New data on isotopic composition of Jurassic-Early Cretaceous cephalopods*

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Abstract The aim of this paper is to reconstruct the Jurassic-Early Cretaceous climatic conditions using new isotopic data. Paleobotanical data indicate that a cooling occurred gradually just after Late Triassic, and a temperature minimum was reached in the Pliensbachian. This was followed by a climatic optimum in the early Toarcian, cooling in the late Toarcian and a second climatic optimum in the Oxfordian. Published isotopic thermometry data and our new results on isotopic composition of some Jurassic invertebrate shells from the Russian Platform, Poland, Germany and England generally confirm this pattern, and also indicate a third climatic optimum in the Middle Callovian. Middle-Late Mesozoic adult belemnites apparently lived during their spawning phase, in shallow waters similar to extant *Nautilus*. However, at least juvenile belemnoids, unlike ammonoids, engaged in significant short-term vertical migrations in the water column, reaching colder waters of the upper bathyal zone.

Keywords: fossil invertebrates, Jurassic and Cretaceous, isotopic paleotemperatures.

The Mesozoic appears to have constituted the most permanent period of equable greenhouse conditions during the Phanerozoic, although conspicuous climatic fluctuations took place and parts of the Earth experienced cooler climates during certain intervals of the Mesozoic[1—5]. Reliable evidence for Mesozoic polar ice is unknown. According to Chumakov's opinion[6], the majority of discovered dropstones dispersed within a fine-grained host sediment[7] were rafted by seasonal river ice, roots of floating logs or algal mats rather than being of glacial origin. Conditions required for the origin of glendonites, stellate ikaite aggregates[7], are not well resolved and the fluctuation of $\delta^{18}O$ and Sr values in sea waters[8,9] seems to provide little evidence of glacial-eustatic sea-level fluctuation. Price[7] admitted that facts interpreted as evidence for glaciation in the Mesozoic seems to be sparse and equivocal.

Many workers have inferred that changes in the global development of carbonate platforms, sea levels, and seawater temperature and chemistry, were responses to periodic major volcanism that contributed additional CO_2 to the atmosphere[10].

Middle Jurassic and Early Cretaceous climatic history is less well resolved than that for the Late Cretaceous because of a lack of satisfactory oxygen-isotope derived paleotemperature data for the middle Mesozoic. This paper aims to present some additional results from oxygen- and carbon-isotope analyses derived from Jurassic and Early Cretaceous invertebrates of Eurasia. The abundance and good preservation of the middle Mesozoic macrofossils of the Mangyshlak Peninsula, Russian Platform, northern France and neighbouring areas presents an opportunity to examine both ocean temperature variation during that time and the mode of life of fossil cephalopods.

1 Material and methods

Material used for our new isotopic analysis consists of various calcareous shells (Fig.1):

(1) brachiopod shells with fibrous structure from the Callovian of the Russian Platform (2 samples);

(2) aragonitic ammonoid shells from the Pliensbachian of England and Germany (2 samples), Callovian of England, Poland and Russian Platform (11 samples);

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(3) Callovian belemnite rostrum of the Russian Platform (1 sample), Tithonian belemnite rostrum subpolar Urals (1 sample), Aptian aragonitic ammonoid shells of the Russian Platform (6 samples), Albian aragonitic ammonoid shells from Mangyshlak, central Asia (5 samples), Koryak Upland (1 sample), *Pas de Calais*, France (1 sample), and Normandy, France (2 samples);

(4) an Albian scaphopod from *Pas de Calais* area (1 sample), and Albian belemnite rostra from the *Pas de Calais* area (30 samples).

