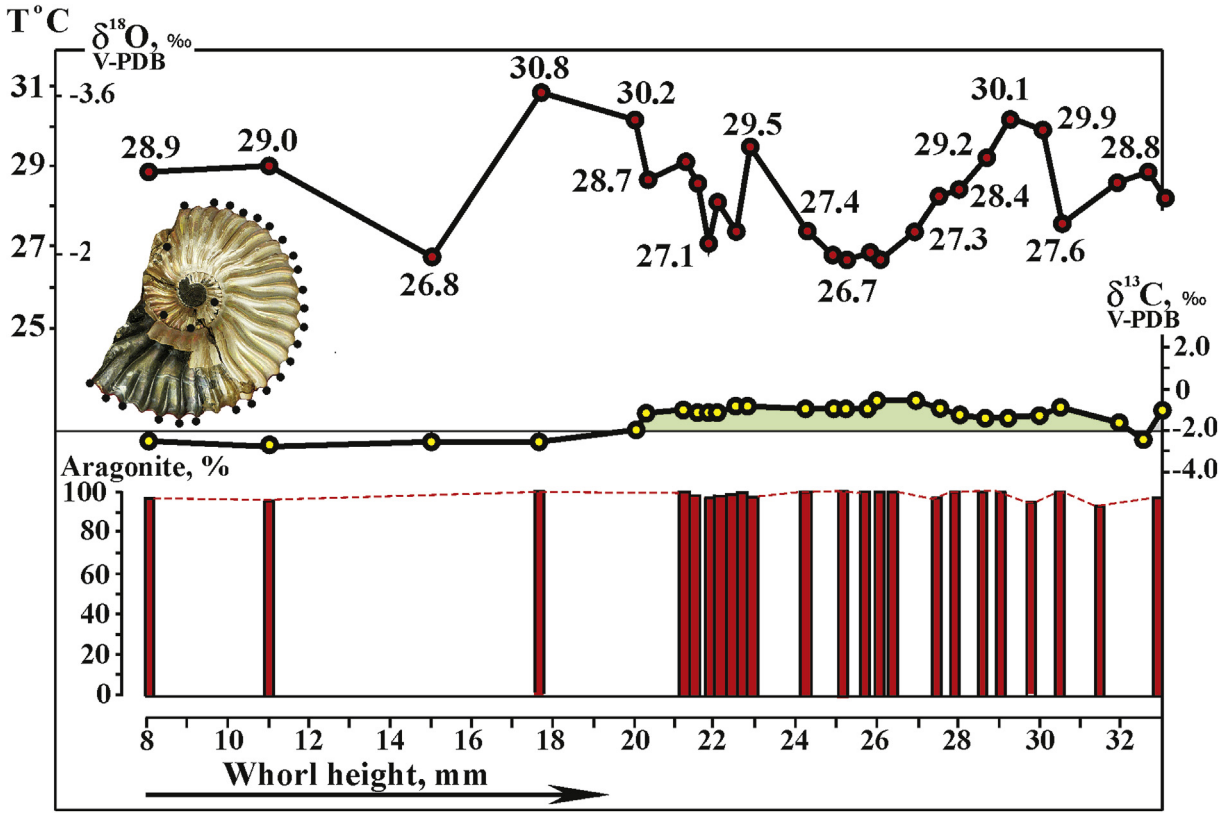

Fig. 7. Lower Aptian Volgensis–Schilovkensis Zone: growth temperatures for the aragonitic planispiral ammonoid *Deshayesites volgensis*-50/96.

salinity, therefore, according to our version, lower Aptian ammonoids of the Ulyanovsk area with low $\delta^{18}O$ values in their shells (fluctuated from −4.6 to −2.2‰) inhabited waters with normal salinity, but with higher (of 25.2–35.5 °C) temperatures (Figs. 9 and 10).

Alternatively, the low $\delta^{18}O$ values in the above described ammonoid shells may be caused by the fresh-water influence in the shallow-water Ulyanovsk marine basin during Early Aptian times. In certain cases, for instance, anomalously low $\delta^{18}O$ signatures (up to −4.9‰) were found in aragonitic ammonoid shells from both the Maastrichtian Fox Hills Formation of the Western Interior Sea Way (WIS) area (Tsujita and Westermann, 1998; Cochran et al., 2003; Zakharov et al., 2007; Zakharov et al., in press) and the lower Campanian Chico Formation of California (Zakharov et al., 2007), caused by their secretion in brackish shallow waters of the upper epipelagic zone. However, most cephalopod fossils from these formations are characterised by higher $\delta^{18}O$ values, reflecting mainly normal salinity conditions during their deposition. This is confirmed by Sr-isotope data from the Fox Hills Formation: $^{87}Sr/^{86}Sr$ values of up to 0.707795 in many *Hoploscaphites* from the WIS represent normal salinity as well as $^{87}Sr/^{86}Sr$ values of up to 0.707781 in many *Discoscaphites* and some *Sphenodiscus.* $^{87}Sr/^{86}Sr$ values of only 0.707699 were measured in rare *Hoploscaphites* and some *Sphenodiscus* occurring in possible brackish facies of the WIS (Cochran et al., 2003; Zakharov et al., in press).

For explanation of low $\delta^{18}O$ signatures in well-preserved (aragonitic) ammonoid shells from the lower Aptian of the Ulyanovsk area only two scenarios seem plausible. One relates the low values to warming, and another one to fresh-water runoff. The second one seems unrealistic because there is no convincing evidence for long-lasting brackish conditions in the early Aptian Ulyanovsk marine basin (during Volgensis–Schilovkensis, Deshayesi–Tuberculatum, Deshayesi–Renauxianum, and Bowerbanki times). On the other hand, there are some indirect evidences: on possible development of monsoon climate during Volgensis–Schilovkensis time (because high *Tasmanites* content in palynofacies has been discovered in Member IV, containing black shales) (Baraboshkin, 2005; Baraboshkin et al., 2002, 2007). However, the abrupt replacement of a Boreal (upper Barremian) belemnite-dominated assemblage by Tethyan (lower Aptian) ammonoid-dominant assemblages on the Russian Platform, indicates that penetration of Tethyan water mass into the basin of the Russian Platform took place during the early Aptian (Baraboshkin, 2005; Baraboshkin et al., 2007) (Fig. S8), This interpretation seems to be in agreement with the first scenario, related to warming. Mollusc incursions and oxygen-isotope data suggest, therefore, that temperatures were repeatedly elevated in the Ulyanovsk marine basin due to incursion of Tethyan water.

5.2. Oceanic Anoxic Event 1a and the negative carbon anomaly of the Shilovkensis Zone

During periods of greenhouse conditions with exceptionally warm climate, sedimentation in the world oceans was characterised by episodic deposition of organic carbon-rich sediments (e.g., bituminous shales), so-called black shales, deposited during short-term OAEs (e.g., Schlanger and Jenkyns, 1976; Jenkyns, 1995; Bersezio et al., 2002; Gavrilov et al., 2002; Savelyeva, 2010). They were formed as a result of oceanographic changes, mainly associated with the breakup of the supercontinent Pangea and episodic pertrubations of global carbon cycle (Weissert and Erba, 2004). The increase in greenhouse gases, closely linked to the global oceanic anoxic events, was trigged, apparently, by extensive volcanic activity (e.g., Veevers, 1989; Tarduno et al., 1991; DeBond et al., 2012;

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Table 2
Carbon and oxygen isotope analyses of bivalve and ammonoid shells from the upper Barremian and lower Aptian of the Ulyanovsk Area, Russian Platform (H – height of the bivalve shell and whorl height in the ammonoid shell).