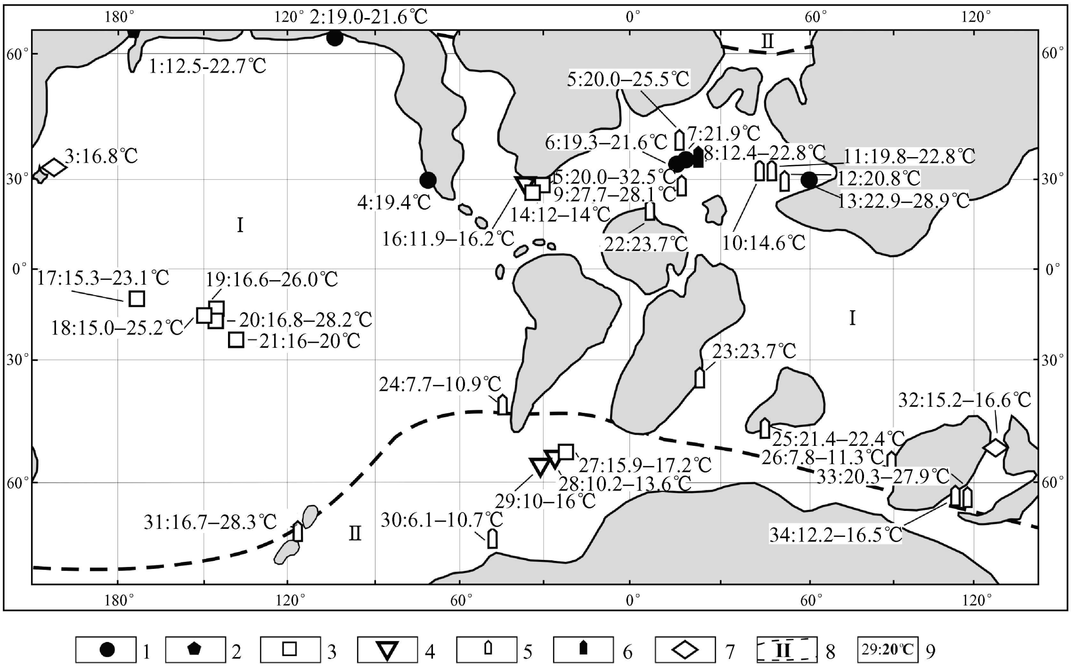

Fig. 1. Map of localities for the Albian isotopic paleotemperatures. 1, from ammonoid shells (original data); 2, from brachiopod shells[31]; 3, from planktic foraminifera (data other workers); 4, from benthic foraminifera (data other workers); 5 and 6, from belemnite rostra: 5 from data other workers, 6 from original data; 7, from bivalves (data other workers), 8, climatic zones (I-Tropical-Subtropical, II-Warm-Temperate); 9, locality and its number. Localities: 1, Melkaya River, Koryak Upland, Late Albian; 2, South Alaska, Early Albian; 3, Hokkaido, Albian; 4, California, Albian; 5, England, Albian; 6, Normandia, Albian (original data); 7 and 8, Pas de Cale, middle Albian (original data): 7 from ammonoid, 8 from belemnite; 9, southern France; 10 and 11, Crimea: 10 is lower Albian, 11 is upper Albian; 12, Kheu, North Caucasus; 13, Mangyshlak, upper lower and upper Albian (original data); 14—16, Blake Nose: 14 is planktic foraminifera, lower Albian, 15 is planktic foraminifera, upper Albian, 16 is benthic foraminifera, upper Albian; 17, Hole 305, Albian; 18—20, Hole 463: 18 is lower Albian, 19 is middle Albian, 20 is upper Albian; 21, Hole 167, upper Albian; 22, Algeria, Albian; 23, Mozambique, Albian; 24, Lago San Martin, Argentina; 25, India, upper Aptian; 26, Carnarvon Basin, Australia,; 27—29, Hole 511: 27 is planktic foraminifera, Albian, 28 is benthic foraminifera, lower Albian, 29 is benthic foraminifera, upper Albian; 30, James Ross Island, Antarctic, lower Albian; 31, New Zealand, upper lower-upper Albian; 32, Queensland, Australia, Albian; 33, Fossil Creek, southern Australia, Albian; 34, South Australia, Albian.

The following signs were used to eliminate material affected by diagenetic alteration:

(1) macroscopic evidence of shell alteration/degradation; (2) percentage of aragonite in a skeleton, when the shells were originally represented by 100% aragonite; (3) a degree of integrity of skeleton microstructure, when the calcitic brachiopod shells were examined.

Oxygen and carbon isotope values were measured using a Finnigan MAT-252 mass spectrometer (Germany) at the Analytical Center of the Far Eastern Geological Institute, Vladivostok. The laboratory gas standard was calibrated relative to calcite NBS (National Bureau of Standards) 19 and equals (1.8 ± 0.10)‰ for oxygen relative to the PDB (Pee Dee belemnite) and (−0.75 ± 0.10)‰ for carbon. Reproducibility of replicate standards was always better than 0.10‰. In calculating the temperatures, the Mesozoic world was free or mainly free from icecaps and, therefore, a $\delta^{18}O$ of −1.2‰ PDB (equivalent to −1.0‰ SMOW) was thought to be appropriate. Two scales were used for palaeotemperature calculation: that of Anderson and Arthur[11—13] using calcitic material and that of Grossman and Ku[14] one using aragonitic material.

X-ray analyses were carried out using a DRON-3 diffractor following the method of Davis and Hooper[15]. Ca and Mg contents in investigated carbonates were determined by using the method of complexometric titration[16].

2 The δ^{18}O and δ^{13}C records and paleotemperature implications

2.1 Pliensbachian

Shells of three ammonoid species were analyzed: *Aegoceras* sp. (EN-5a, 73% aragonite) and *Tragophylloceras loscombi* (Sowerby) (EN-3, 100% aragonite) from the lower Pliensbachian of England and *Pleuroceras costatus* Reinecke (WG-1, 98% aragonite) from the upper Pliensbachian of Germany (Y. Shigeta's collection) (Table 1). δ^{18}O and δ^{13}C values in the Early Pliensbachian shells vary between −2.0‰ and −1.5‰ and between 0.5‰ and 0.6‰, respectively (calculated paleotemperatures are 23.1—24.2). δ^{18}O and δ^{13}C values in the Late Pliensbachian shell are −1.2‰ (T = 20.7℃) and −0.3‰, respectively.

Table 1. Carbon and oxygen isotope composition of Aptian aragonitic ammonoid shells of the Ulyanovsk area, Russian Platform

Sample (Collector)	Species	Substage	Location (Height)	Diagenetic alteration			δ^{13}C (PDB) (‰)	δ^{18}O (PDB) (‰)	T(℃)
				Araginite (%)	Admixture (α-SiO$_2$)	Colour			
UL-21 (Choi Young Geul)	*Acanthohoplites* sp.	Upper Aptian	23 mm	100	—	Cream	−1.3	−2.3	25.4
UL-22 (Choi Young Geul)	*Aconeceras* (*Sinzovia*) sp.	Upper Aptian	17 mm	97±3	Trace	Cream	−1.9	−3.0	28.4
V-1-1 (K. Tanabe)	*Deshayesites deshayesi* d'Orbigny	Lower Aptian	15 mm	100	—	Silvery-cream	−1.2	−4.0	32.8
V-1-2 (K. Tanabe)	*Aconeceras* (*Sinzovia*) *traut-scholdi* (Sinzow)	Lower Aptian	12 mm	100	—	Silvery-white	−2.0	−3.1	28.9
UL-2 (Y. Shigeta)	*Aconeceras* (*Sinzovia*) *traut-scholdi* (Sinzow)	Lower Aptian	17 mm	96±3	—	Silvery-white	−1.5	−3.3	29.8
UL-1 (Y. Shigeta)	*Deshayesites deshayesi* d'Orbigny	Lower Aptian	14 mm	96±3	—	Silvery-cream	−1.2	−4.1	33.2

2.2 Callovian

2.2.1 Russian Platform From the *Cadoceras elathmae* Zone of the middle part of the lower Callovian of Mikhailovsky Mine, Kursk Magnetic Anomaly, only one aragonitic ammonoid *Keplerites gowerianus* Sowerby shell (889-1-1, 100% aragonite and α-SiO$_2$ trace) was used for isotopic investigation. Samples from several parts of the living chamber show a range in δ^{18}O and δ^{13}C values from −0.6‰ to −0.4‰, and from 1.1‰ to 1.4‰, respectively. These give calculated early Callovian paleotemperatures ranging from 17.2℃ to 18.1℃ (Table 1).

From the Jurassic (lower-middle Callovian) Black Clay of the Kineshma area shells of two ammonoid species (*Cadoceras elathmae* Nikitin, *Cadoceras* sp. (889-1-4,10,11, 95%—100% aragonite), one brachiopod species-*Praecyclothyris badensis* (Oppel) (889-1-6a) and a belemnite rostrum (889-1-9) found in a single boulder were analyzed (Y.L. Bolotsky's collection) (Table 1). Ammonoid δ^{18}O values fluctuate from −1.2‰ to 0.4‰ (T = 13.3—20.7℃), and ammonoid δ^{13}C values vary between 0 and 3.2‰; brachiopod δ^{18}O values range from −1.2‰ to 0.6‰ (T=9.8—16.7℃), and brachiopod δ^{13}C values are 1.0‰—1.8‰; the belemnite δ^{18}O value equals 0 which corresponds to 11.9℃, the belemnite δ^{13}C value is 1.3‰.

From the upper Callovian of the Russian Platform (Ryazan area) only a single ammonoid *Cosmoceras aculcatum* Michailow shell (RZ-1, 100% aragonite) was investigated by us (Y. Shigeta's collection) (Table 1). The sample has δ^{18}O and δ^{13}C values of −1.3 (T=21.0℃) and 3.3, respectively.

2.2.2 England A shell of the ammonoid *Kossmoceras* sp. from the lower part of the middle Callovian of England (EN-4a, 78% aragonite) was investigated (Y. Shigeta's collection) (Table 1). Its δ^{18}O and δ^{13}C values are −3.2 (T = 29.4℃) and 0.1, respectively.

2.2.3 Poland A single ammonoid *Quenstedtoceras* sp. (PL-1, 98% aragonite) was studied from the upper Callovian of Poland (Y. Shigeta's collection). The δ^{18}O and δ^{13}C values are −0.4‰ (T = 17.2℃) and −0.1‰, respectively (Table 1).

2.3 Tithonian

Well preserved calcitic belemnite rostra were recently collected by A.M. Panichev in the middle portion of the Volgian Regional Stage of subpolar Urals（Yatriya River，Ayapin River basin，Saranpaul area）. They were found together with ammonoid shells（*Strajevskia* sp.），but the latter are recrystalizsed and，therefore，were not used for isotopic analyses. These beds contain some bivalve shells，but they are partly recrystalized also（contain only 62% of aragonite）. The δ^{18}O and δ^{13}C values for a large belemnite rostrum（895-5；Table 1），about 83 mm long and 24 mm in diameter，are −1.2‰（$T=16.8$℃）and 0.2‰，respectively.

2.4 Aptian

Well-preserved Aptian ammonoid shells were collected in the Ulyanovsk area of the Russian Platform（Choi Young Geul's（Seoul），Y. Shigeta's and K. Tanabe's（Tokyo）collections）. Analyzed Early Aptian ammonoid shells are represented by two species：*Deshayesites deshayesi* d'Orbigny（V-1-1，100% aragonite；UL-1，96% aragonite）and *Aconeceras*（*Sinzovia*）*trautscholdi*（Sinzow）（V-1-2，100% aragonite；UL-2，96% aragonite）. Late Aptian ammonoids are also represented by two species：*Acanthohoplites* sp.（UL-21，100% aragonite）and *Aconeceras*（*Sinzovia*）sp.（UL-22，97% aragonite；Table 2）. δ^{18}O and δ^{13}C values for the Early Aptian ammonoid shells fluctuate from −4.1‰ to −3.1‰（$T=28.9$—33.2℃）and from −2.0‰ to −1.2‰，respectively. δ^{18}O and δ^{13}C values of the Late Aptian ammonoids vary between −3.0‰ and −2.3‰（$T=25.4$—28.4℃）and between −1.9‰ and −1.3‰，respectively.

Table 2. Carbon and oxygen isotope composition of Albian ammonoid and scaphopod shells of Western Europe，Mangyshlak，Koryak Upland and Alaska