Sample	Shell	Species (locality; zone)	Location (H in mm)	Diagenetic alterations				$\delta^{13}C$ (VPDB), ‰	$\delta^{18}O$ (VPDB), ‰	T, °C
				Diagenetic stage	Aragonite %	Admixture (e.g., α-SiO_2) %	Colour			
U28-B-2-1	U28-B-2	Cyprina *sp. (Novoulyanovsk; Germanica Zone)*	H = 20.0	1st	100	No	Cream	4.79	−0.24	16.43
U28-B-2-2	Same shell	Cyprina *sp. (Novoulyanovsk; Germanica Zone)*	H = 10.0	1st	100	No	Cream	3.61	−0.34	16.90
U28-B-2-3	Same shell	*Cyprina* sp. (Novoulyanovsk; Germanica Zone)	H = 4.0	1st	100	No	Cream	4.64	−0.68	18.34
U28-B-2-4	Same shell	*Cyprina* sp. (Novoulyanovsk; Germanica Zone)	H = 15.0	1st	100	No	Cream	2.11	0.84	15.78
U28-10A(2)	U28-10A	*Neocomiceramus* cf, *borealis* (Shilovka, Volgensis–Schilovkensis Zone)	H = 4.0	1st	100	No	Silvery-grey	−3.00	−4.28	34.00
49-1	49/96(1)	*Neocomiceramus volgensis* (Novyj Most, Bowerbanki Zone)	H = 9.8	1st	100	No	White	5.68	−3.56	30.80
49-3	Same shell	*Neocomiceramus volgensis* (Novyj Most, Bowerbanki Zone)	H = 20.0	1st	100	No	White	5.97	−3.45	30.40
49-4	Same shell	*Neocomiceramus volgensis* (Novyj Most, Bowerbanki Zone)	H = 23.0	1st	100	$MnCO_3$ (trace)	White	5.88	−3.51	30.60
49-5	Same shell	*Neocomiceramus volgensis* (Novyj Most, Bowerbanki Zone)	H = 30	1st	100	No	White	5.93	−3.50	30.60
49-6	Same shell	*Neocomiceramus volgensis* (Novyj Most, Bowerbanki Zone)	H = 39	–	–	–	White	5.47	−3.46	30.40
49-7	Same shell	*Neocomiceramus volgensis* (Novyj Most, Bowerbanki Zone)	H = 44	–	–	$MnCO_3$ and gypsum (traces)	White	5.54	−3.45	30.40
49-9	49a/96	*Neocomiceramus volgensis* (Novyj Most, Bowerbanki Zone)	H = 52.8	1st	100	Gypsum (trace)	White	5.82	−3.53	30.70
50-1	50/96	*Deshaesites volgensis* (Kriushi; Volgensis–Schilovkensis Zone)	H = 18.9	–	–	Gypsum (trace)	Silvery-white	−2.34	−2.24	25.10
50-3	Same shell	*Deshaesites volgensis* (Kriushi; Volgensis–Schilovkensis Zone)	H = 18.2	1st	95±5	Gypsum (trace	Silvery-white	−2.80	−2.41	25.90
50-7	Same shell	*Deshaesites volgensis* (Kriushi; Volgensis–Schilovkensis Zone)	H = 15.2	1st	100	No	Silvery-white	−2.26	−2.59	26.60
50-9	Same shell	*Deshaesites volgensis* (Kriushi; Volgensis–Schilovkensis Zone)	H = 4.2	1st	97±3	No	Silvery-white	−3.80	−2.24	25.10
50-11	Same shell	*Deshaesites volgensis* (Kriushi; Volgensis–Schilovkensis Zone)	H = 13.8	–	–	–	Silvery-white	−0.95	−2.95	28.20
50-12	Same shell	*Deshaesites volgensis* (Kriushi; Volgensis–Schilovkensis Zone)	H = 13.2	–	–	–	Silvery-white	−1.97	−2.34	25.50
50-17	Same shell	*Deshaesites volgensis* (Kriushi; Volgensis–Schilovkensis Zone)	H = 11.5	1st	100	No	Silvery-white	−2.48	−2.52	26.30
50-21	Same shell	*Deshaesites volgensis* (Kriushi; Volgensis–Schilovkensis Zone)	H = 10.5	1st	97±3	No	Silvery-white	−1.39	−2.62	26.80
281-1	45/96	*Deshaesites volgensis* (Kriushi; Volgensis–Schilovkensis Zone)	H = 32.9	1st	97±3	No	Silvery-white	−1.05	−2.96	28.20
281-2	Same shell	*Deshaesites volgensis* (Kriushi; Volgensis–Schilovkensis Zone)	H = 32.6	2nd	84±3	No	Silvery-white	−2.50	−3.09	28.80
281-3	Same shell	*Deshaesites volgensis* (Kriushi; Volgensis–Schilovkensis Zone)	H = 31.9	2nd	93±3	No	Silvery-white	−1.73	−3.04	28.59
281-5	Same shell	*Deshaesites volgensis* (Kriushi; Volgensis–Schilovkensis Zone)	H = 30.5	1st	100	No	Silvery-white	−1.01	−2.82	27.63
281-6	Same shell	*Deshaesites volgensis* (Kriushi; Volgensis–Schilovkensis Zone)	H = 30.0	1st	95±5	No	Silvery-white	−1.40	−3.35	29.93
281-7	Same shell	*Deshaesites volgensis* (Kriushi; Volgensis–Schilovkensis Zone)	H = 29.2	–	–	–	Silvery-white	−1.47	−3.39	30.10
281.9	Same shell	*Deshaesites volgensis* (Kriushi; Volgensis–Schilovkensis Zone)	H = 28.6	1st	100	No	Silvery-white	−1.43	−3.18	29.19
281-10	Same shell	*Deshaesites volgensis* (Kriushi; Volgensis–Schilovkensis Zone)	H = 28.0	1st	100	No	Silvery-white	−1.33	−3.00	28.41
281-13	Same shell	*Deshaesites volgensis* (Kriushi; Volgensis–Schilovkensis Zone)	H = 26.9	1st	100	No	Silvery-white	−0.65	−2.75	27.30
281-15	Same shell	*Deshaesites volgensis* (Kriushi; Volgensis–Schilovkensis Zone)	H = 26.0	–	–	–	Silvery-white	−0.61	−2.61	25.72
281-16	Same shell	*Deshaesites volgensis* (Kriushi; Volgensis–Schilovkensis Zone)	H = 25.8	1st	100	No	Silvery-white	−1.01	−2.63	26.80
281-17	Same shell	*Deshaesites volgensis* (Kriushi; Volgensis–Schilovkensis Zone)	H = 25.2	1st	100	No	Silvery-white	−1.02	−2.60	26.68
281-18	Same shell	*Deshaesites volgensis* (Kriushi; Volgensis–Schilovkensis Zone)	H = 24.9	–	–	–	Silvery-white	−1.02	−2.63	26.81
281-19	Same shell	*Deshaesites volgensis* (Kriushi; Volgensis–Schilovkensis Zone)	H = 24.2	1st	100	No	Silvery-white	−1.05	−2.76	27.37
281-20	Same shell	*Deshaesites volgensis* (Kriushi; Volgensis–Schilovkensis Zone)	H = 22.8	1st	100	No	Silvery-white	−1.15	−3.24	29.45
281-21	Same shell	*Deshaesites volgensis* (Kriushi; Volgensis–Schilovkensis Zone)	H = 22.5	1st	100	No	Silvery-white	−0.93	−2.76	27.37
281-22	Same shell	*Deshaesites volgensis* (Kriushi; Volgensis–Schilovkensis Zone)	H = 22.0	1st	97±3	No	Silvery-white	−1.21	−2.96	28.24
281-23	Same shell	*Deshaesites volgensis* (Kriushi; Volgensis–Schilovkensis Zone)	H = 21.8	–	–	–	Silvery-white	−1.13	−2.70	27.11
281-24	Same shell	*Deshaesites volgensis* (Kriushi; Volgensis–Schilovkensis Zone)	H = 21.5	1st	97±3	No	Silvery-white	−1.22	−3.02	28.50
281-25	Same shell	*Deshaesites volgensis* (Kriushi; Volgensis–Schilovkensis Zone)	H = 21.2	1st	100	No	Silvery-white	−1.12	−3.16	29.11
281-26	Same shell	*Deshaesites volgensis* (Kriushi; Volgensis–Schilovkensis Zone)	H = 20.3	–	–	–	Silvery-white	−1.32	−3.07	28.72
281-27	Same shell	*Deshaesites volgensis* (Kriushi; Volgensis–Schilovkensis Zone)	H = 20.0	–	–	–	Silvery-white	−1.97	−3.41	30.19
281-28	Same shell	*Deshaesites volgensis* (Kriushi; Volgensis–Schilovkensis Zone)	H = 17.6	1st	100	No	Silvery-white	−2.69	−3.56	30.84
281-29	Same shell	*Deshaesites volgensis* (Kriushi; Volgensis–Schilovkensis Zone)	H = 15.0	–	–	–	Silvery-white	−2.61	−2.63	26.81
281-30	Same shell	*Deshaesites volgensis* (Kriushi; Volgensis–Schilovkensis Zone)	H = 11.0	1st	95±3	No	Silvery-white	−2.76	−3.14	29.02