Sample，area（Collector）	Species	Formation（Stage or substage）	Location[1]	Diagenetic alteration			δ^{13}C（PDB）（‰）	δ^{18}O（PDB）（‰）	T（℃）
				Aragonite（%）	Admixture（α-SiO$_2$）	Colour			
LAM-2-19；*Pas de Calais*（Y.D. Zakharov）	*Oxytropidoceras* sp.	Sent-Po（upper Albian）	H=13 mm	86±5	Trace	Greyish-cream	2.6	−1.5	21.9
LAM-2-20；*Pas de Calais*（Y.D. Zakharov）	*Dentalium* sp.	Sent-Po（upper Albian）	D=6.2 mm	Have not been determined	Have not been determined	Greyish-cream	2.1	−0.6	18.0
FR-1；Normandia（Y. Shigeta）	*Otohoplites raulinianus*（d'Orbigny）	middle Albian	H=10 mm	100	Trace	Beige	1.2	−1.4	21.6
FR-2；Normandia（Y. Shigeta）	*Beudanticeras beudanti*（Bron.）	upper Albian	H=25 mm	100	—	Silvery cream	−1.1	−0.9	19.3
3150；Mangyshlak（A.A. Savelyev）	*Placenticeras* sp.（="*Karomaicera*"sp.）	*P. studeri* Zone（upper Albian）	H=52 mm	82±3	—	Cream	−4.4	−2.8	27.6
1562；Mangyshlak，Tyubentii（A.A. Savelyev）	*Anahoplites* sp.	*A. rossicus* Zone（middle or upper Albian）	H=26 mm	93±3	—	Cream	−3.0	−1.7	22.9
3147；Mangyshlak（A.A. Savelyev）	*Pleurohoplites* aff. *studeri* Pictet et. Campliche	upper Albian	H=18 mm	100	—	White	−1.6	−2.4	25.9
1836；Mangyshlak（A.A. Savelyev）	*Sulcatihoplites* sp.	Albian	H=46 mm	100	—	Light-cream	−3.0	−2.0	24.6
4156；Mangyshlak，Tyubo Nuyul（A.A. Savelyev）	*Anahoplites* sp.	*A. montelli intermedius* Zone（middle or upper Albian）	H=41 mm	82±3	Trace	Cream	−5.0	−3.1	28.9
47/13088；Koryak Upland，Tikhlyavayam River.（T.D. Zonova）	*Proplacenticeras sutherlandbrawni* McLearn	upper Albian	H=28 mm	97±3	Ceolyte（trace）	Cream	3.8	−3.0	（28.5）
AL-3；Alaska（Y. Shigeta）	*Brewiceras hulense*（Anderson）	Matanuska（upper lower Albian）	H>25 mm	65±5	Trace	Silvery-white	−3.5	−1.4	21.6
AL-1；Alaska（Y. Shigeta）	*Grantziceras affine*（Whiteave）	Matanuska（upper lower Albian）	H>25 mm	100	—	Silvery-cream	−0.8	0.6	19.0
AL-2；Alaska（Y. Shigeta）	*Freboldiceras singulare* Imlay	Matanuska（upper lower Albian）	H=23 mm	69±3	Trace	Cream	2.0	−8.4	—

1）H，height；D，diameter.

2.5 Albian

2.5.1 Mangyshlak (Kazakhstan) Well-preserved Albian ammonoids from the Mangyshlak Peninsula were collected by A.A. Saveliev during his Jurassic-Cretaceous biostratigraphical investigation and we were able to conduct isotopic analyses on some of them (Fig. 1). Shells of two middle-late Albian ammonoid species [*Anahoplites* sp. (1562, 93% aragonite; 4156, 82% aragonite) and apparently *Sulcatihoplites* sp. (1836, 100% aragonite)] and two late Albian ammonoid species [*Placenticeras* sp. (3150, 82% aragonite) and *Pleurohoplites* aff. *studeri* P. and C. (3147, 100% aragonite)] were analyzed (Table 3). $\delta^{18}O$ and $\delta^{13}C$ values in middle-late Albian ammonoid shells fluctuate from −3.1‰ to −2.0‰ (T=22.9—28.9℃) and from −5.0‰ to −1.6‰, respectively; $\delta^{18}O$ and $\delta^{13}C$ values in late Albian ammonoid shells vary correspondingly between −2.8‰ and −2.4‰ (T=25.9—27.6℃) and between −4.4‰ and −1.6‰.

Table 3. Carbon and oxygen isotope analyses of Albian calcitic belemnite rostra from the *Saint-Pô* Formation of the Blan Nez Cape, *Pas de Calais* area (Y.D. Zakharov's collection)

Sample	Formation	Location[a)]	Diagenetic alteration			$\delta^{13}C$ (PDB) (‰)	$\delta^{18}O$ (PDB) (‰)	T(℃)
			Original calcite, %	Admixture	Colour			
LAM-2-2	*Saint-Pô*	D=5.0—5.5 mm	100	—	Colourless	1.3	−1.7	19.0
LAM-2-3 (same rostrum)	*Saint-Pô*	D=4.5—5.0 mm	100	—	Colourless	1.0	−1.0	16.0
LAM-2-4 (same rostrum)	*Saint-Pô*	D=4.5—5.0 mm	100	—	Colourless	1.5	−0.9	15.6
LAM-2-5	*Saint-Pô*	D=3.5—4.0 mm	100	—	Colourless	1.8	−0.9	15.6
LAM-2-6 (same rostrum)	*Saint-Pô*	D=3.0—3.5 mm	100	—	Colourless	1.9	−0.8	15.2
LAM-2-7 (same rostrum)	*Saint-Pô*	D=2.5—3.0 mm	100	—	Colourless	1.8	−0.8	15.2
LAM-2-8	*Saint-Pô*	D=1.7—2.5 mm	100	—	Colourless	1.4	−0.9	15.6
LAM-2-9 (same rostrum)	*Saint-Pô*	D=0—1.7 mm	100	—	Colourless	1.3	−1.1	16.4
LAM-2-10 (surface of the alveola)	*Saint-Pô*	D=7.7—7.9 mm	100	α-SiO_2 (trace)	Light-cream	2.1	−2.2	21.2
LAM-2-11 (surface of the same rostrum)	*Saint-Pô*	D=9.5 mm	100	α-SiO_2 (trace)	Light-cream	2.2	−2.2	21.2
LAM-2-12 (chalk)	*Saint-Pô*	—	—	—	White	1.7	−1.1	(16.4)
LAM-2-13 (surface of the alveola)	*Saint-Pô*	D=16.0 mm	100	Have not been determined	White	1.5	−0.7	14.7
LAM-2-14 (surface of the same rostrum)	*Saint-Pô*	D=16.9 mm	100	Have not been determined	Colourless	1.0	0.4	10.6
LAM-2-15 (surface of the alveola)	*Saint-Pô*	D=7.0 mm	100	Have not been determined	White	1.1	−1.2	16.7
LAM-2-16	*Saint-Pô*	D=15.0 mm	100	Have not been determined	Colourless	1.5	0.5	10.1
LAM-2-17 (chalk from the alveola)	*Saint-Pô*	—	—	—	White	2.0	−1.2	—
LAM-2-21	*Saint-Pô*	D=6.1—6.6 mm	100	Have not been determined	Colourless	1.8	−0.8	15.2
LAM-2-22 (same rostrum)	*Saint-Pô*	D=5.8—6.1 mm	100	Have not been determined	Colourless	2.6	−0.2	12.8
LAM-2-23 (same rostrum)	*Saint-Pô*	D=5.2—5.8 mm	100	Have not been determined	Colourless	2.6	−0.3	13.2
LAM-2-24 (same rostrum)	*Saint-Pô*	D=4.8—5.2 mm	100	Have not been determined	Colourless	2.7	−0.3	13.2
LAM-2-25 (same rostrum)	*Saint-Pô*	D=4.2—4.8 mm	100	Have not been determined	Colourless	2.6	−0.1	12.4
LAM-2-26 (same rostrum)	*Saint-Pô*	D=3.6—4.2 mm	100	Have not been determined	Colourless	2.3	−0.2	12.8
LAM-2-27	*Saint-Pô*	D=3.0—3.6 mm	100	Have not been determined	Colourless	2.0	−0.3	13.2
LAM-2-28	*Saint-Pô*	D=1.5—3.0 mm	100	Have not been determined	Colourless	1.8	−0.2	12.8
LAM-2-29	*Saint-Pô*	D=0—1.5 mm	100	Have not been determined	Colourless	1.3	−0.6	14.4

(To be continued)

Continued

Sample	Formation	Location1）	Diagenetic alteration			$\delta^{13}C$ （PDB） （‰）	$\delta^{18}O$ （PDB） （‰）	T（℃）
			Original calcite，%	Admixture	Colour			
LAM-2-30	*Saint-Pô*	D=4.0 mm	100	Have not been determined	Colourless	0.8	−1.0	16.0
LAM-2-31	*Saint-Pô*	D=3.5 mm	100	Have not been determined	Colourless	−0.2	−2.1	20.7
LAM-2-32	*Saint-Pô*	D=3.7 mm	100	Have not been determined	Colourless	0.9	−0.5	14.0
LAM-2-33	*Saint-Pô*	D=3.5 mm	100	Have not been determined	Colourless	1.7	−0.6	14.4
LAM-2-10 （surface of the rostrum，just below a white，thin （0.14 mm），calcite lamina	*Saint-Pô*	D=4.9—5.0 mm	100	Have not been determined	Colourless	0.2	−0.7	14.7

a） D，diameter.

2.5.2 Koryak Upland （north-east Russia） We investigated a single ammonoid *Proplacenticeras sutherlandbrawni* McLearn （47/13088，97% aragonite and ceolyte trace） from the upper Albian of Tikhlyavayam River （T. D. Zonova 's collection）. $\delta^{18}O$ and $\delta^{13}C$ values in its shell are −3.0‰ （$T=28.5$℃） and 3.8‰，respectively （Table 3）.

2.5.3 *Pas de Calais* （north France） Fourteen well-preserved calcitic belemnite rostra were collected by Y. D. Zakharov from the middle-upper Albian de *Saint-Pô* Formation （*Blanc-Nez*，North France；Fig. 2）. The sequence is listed here in a descending order[17]：

12. Grey，marly clay （4.0 m）：Ammonoids *Mortoniceras* （*Deiradoceras*），*Prohystoceras* （*Goodhallites*），*Semenovites* and *Epihoplites*.

11. Phosphatic bed （P6） with grey to brown nodules （0.3 m）：Ammonoids *Birostrina*，*Hysteroceras*，*Beudanticeras*，*Anahoplites*，*Metaclavites*，*Epihoplites*，*Euhoplites*，*Mortoniceras* （*Mortoniceras*），*M.* （*Deiradoceras*），*Prohystoceras*，*Hysteroceras*，*Idiohamites*，*Semenovites*，and bivalve *Plicatula*.

10. Grey marly clay （2.5 m）：Ammonoids *Birostrina*，*Hysteroceras*，*Beudanticeras*，*Anahoplites*，*Metaclavites*，*Epihoplites*，*Euhoplites*，*Mortoniceras* （*Mortoniceras*），*M.* （*Deiradoceras*），*Prohystoceras*，*Hysteroceras*，and *Idiohamites*.

9. Phosphatic bed （P5） with very abundant nacreous nodules （0.08 m）：Ammonoids *Birostrina*，*Beudanticeras*，*Anahoplites*，*Dimorphoplites*，*Oxytropidoceras*，*Metaclavites*，*Euhoplites*，*Neophlyctoceras*，*Dipoloceras*，*Histeroceras*，and *Hamites*.

8. Dark grey clay with abundant burrows and partly pyritic and phosphatic macrofossils （0.5 m）：Ammonoids *Anahoplites*，*Semenovites*，*Birostrina*，*Diploceras* and belemnites.