(*continued on next page*)

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Table 2 (*continued*)

Sample	Shell	Species (locality; zone)	Location (H in mm)	Diagenetic alterations				$\delta^{13}C$ (VPDB), ‰	$\delta^{18}O$ (VPDB), ‰	T, °C
				Diagenetic stage	Aragonite %	Admixture (e.g., α-SiO_2) %	Colour			
281-31	Same shell	*Deshaesites volgensis* (Kriushi; Volgensis–Schilovkensis Zone)	H = 8.0	1st	97±3	No	Silvery-white	−2.53	−3.10	28.85
U28-6A(2)-1-1	U28-6A(2)-1	*Deshaesites volgensis* (Shilovka, Volgensis–Schilovkensis Zone)	H = 23.2	–	87±3	No	Cream	−2.29	−3.45	30.40
U28-6A(1)-1	U28-6A(1)	*Sinzovia sazonovae* (Shilovka, Volgensis–Schilovkensis Zone)	H = 16.0	2nd	78±3	No	Cream	1.88	−2.80	27.50
U28-9(A)(2)-1	U28-9A(2)	*Deshaesites volgensis* (Shilovka, Volgensis–Schilovkensis Zone)	H = 13.6	2nd	76±3	α-SiO_2 (trace)	Cream			
U28-9A(1)-1	U28-9A(1)	*Sinzovia sazonovae* (Shilovka, Volgensis–Schilovkensis Zone)	H = 27.0	–	–	–	Cream	−3.45	−2.88	27.90
U28-10A(2)	U28-10A(2)-1	*Neocomiceras* cf. *boreale* (Shilovka, Volgensis–Schilovkensis Zone)	H = 4.0	–	–	–	Cream	−3.00	−4.28	34.00
40-1	48/96	*Proaustraliceras tuberculatum* (Solovyev Ravine, Tuberculatum)	H = 59.5	1st	97±3	No	Cream	4.12	−3.8	31.88
40-3	*Same shell*	Proaustraliceras tuberculatum *(Solovyev Ravine, Ravine,Deshayesi–Tuberculatum Zone)*	H = 55.4	2nd	93±3	No	Cream	3.23	−3.75	31.67
40-4	*Same shell*	Proaustraliceras tuberculatum *(Solovyev Ravine, Deshayesi–Tuberculatum Zone)*	H = 54.0	1st	95±3	No	Cream	1.68	−3.73	31.60
40-6	*Same shell*	Proaustraliceras tuberculatum *(Solovyev Ravine, Deshayesi–Tuberculatum Zone)*	H = 53.0	2nd	84±3	No	Cream	0.14	−3.52	30.7
40-8	*Same shell*	Proaustraliceras tuberculatum *(Solovyev Ravine, Deshayesi–Tuberculatum Zone)*	H = 52.0	2nd	89±3	No	Cream	1.40	−3.73	31.60
40-10	*Same shell*	Proaustraliceras tuberculatum *(Solovyev Ravine, Deshayesi–Tuberculatum* Zone)	H = 50.8	–	–	–	Cream	−2.54	−3.19	29.24
40-12	Same shell	Proaustraliceras tuberculatum (Solovyev Ravine, Deshayesi-Tuberculatum Zone)	H = 49.5	2nd	82±3	No	Cream	1.01	−3.38	30.06
40-13	*Same shell*	Proaustraliceras tuberculatum *(Solovyev Ravine, Deshayesi–Tuberculatum Zone)*	H = 48.5	–	–	No	Cream	−0.95	−3.28	29.63
40-14	*Same shell*	Proaustraliceras tuberculatum *(Solovyev Ravine, Deshayesi–Tuberculatum Zone)*	H = 48.0	2nd	77±3	No	Cream	0	−3.51	30.63
40-16	*Same shell.*	Proaustraliceras tuberculatum *(Solovyev Ravine, Deshayesi–Tuberculatum Zone)*	H = 46.0	–	–	No	Cream	0.65	−3.51	30.63
40-18	Same shell	*Proaustraliceras tuberculatum* (Solovyev Ravine; Deshayesi–Tuberculatum Zone)	H = 45.0	–	–	No	Cream	3.35	−3.91	32.36
40-23	Same shell	*Proaustraliceras tuberculatum* (Solovyev Ravine, *Deshayesi*–Tuberculatum Zone)	H = 41.0	2nd	93±3	No	Cream	3.99	−3.77	31.75
40-25	Same shell	Proaustraliceras tuberculatum *(Solovyev Ravine, Deshayesi–Tuberculatum Zone)*	H = 40.2	2nd	77±3	No	Cream	−0.04	−3.39	30.10
40-28	Same shell	Proaustraliceras tuberculatum *(Solovyev Ravine, Deshayesi–Tuberculatum Zone)*	H = 38.2	2nd	93±3	No	Cream	3.01	−3.39	30.10
40-30	Same shell	Proaustraliceras tuberculatum *(Solovyev Ravine, Deshayesi–Tuberculatum Zone)*	H = 37.4	2nd	83±3	No	Cream	1.84	−3.65	31.23
40-32	Same shell	Proaustraliceras tuberculatum *(Solovyev Ravine, Deshayesi–Tuberculatum* Zone)	H = 36.6	2nd	76±3	No	Cream	−0.85	−3.44	30.32
40-40	Same shell	Proaustraliceras tuberculatum *(Solovyev Ravine, Deshayesi–Tuberculatum* Zone)	H = 33.4	2nd	81±3	No	Cream	−0.29	−3.60	31.0
40-49	Same shell	Proaustraliceras tuberculatum *(Solovyev Ravine, Tuberculatum* Zone*)*	H = 30.6	2nd	81±3	No	Cream	1.59	−4.08	33.10
40-51	Same shell	Proaustraliceras tuberculatum *(Solovyev Ravine, Deshayesi–Tuberculatum* Zone)	H = 29.2	–	–	–	Cream	−0.06	−3.94	32.5
40-55	Same shell	Proaustraliceras tuberculatum *(Solovyev Ravine, Deshayesi–Tuberculatum* Zone*)*	H = 27.6	–	–	–	Cream	−0.56	−3.87	32.2
40-57	Same shell	Proaustraliceras tuberculatum *(Solovyev Ravine, Deshayesi–Tuberculatum* Zone)	H = 26.8	4th	34±5	No	Cream	−7.9	−2.79	27.5
40-61	Same shell	Proaustraliceras tuberculatum *(Solovyev Ravine, Deshayesi–Tuberculatum* Zone)	H = 24.6	2nd	70±5	No	Cream	0.36	−3.91	32.40
40-63	Same shell	Proaustraliceras tuberculatum *(Solovyev Ravine, Deshayesi–Tuberculatum* Zone)	H = 22.6	2nd	91±3	No	Cream	0.28	−3.69	31.40
40-67	Same shell	Proaustraliceras tuberculatum *(Solovyev Ravine, Deshayesi–Tuberculatum* Zone)	H = 20.0	2nd	72±3	No	Cream	−0.80	−3.62	31.10