7. Light grey clay with small burrows （0.7 m）.

6. Dark grey clay with burrows （0.3 m）：*Birostrina*，ammonoids *Anahoplites*，*Dimorphohoplites*，*Euhoplites*，*Hamites*.

5. Phosphatic bed （P4） with small nodules （0.03 m）：Ammonoids *Birostrina*，*Anahoplites*，*Dimorphoplites*，*Euhoplites*，*Mojsisovicsia*，*Eubranoceras*，*Hamites*，and decapod crustaceans.

4. Light grey clay （0.60 m）：Ammonoids *Birostrina*，*Anahoplites*，*Dimorphoplites*，*Euhoplites*，spatangoid echinoids.

3. Black clay with scattered nodules of sedimentary barite （1.4 m）.

2. Black glauconitic clay passing up to less glauconitic clay （0.6 m）.

1. Phosphatic bed （P3） with grey or black rolled nodules and partly phosphatic macrofossils （0.05 m）：Ammonoids *Hoplites* （*Hoplites*），*Anahoplites*，*Oxytropidoceras* and *Hamites*，belemnites，bivalves，and brachiopods.

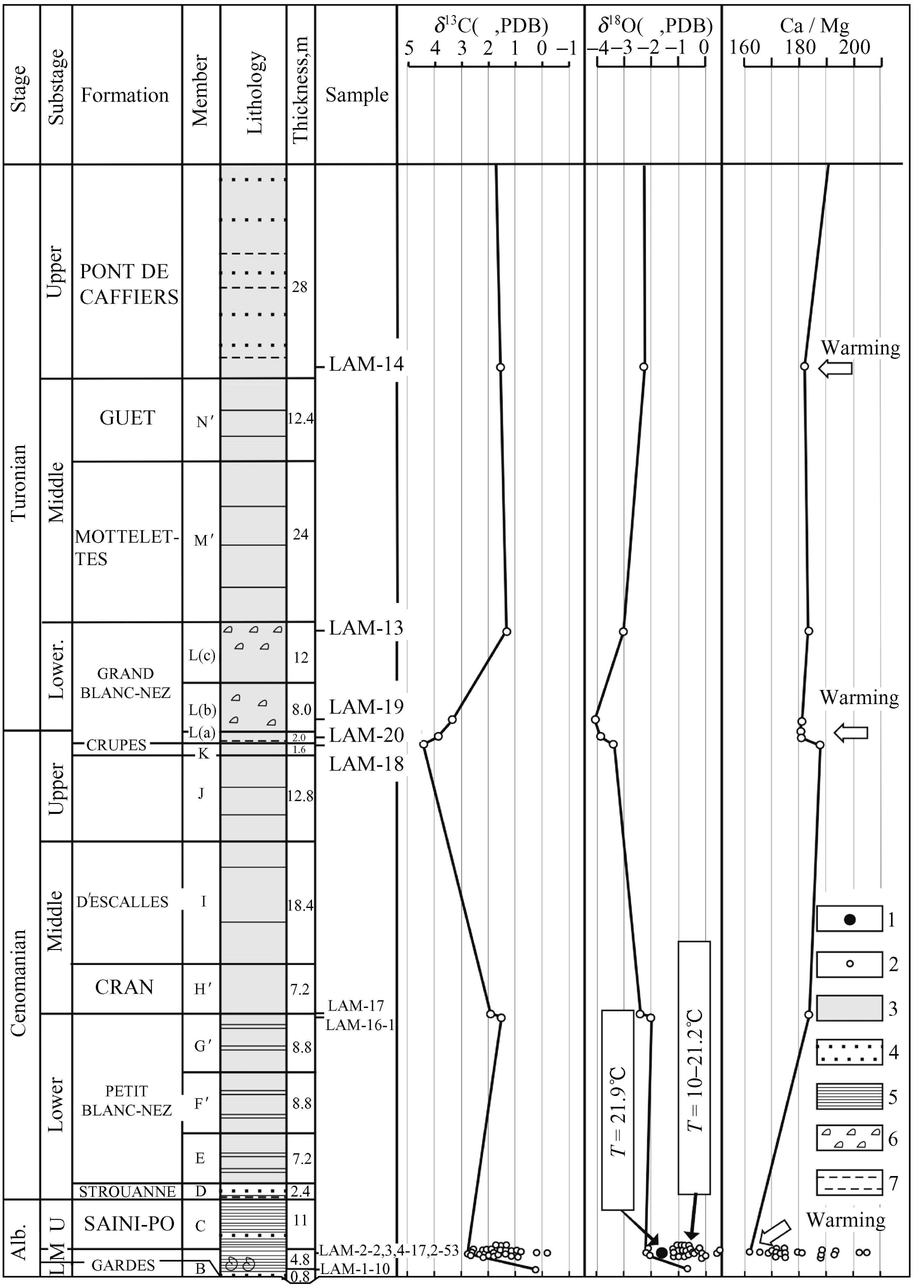

Fig. 2. $\delta^{18}O$ and $\delta^{13}C$ values and Ca/Mg ratio in the Albian-Turonian organogenic carbonates of the *Pas de Cale area*, north France. 1, ammonoid; 2, belemnite; 3, chalk; 4, sandstone; 5, mudstone; 6, nodular chalk; 7, flint level.

The middle-upper Albian *de Saint-Pô* Formation is 11.06 m thick. Many well-preserved Aptian fossils were used for isotopic analyses from two levels in the section described above.

From the lower level [middle Albian Bed 1 (phosphatic bed P3) of the *de Saint-Pô* Formation, 1 m above the top of the upper Aptian Formation *de Wissant*] only a single small belemnite rostrum (LAM-1-10, calcite 100%) was used for analyses (Fig. 1; Table 2). A single $\delta^{18}O$ value (−0.7‰), corresponding to a paleotemperature of 14.7℃, was obtained from the rostrum layer located just below the thin external lamina. The $\delta^{13}C$ value is positive (0.2‰). The external laminar layer also consists of calcite, but has α-SiO_2 trace. Some other belemnite rostra, hoplitid ammonoid and bivalve shells associated with the investigated belemnites are recrystalized (consist of fluorapatite and apatite, a small portion of calcite and α-SiO_2 trace).

From the upper level (upper middle Albian Bed

10 of the de Saint-Pô Formation, at 3.2 m above its base, just below phosphatic bed P5) 14 well preserved belemnite rostra (LAM-2-2 to LAM-2-33) calcite 100%, some with α-SiO_2 apatite traces), a single ammonoid *Oxytropidoceras* sp. shell (LAM-2-19, living chamber, 86% aragonite and α-SiO_2 trace), and a single well-preserved light cream scaphopod *Dentalium* sp. shell (LAM-20-2) were investigated. The most detailed information on ontogenetic fluctuation in isotopic composition was obtained from two belemnite rostra on the basis of samples Lam-2-2,3,4,5,6,7,8,9 and Lam-2-2-21 to Lam-2-2-29 (Fig. 3; Table 4).

Table 4. Carbon and oxygen isotope analyses of aragonitic ammonoid and calcitic brachiopod shells and belemnite rostra belemnite rostra from the Jurassic of Europe

Sample (collector)	Species	Stage, substage (Zone)	Locality	Location	Diagenetic alteration				$\delta^{13}C$ (PDB) (‰)	$\delta^{18}O$ (PDB) (‰)	*T* (℃)
					Aragonite (%)	Original calcite (%)	α-SiO_2 (%)	Colour			
889-1-1 (Y.L. Bolotsky)	*Kepplerites goweri-anus* Sowerby	Middle lower Callovian, (*Cadoceras elathmae*)	Kursk Magnetic Anomaly, Mikhailovsky Mine, Russian Platform	H=14 mm	100	—	Trace	Silvery-white, ream	1,1	−0.6	18.1
889-1-3	Same shell	Middle lower Callovian, (*Cadoceras elathmae*)	Kursk Magnetic Anomaly, Mikhailovsky Mine, Russian Platform	H=16 mm	100	0	—	Silvery-white, ream	1,4	−0.4	17.2
889-1-3б	Same shell	Middle lower Callovian, (*Cadoceras elathmae*)	Kursk Magnetic Anomaly, Mikhailovsky Mine, Russian Platform	H=16 mm	100	—	—	Silvery-white, ream	1,2	−0.4	17.2
889-1-4 (Y.L. Bolotsky)	*Cadoceras elathmae* Nikitin	Middle-lower Callovian Black Clay	Ivanovsk area, Kineshma region, Volga River, right-bank, at 1 km upper of the Village of Navoloki, Russian Platform	H=25 mm	95±4	—	0	Cream	0,0	0.4	13.3
889-1-10	Same shell	Middle-lower Callovian Black Clay	Ivanovsk area, Kineshma region, Volga River, right-bank, at 1 km upper of the Village of Navoloki, Russian Platform	H=25 mm (another side)	~100	—	Trace	Cream	2.1	−1.2	20.7
889-1-11 (Y.L. Bolotsky)	*Cadoceras* sp.	Middle-lower Callovian Black Clay	Ivanovsk area, Kineshma region, Volga River, right-bank, at 1 km upper of the Village of Navoloki, Russian Platform	W=75 mm	~100	—	Trace	Cream	3.2	−0.5	17.6
889-1-9 (Y.L. Bolotsky)	Ростр белемнита	Middle-lower Callovian Black Clay	Ivanovsk area, Kineshma region, Volga River, right-bank, at 1 km upper of the Village of Navoloki, Russian Platform	D=2.8 mm	0	100	—	White	1.3	0.0	11.9
889-1-6a (Y.L. Bolotsky)	*Praecyclothyris badensis* (Oppel)	Middle-lower Callovian Black Clay	Ivanovsk area, Kineshma region, Volga River, right-bank, at 1 km upper of the Village of Navoloki, Russian Platform	L=23 mm	0	100	—	Silvery-white	1.0	−1.2	16.7
889-1-6	Same shell	Middle-lower Callovian Black Clay	Ivanovsk area, Kineshma region, Volga River, right-bank, at 1 km upper of the Village of Navoloki, Russian Platform	L=23 mm	0	100	—	Silvery-white	1.8	0.6	9.8
EN-3 (Y. Shigeta)	*Tragophylloceras loscombi* (Sowerby)	Lower Pliensbachian (*Tragophyl-loceras ibex* Zone)	England	D=46 mm	95±3	—	—	White-cream	0.5	−1.5	23.1

(To be continued)