47-1	*47/96*	Arioceras*? sp. (Ulyanovsk, Deshayesi–Renauxianum Zone)*	H = 15.5	3rd	59±3	No	Cream	−3.67	−3.03	28.50
47-7	*47/96*	Arioceras*? sp. (Ulyanovsk, Deshayesi–Renauxianum Zone)*	H = 14.5	3rd	59±3	No	Cream	−4.39	−3.25	29.50
47-11	*47/96*	Arioceras*? sp. (Ulyanovsk, Deshayesi–Renauxianum Zone)*	H = 12.9	3rd	52±3	No	Cream	−9.42	−2.71	27.20
47-13	*47/96*	Arioceras*? sp. (Ulyanovsk, Deshayesi–Renauxianum Zone)*	H = 11.5	–	–	–	Cream	−7.69	−2.88	27.90
47-19	*47/96*	Arioceras*? sp. (Ulyanovsk, Deshayesi–Renauxianum Zone)*	H = 5.0	–	–	–	Cream	−8.81	−2.67	27.0
46-1	*45*	Volgoceratoides schilovkensis (Shilovka, Volgensis–Shilovkensis Zone)	H = 7.2	2nd	83±3		Cream	−7.86	−2.69	27.10
44-1	44	*Helicancylus*? cf. *philadelius* (New Bridge, Bowerbanki Zone)	H = 19.0			No	Silvery-brown	3.00	−4.02	32.8
44-2	Same shell	*Helicancylus*? cf. *philadelius* (New Bridge, Bowerbanki Zone)	H = 17.5			No	Silvery-brown	3.69	−4.25	33.80
44-3	Same shell	*Helicancylus*? cf. *philadelius* (New Bridge, Bowerbanki Zone)	H = 17.0			No	Silvery-brown	4.14	−4.11	33.20
44-5	Same shell	*Helicancylus*? cf. *philadelius* (New Bridge, Bowerbanki Zone)	H = 13.0	1st	100	No	Silvery-brown	3.67	−4.41	34.50
44-7	Same shell	*Helicancylus*? cf. *philadelius* (New Bridge, Bowerbanki Zone)	H = 9.0	1st	100	α-SiO_2 (trace)	Silvery-brown	4.86	−4.17	33–50
44-9	Same shell	*Helicancylus*? cf. *philadelius* (New Bridge, Bowerbanki Zone)	H = 6.2	–	–	–	Silvery-brown	3.05	−4.23	33.80
44-10	Same shell	*Helicancylus*? cf. *philadelius* (New Bridge, Bowerbanki Zone)	H = 4.0	–	–	–	Silvery-brown	4.68	−4.56	35.20
49-1	49/96	*Neocomiceramus volgensis*	H = 9.8	1st	100	$MnCO_3$ ((trace)	White	5.68	−3.56	30.84
49-3	Same shell	*Neocomiceramus volgensis*(New Bridge, Bowerbanki Zone)	H = 20.0	1st	100	No	White	5.97	−3.45	30.37
49-4	Same shell	*Neocomiceramus volgensis*(New Bridge, Bowerbanki Zone)	H = 23.0	1st	100	$MnCO_3$ ((trace	White	5.88	−3.51	30.63
49-.5	Same shell	*Neocomiceramus volgensis* (New Bridge, Bowerbanki Zone)	H = 30.0	1st	100	$MnCO_3$ (trace)	White	5.93	−3.50	30.60
49-6	Same shell	*Neocomiceramus volgensis* (New Bridge, Bowerbanki Zone)	H = 39.0	1st	100	$MnCO_3$ ((trace	White	5.47	−3.46	30.41
49-7	Same shell	*Neocomiceramus volgensis* (New Bridge, Bowerbanki Zone)	H = 44.0	1st	100	$MnCO_3$ and gypsum (traces)	White	5.54	−3.45	30.37
49-9	Same shell	*Neocomiceramus volgensis* (New Bridge, Bowerbanki Zone)	H = 52.0	1st	100	No	White	5.82	−3.53	30.71
Y95-9/1	Y95-9	*Paradeshayesites* sp. (Ulyanovsk section, Deshayesi–Tuberculatum Zone)	Large shell	–	–	–	Cream	1.95	–	–
Y95-9/15	Y95-9/15	*Deshayesites* sp. (Ulyanovsk section, Deshayesi–Tuberculatum Zone)	Large shell	–	–	–	Cream	2.77	–	–
Y95-9/15-1	Same shell	*Deshayesites* sp. (Ulyanovsk section, Deshayesi–Tuberculatum Zone)	Large shell	–	–	–	Cream	3.02	–	–
Y95-9/16	Y95-9/16	*Audouliceras*? sp. (Ulyanovsk section, Tuberculatum Zone)	–	–	–	–	Cream	5.44	–	–
Y95-9/16-1	Same shell?	*Audouliceras*? sp. (Ulyanovsk section, Tuberculatum Zone)	–	–	–	–	Cream	6.44	–	
Y95-9/32	Y95-9/32	*Aconeceras*? sp. (Ulyanovsk section, Tuberculatum Zone)	–	–	–	–	Cream	3.42	–	–

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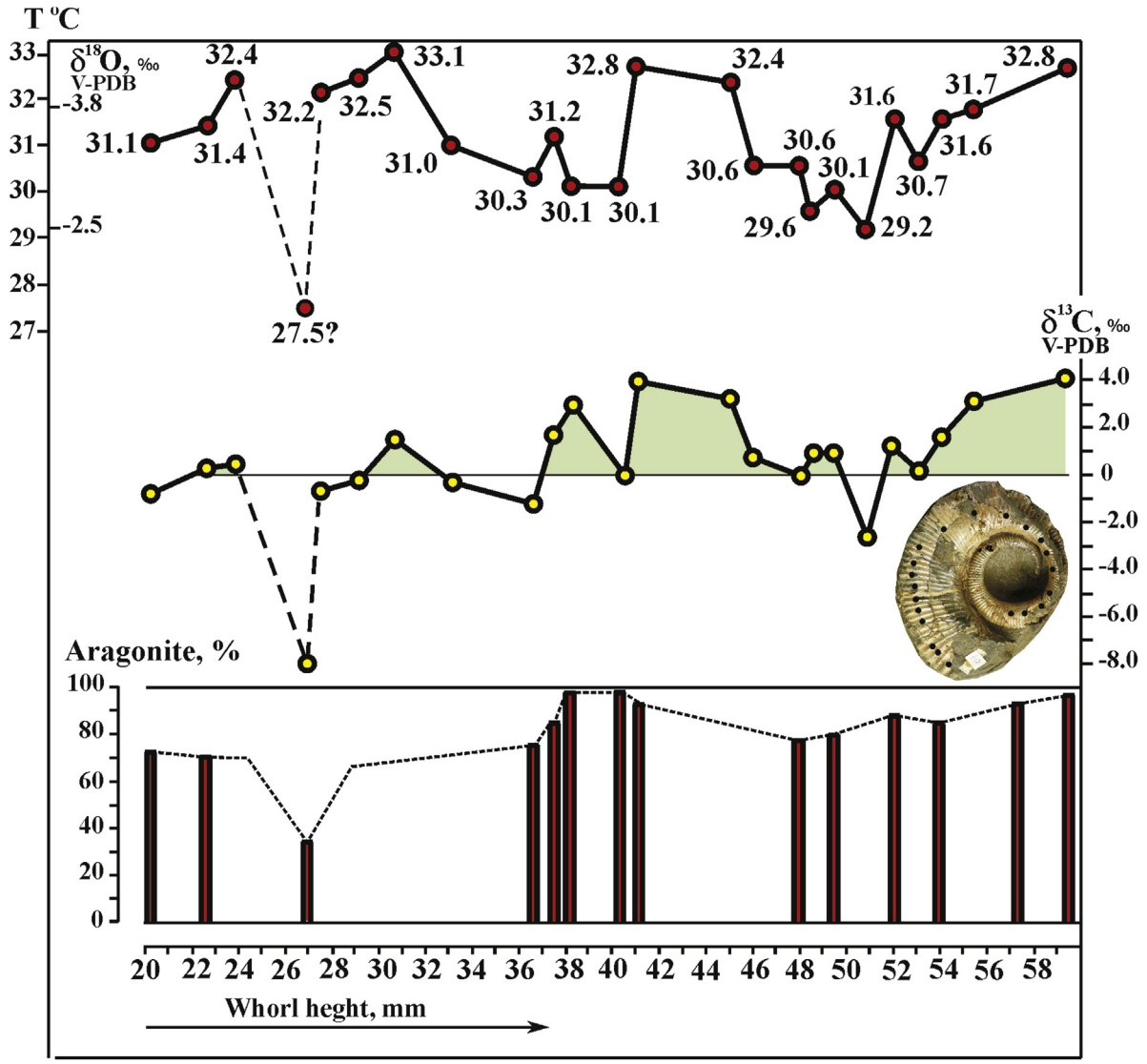

Fig. 8. Lower Aptian Deshayesi–Tuberculatum Zone: growth temperatures for the aragonitic heteromorph ammonoid *Proaustraliceras tuberculatum*-48/96.

Mehay et al., 2009) and/or dissociation of methane gas hydrate trapped in marine sediments (e.g., Beerling et al., 2002; Jenkyns, 2003; Ando et al., 2008; Lorenzen et al., 2013).

Aptian (OAE 1a) black shales have been documented in many regions (e.g., Jenkyns, 1995; Jenkyns and Wilson, 1999; Ando et al., 2002, 2008; Beerling et al., 2002; Jenkyns, 2003; Weissert and Erba, 2004; Li et al., 2008; Emeis and Weissert, 2009; Da Gama et al., 2009; Mehay et al., 2009; Mutterlose et al., 2009; Kuroda et al., 2011; DeBond et al., 2012; Moreno-Bedmar et al., 2012; Lorenzen et al., 2013).

The interval of organic carbon-rich sediments in the Russian Platform, deposited during OAE 1a, has been known since the time of Pavlow's (1901) and Arkhangelsky's (1923) investigations and has been studied recently in detail by several authors (Baraboshkin, 1996a, 1996b, 2001, 2005; Baraboshkin et al., 1999, 2002, 2007; Baraboshkin and Michailova, 2002; Gavrilov et al., 2002; Guzhikov and Baraboshkin, 2004; Shchepetova et al., 2011).

New isotopic data on this area (Table 2) provide information on a negative carbon isotope excursion, which coincides just with the onset of OAE 1a. Discovery of the low values of $\delta^{13}C$ (fluctuating mainly between −2 and 0‰) in both planispiral and heteromorph ammonoid shells of the Volgensis–Shilovkensis Zone allows better correlation of the black shale facies of the Russian Platform (Volgensis–Shilovkensis Zone) with Selli and Fischschiefer intervals in Italy and Germany and the Forbesi Zone in Spain, France and England, where the negative C isotopic anomaly was also recorded at the onset of mid early Aptian OAE 1a. (e.g., Weissert and Erba, 2004; Moreno-Bedmar et al., 2012).

5.3. Positive carbon isotope anomalies

Until the present study, a single positive carbon isotope anomaly within the upper Barremian-lower Aptian interval of the Russian Platform ($\delta^{13}C$ value up to 6.44‰) has been recognised by H. Weissert and E.Y. Baraboshkin in 1995 (Table 2, collection Y95). It is located at the base of Member VI in the Deshayesi–Tuberculatum Zone, above a black shale interval (Baraboshkin, 1996a). New isotopic data on this area (Table 2) provide better information on this topic.

New carbon isotope evidence obtained for the upper Barremian belemnites ($\delta^{13}C = 1.1–2.6‰$) and bivalve ($\delta^{13}C = 3.6–4.8‰$) and lower Aptian ammonoids ($\delta^{13}C$ values up to 4.12‰) from the Germanica and Deshayesi–Tuberculatum zones for the Ulyanovsk area confirms information concerning the presence of the positive carbon isotope anomalies in the upper Barremian (Germanica

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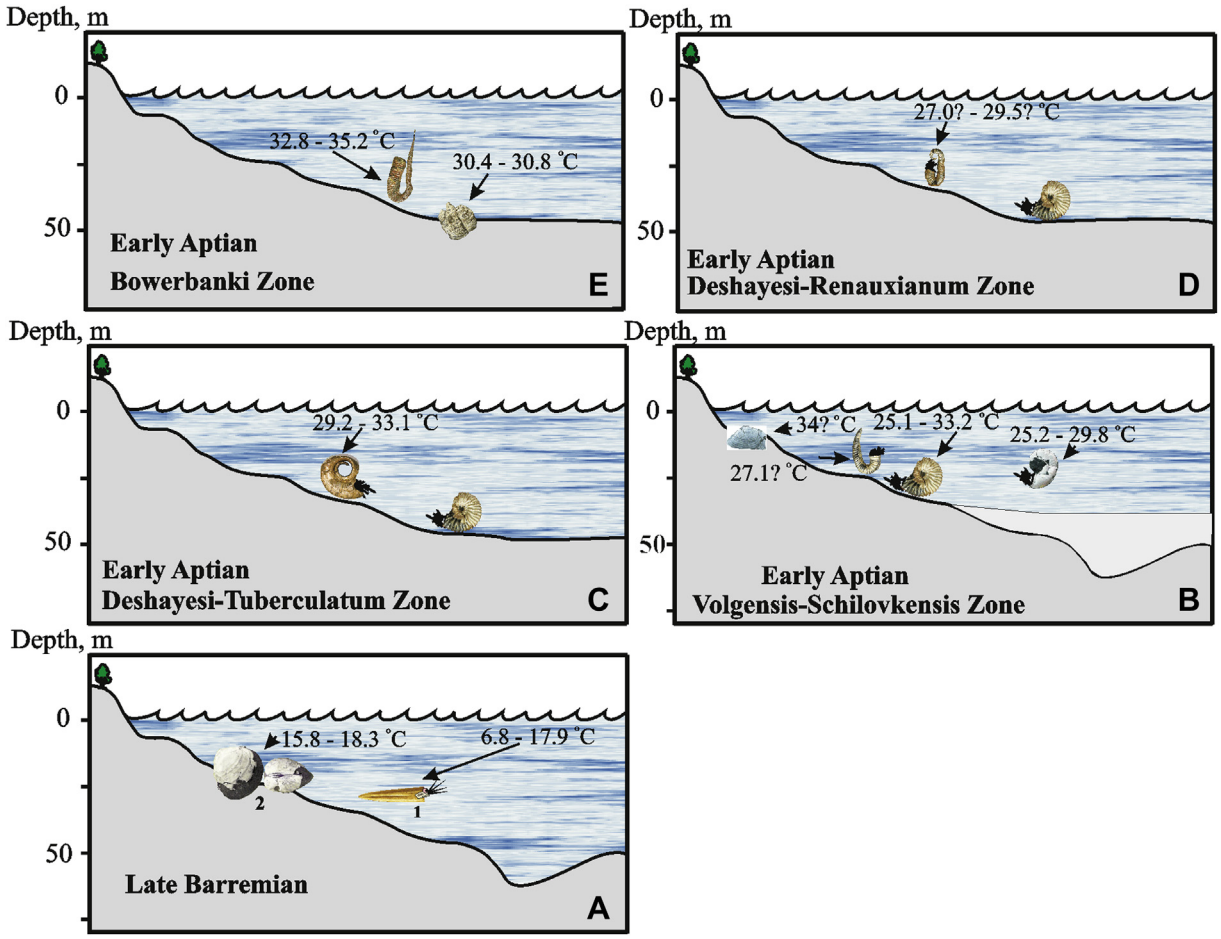

Fig. 9. Assumed natural habitat for upper Barremian and lower Aptian (Volgensis–Schilovkensis, Deshayesi–Tuberculatum, and Deshayesi–Renauxianum zones) bivalve and cephalopod molluscs of the Ulyanovsk area. A – Hermanica Zone (*Oxyteuthys* sp. and *Cyprina* sp.); B – Volgensis–Schilovkensis Zone (*Neocomiceramus* cf. *borealis*, *Volgoceratoides schilovkensis*, *Deshayesites volgensis* Sazonova, *Sinzovia trautscholdi*; C – Deshayesi–Tuberculatum Zone (*Proaustraliceras tuberculatum*, *Deshayesites* sp.; D – Deshayesi–Renauxianum Zone (?*Arioceras* sp., *Deshayesites* sp.); E – Bowerbanki Zone (*Helicancylus*? cf. *philadelphius*).

level) and lower Aptian (Deshayesi level) on the basis of data, for instance, from Italy (Erba et al., 1996; Weissert and Erba, 2004), Germany (Mutterlose et al., 2009), Spain (Moreno-Bedmar et al., 2012). Less is known about carbon isotope composition of upper lower Aptian carbonates from Italy and Germany. Isotopic data for the uppermost part of the lower Aptian of the Alps (Weissert and Erba, 2004, Fig. 2) seem to be limited, and correlation of carbon isotope patterns from Resolution Guyot, Mid-Pacific Mountains (Jenkyns, 1995), and the Tethys is not assured. However, Herrle et al. (2004) documented at least two positive carbon isotope excursions within the Lower Aptian foraminifera-bearing interval (*Leupoldina* Zone) in the Vocontian basin, SE France, and Mazagan Plateau, Central Atlantic. Similar results were recently obtained for lower Aptian ammonoid-bearing facies of northern and southeastern Spain (e.g., García-Mondéjar et al., 2009, Millán et al., 2011; Moreno-Bedmar et al., 2012). Calibration of these isotopic records with the ammonoid zonation show that their ages are mainly constrained to the Deshayesi and most part of the Furcata zones.

Carbon isotope data from the Bowerbanki Zone of the Russian Platform also provide evidence on a positive carbon isotope anomaly in this level ($\delta^{13}C$ values fluctuate between 3.0 and 4.86‰ in ammonoid and 5.47 and 5.98‰ in bivalves). Thus, the three positive carbon isotope anomalies seem to be present through the upper Barremian–lower Aptian interval. (Fig. 11).

5.4. Palaeotemperature trends

The oxygen-isotope pattern observed for the Ulyanovsk area is in agreement with published isotopic, palynological, and lithological evidences (e.g., Jenkyns and Wilson, 1999; McArthur et al., 2004; Weissert and Erba, 2004; Baraboshkin, 2001; Barragán and Melinte, 2006; Baraboshkin et al., 2007; Malkoč and Mutterlose, 2010; Amiot et al., 2011). The values illustrate a global warming trend during the late Barremian–early Aptian. The mid-Cretaceous "super-greenhouse" was preceded by unstable climate and oceanography, starting in the Valanginian. However, in contrast to some other regions, for instance to the Alps (Weissert and Erba, 2004) or central Pacific (Ando et al., 2008), the Ulyanovsk area is characterised by a more significant regional shift in $\delta^{18}O$ during the late Barremian–early Aptian (rise in sea-surface temperatures by 16–19 °C Zakharov et al., 2012a). The peculiar geographic position of the Russian Platform may explain these peculiar trends: cool polar waters entered the Russian Platform area during the Barremian (Fig. S7), but warm Tethyan waters affected the environment of the Russian Platform only since the early Aptian (Fig. S8).

The onset of the early Aptian OAE 1a, corresponding to the upper Volgensis–Shilovkensis Zone, seems to be characterised in the Ulyanovsk area by extremely warm conditions (24–33.2 °C), which are ~3° lower than those, indicated for early Aptian sea-surface palaeotemperatures, measured in the equatorial Pacific

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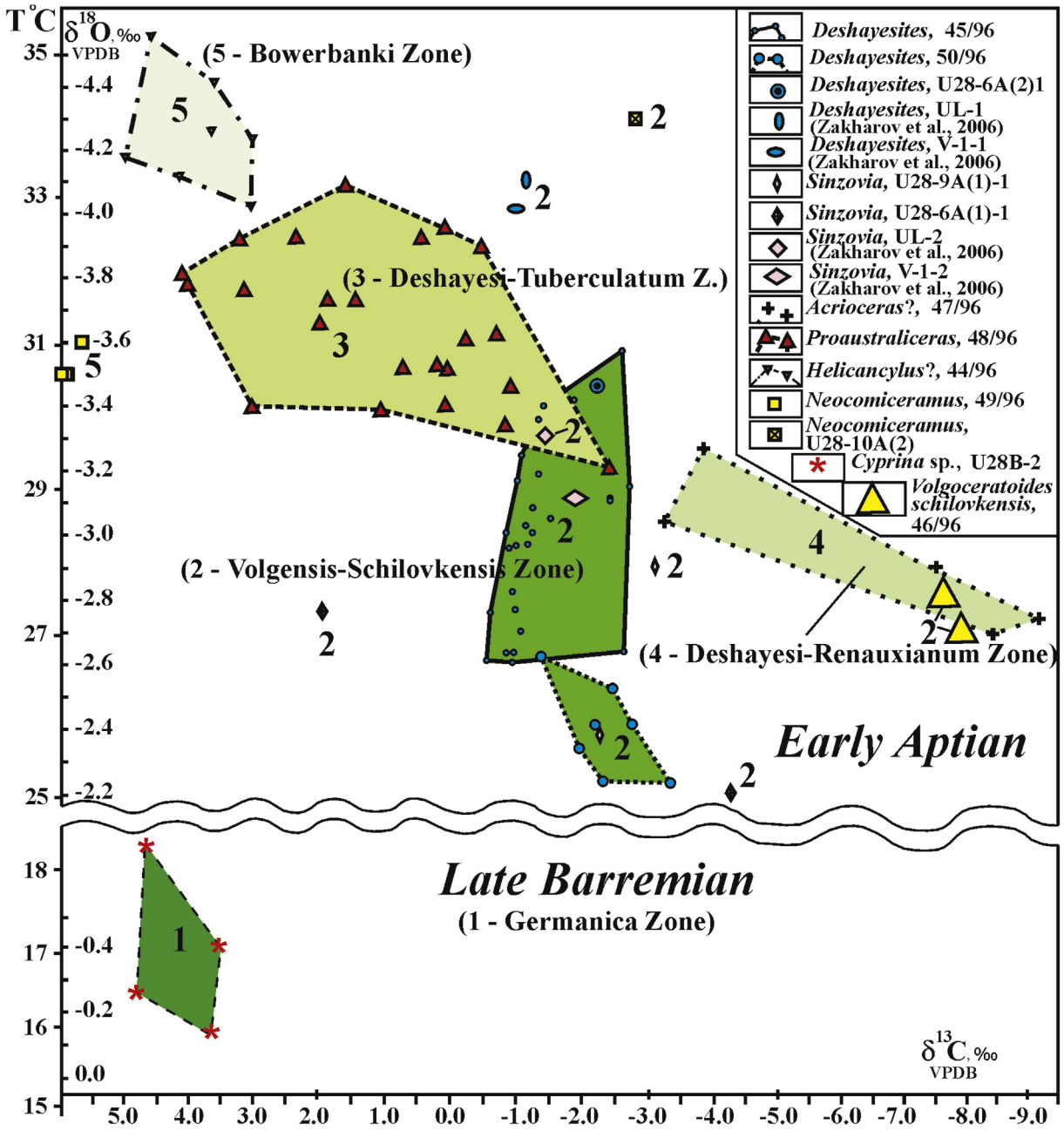

Fig. 10. Temperature reconstruction from data on isotopic composition of upper Barremian–lower Aptian fossils.

(Schouten et al., 2003) and proto-North Atlantic (Schouten et al., 2003). But the values are somewhat higher than those, calculated from the isotopic composition of belemnite rostra (19.2–28.0 °C; Bowen, 1961, 1963; Teiss and Naidin, 1973) from the western Tethys. Warming trend in this level (OAE 1a) for the Alps is illustrated by Weissert and Erba (2004) on the basis of the oxygen-isotope evidence of the Alps.

In contrast, as it was mentioned earlier, late Barremian palaeotemperatures, calculated from well-preserved belemnite rostra of the Germanica Zone of the Ulyanovsk area are rather low (<17.9 °C). A well preserved (aragonitic) bivalve shell from the same locality gives comparable temperatures of 16.9–18.3 °C (Fig. 10). On the Russian Platform, late Barremian seawater probably was cooler than at the Jurassic–Cretaceous transition (20–22 °C) (Price and Rogov, 2009), including the Berriasian, when the Russian Platform basin was affected of Tethyan water mass (Baraboshkin, 2005; Baraboshkin et al., 2007). Belemnite rostra from the upper Barremian of the Barreme locality in France (Table 1) also show low palaeotemperatures of about 12–13 °C. Although belemnite rostra from France are grey coloured, their $\delta^{13}C$ values are positive (0.78–1.03‰), which could be construed as evidence for good preservation of original isotopic signals in these belemnite rostra.

There is oxygen-isotope evidence for short-term cooling in the early Aptian, immediately after deposition of black shales in some regions, e.g. in Northern Germany (from belemnites – Fischschiefer level) (Mutterlose et al., 2009), in the North Atlantic (from planktic foraminifera) (Huber et al., 2011), in France, Italy and Switzerland (from fish-teeth phosphate; Pucéat et al. (2005) and from bulk carbonates, e.g., Weissert et al., 1985; Weissert and Channell, 1989; Padden et al., 2002; Weissert and Erba, 2004)), in China, Thailand and Japan (from apatite phosphatic reptile remains; Amiot et al., 2011). This trend is supported by palynological data. A decrease

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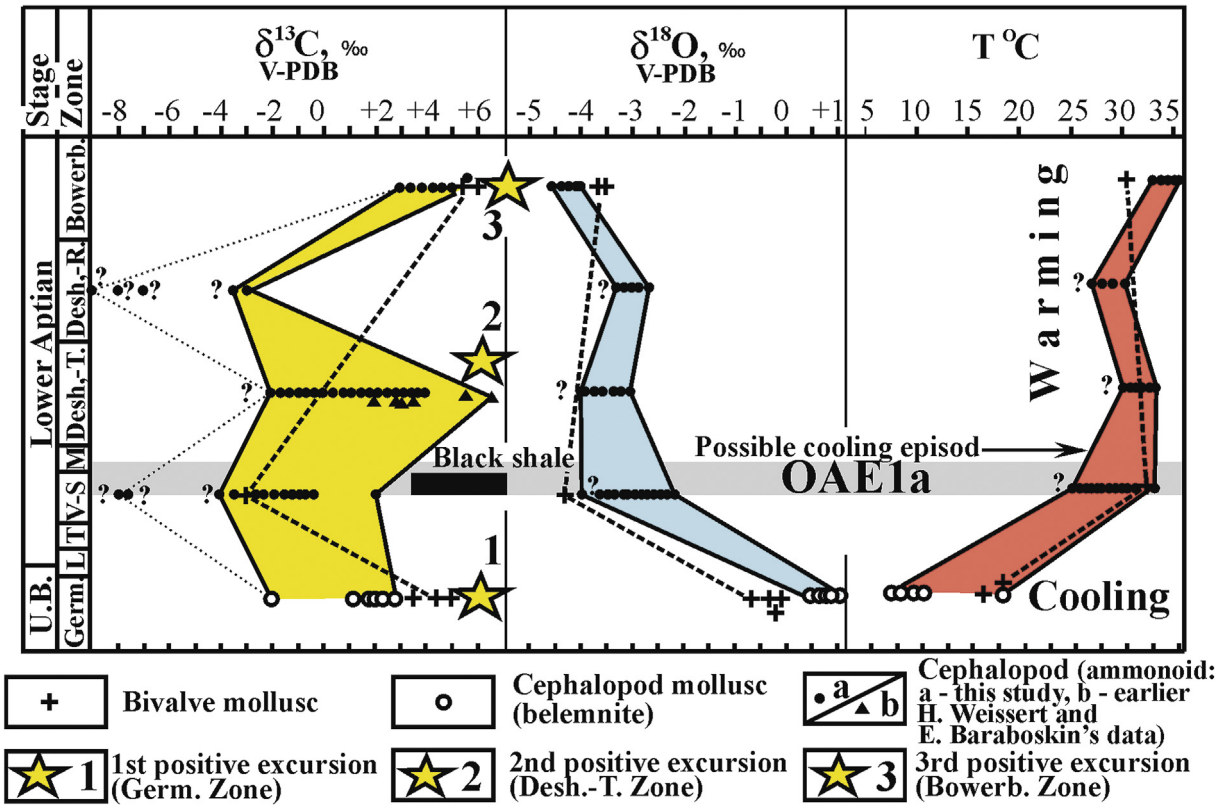

Fig. 11. Upper Barremian–lower Aptian positive C-isotope anomalies and temperature trends: evidence from the Ulyanovsk area. Zones: Germ. – Germanica, L – Lahuseni, T – Tenuicostatus, V–S – Volgensis–Schilovkensis, M – Matherianum, Desh.–R. – Deshayesi–Renauxianum, Bowerb. – Bowerbanki.

in abundance of the thermophilic pollen *Classopollis* (*Corollina*) and increase in boreal floral elements (bisacate pollen) is observed just above the OAE 1a black shales (e.g., Hochuli et al., 1999; Jenkyns, 2003). Pucéat et al. (2003, 2005) measured post OAE1a palaeotemperatures which did not exceed of 18–22 °C in the alpine Tethys. It seems remarkable, that the post-OAE1a cooling is also documented by palynological data on the Russian Platform (Baraboshkin, 2001; Baraboshkin et al., 2007).

There is a gap in our knowledge concerning the oxygen-isotope composition of carbonates from the upper part of the Deshayesi Zone and there is only restricted information on this topic from some other lower Aptian horizons in the Alps and Apennines (Weissert and Erba, 2004) and their equivalents in Germany (Mutterlose et al., 2009). However, very warm conditions for the three zones of the mentioned lower Aptian interval were documented in the Ulyanovsk area on the basis of oxygen-isotope data from aragonitic ammonoid and bivalve shells: from the Deshayesi–Tuberculatum (29.2–33.1 °C), Deshayesi–Renauxianum (27.0–29.5 °C), and Bowerbanki (30–35.2 °C) zones.

The new isotopic data on the Russian platform and published palaeobotanical evidences from other areas suggest that the early Aptian (likely late early Aptian) climatic optimum (Fig. 11) seems to be one of the most prominent among other optima of Phanerozoic time, e.g., early Ordovician (28.8–29.3 °C in Cincinnati, USA, Table 1), early Toarcian (33 °C in Yorkshire, England) (Jenkyns, 2003), late Berriasian (26.3–28.7 °C in South West England (Table 1), late Albian (28.5–28.9 °C in Mangyshlak and the Koryak Upland) (Zakharov et al., 2006), Cenomanian (27.8–35.0 °C in the Pacific and Atlantic) (Huber et al., 1999; Price and Hart, 2002; Voigt et al., 2003; Pucéat et al., 2003), or late Santonian (23.1–33.7 °C in British Columbia (Zakharov et al., 2012b). Palaeobotanical results (e.g., Krassilov, 1973, 1981, 1985; Vakhrameev, 1988; Lebedev, 1990; Markevich, 1995; Golovneva, 1998; Hochuli et al., 1999; Volynets, 2011), as well as oxygen-isotope composition of lower Aptian bivalve shells from the Koryak Upland (Zakharov et al., 2004), showing relatively high palaeotemperatures at high northern hemisphere latitudes (18.4–25.9 °C), and information on the unusually wide equatorial evaporitic belt of the Aptian time (Chumakov, 2004; Zharkov et al., 2004) have provided important confirmation of a distinct climatic optimum during the late early Aptian.

Evidences on isotopic composition of upper Aptian–lower Albian foraminifera from Blake Nose, North Atlantic (Ocean Drilling Program Site 1049; Huber et al., 2011), upper Aptian fish teeth from France and Switzerland (Pucéat et al., 2003), upper Aptian aragonite-bearing (37–68%) ammonoids *Cheloniceras* and *Hypophylloceras* from the of North Caucasus (Afipskaya Formation) (Zakharov et al., 2000), and belemnite *Neohibolites*? sp. rostra from Crimea (Biyasalinskaya Formation, ?*Aconeceras nisum* Zone) (Table 1) show palaeotemperatures of 10–14 °C, 18.1–22.1 °C, 13.1–23.9 °C, and 14.0–18.0 °C, respectively. We believe also that belemnite *Mesohibolites* rostrum from Crimea (Teiss and Naidin, 1973), showing palaeotemperature of 14.6 °C, also originates from the upper Aptian. These evidences indicate that the estimated late early Aptian climatic optimum was followed by a cooling in the late Aptian, which seems to be in agreement with finding of mid (?) Aptian glendonite concretions in the *Tropaeum arcticum*-bearing shaly member at Spitsbergen (Rogov and Zakharov, 2010) and detailed data on the late Aptian sea-level fluctuations (Maurer et al., 2013).

6. Conclusions

1. Palaeotemperatures estimated from oxygen isotopic analyses on early Aptian aragonitic fossils of the Ulyanovsk area show that both heteromorph and planispiral ammonoid shells were

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secreted in similar temperature conditions of the shallow marine basin.

2. Marked temperature changes on the Russian Platform during the late Barremian–early Aptian were most likely linked to global trends and to local palaeonvironmental conditions. Influx of cool polar waters into the Ulyanovsk Basin during the late Barremian was followed by a significant increase of warmer water influence from the Tethys lasting through the early Aptian times. Warmest conditions were reached on the Russian Platform during the late early Aptian climatic optimum, corresponding mainly to the Bowerbanki Zone (Furcata Zone in the Alps).
3. There were apparently the three positive C-isotope anomalies during the late Barremian–early Aptian: (1) late Barremian (Germanica Zone), (2) mid early Aptian (Deshayesi–Tuberculatum Zone), and (3) late early Aptian (Furcata and Bowerbanki zones). The upper Barremian and upper lower Aptian positive C-isotope excursions have been documented for the first time in sediments from the Russian Platform.
4. Both published palynological evidence (Baraboshkin, 2001; Baraboshkin et al., 2007) and new isotopic data on the Russian platform suggest that the onset of mid early Aptian global anoxia (OAE 1a) of the Volgensis–Shilovkensis Zone coincided with both the beginning of significant warming (following by short-term cooling) and a drop in $\delta^{13}C$ values in marine carbonates. It may be partly caused by a fundamental perturbation of the carbon cycle, triggered by sudden addition of isotopically light volcanic CO_2 to the atmosphere and oceans (Larson and Erba, 1999; Millán et al., 2011) and/or dissociation of methane gas hydrate trapped in oceanic sediments (e.g., Lorenzen et al., 2013).

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Appendix A. Supplementary data

Supplementary data related to this article can be found at http://dx.doi.org/10.1016/j.cretres.2013.04.007.

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