Continued

Sample (collector)	Species	Stage, substage (Zone)	Locality	Location	Diagenetic alteration				$\delta^{13}C$ (PDB) (‰)	$\delta^{18}O$ (PDB) (‰)	T (℃)
					Aragonite (%)	Original calcite (%)	α-SiO_2 (%)	Colour			
895-1 (A. M. Panichev)	Belemnite rostrum (in association with ammonoid *Strajevskia* sp.)	Middle Volzhsky Stage	Subpolar Urals, Yatria River, at 1 km lower the Sartynya River mouth (Ayapin River basin, Saranpul area)	D=24 mm	—	100	—	—	0.2	−1.2	16.8
EN-4a (Y. Shigeta)	*Kossmoceras* sp.	Lower middle Callovian	England	H=11 mm	78±5	—	—	White	0.1	−3.2	29.4
EN-5a (Y. Shigeta)	*Aegoceras* sp.	Lower Pliensbachian	England	H=8 mm	73±3	—	—	White	0.6	−2.0	24.2
PL-1 (Y. Shigeta)	*Quenstedtoceras* sp.	Upper Callovian	Poland	H=10 mm	98±2	—	—	Cream	−0.1	−0.4	17.2
RZ-1 (Y. Shigeta)	*Kossmoceras aculcatum* Michailow	Upper Callovian	Ryazan, Russian Platform	H=15 mm	100	—	—	Silvery-white	3.3	−1.3	21.0
WG-1 (Y. Shigeta)	*Pleuroceras costatus* Reinecke	Upper Pliensbachian	Germany	H=11 mm	98±2	—	—	White-cream	−0.3	−1.2	20.7

H, height; W, width; L, length; D, diameter.

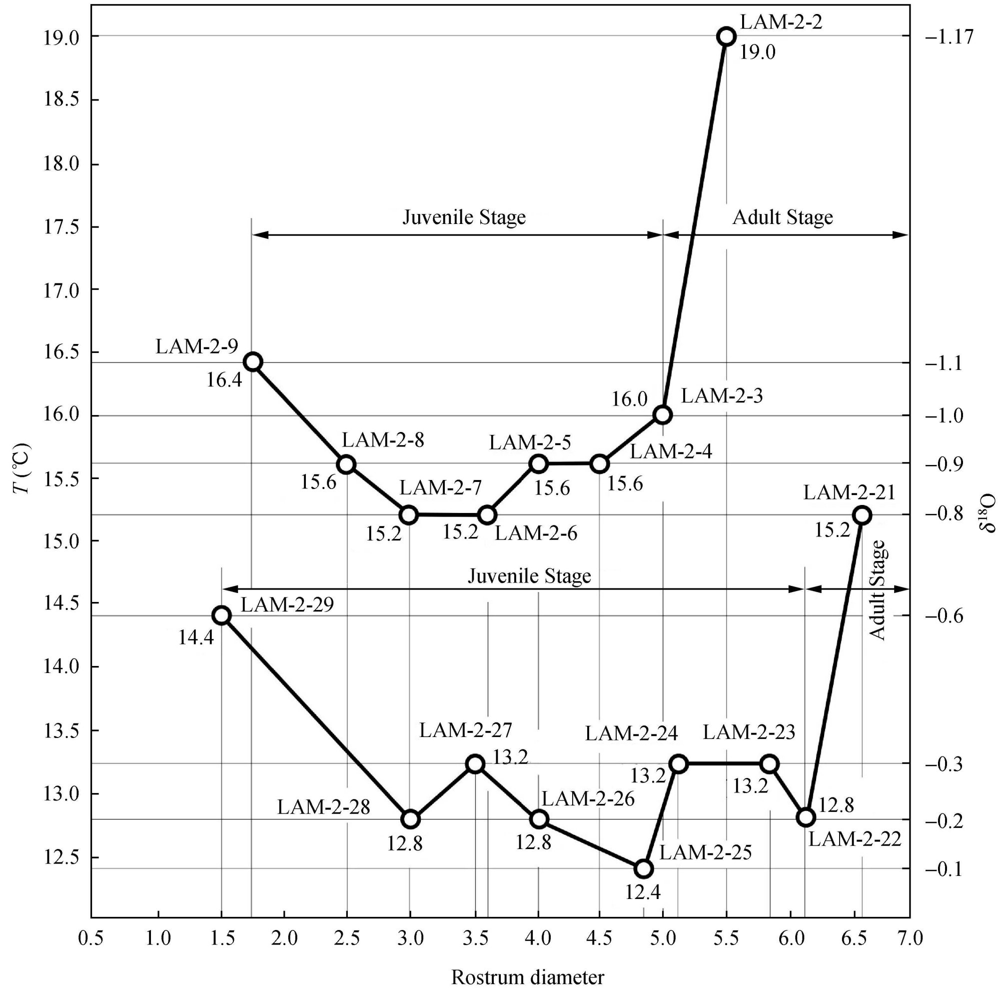

Fig. 3. $\delta^{18}O$ value fluctuation based on analysis of the two Albian belemnite rostra from the Bed LAM-2 of the *Saint-Pô* Formation; Blanc Nez, north France.

δ^{18}O and δ^{13}C values in the belemnite rostrum from the lower level are − 0. 7‰ (14. 7℃) and 0.2‰, respectively. δ^{18}O values in the belemnite rostra from the upper level fluctuate from −2.2℃ to 0.5‰ ($T = 10.1$—21.2℃；Table 2)；δ^{13}C values range from − 0. 2‰ to 2. 7‰；Ca/Mg ratios in belemnite rostra fluctuate between 161 and 207 (Fig. 2). A single δ^{18}O value (−1.5‰), corresponding to a paleotemperature of 21. 9℃ is comparable with temperature maximum obtained from belemnite.

2.5.4 Normandy (north France) Only two Albian ammonoid species from Normandy were investigated： middle Albian *Otohoplites raulinianus* (Orb.) (FR-1, 100% aragonite, with α-SiO_2 trace) and Late Albian *Beudanticeras beudanti* (Bron.) (FR-2, 100% aragonite). Their δ^{18}O values are −1.4‰ and − 0. 9‰, corresponding to paleotemperatures of 21. 6 and 19. 3℃, respectively；δ^{13}C values are 1.2‰ and − 1. 1‰, correspondingly (Fig. 4；Table 3).

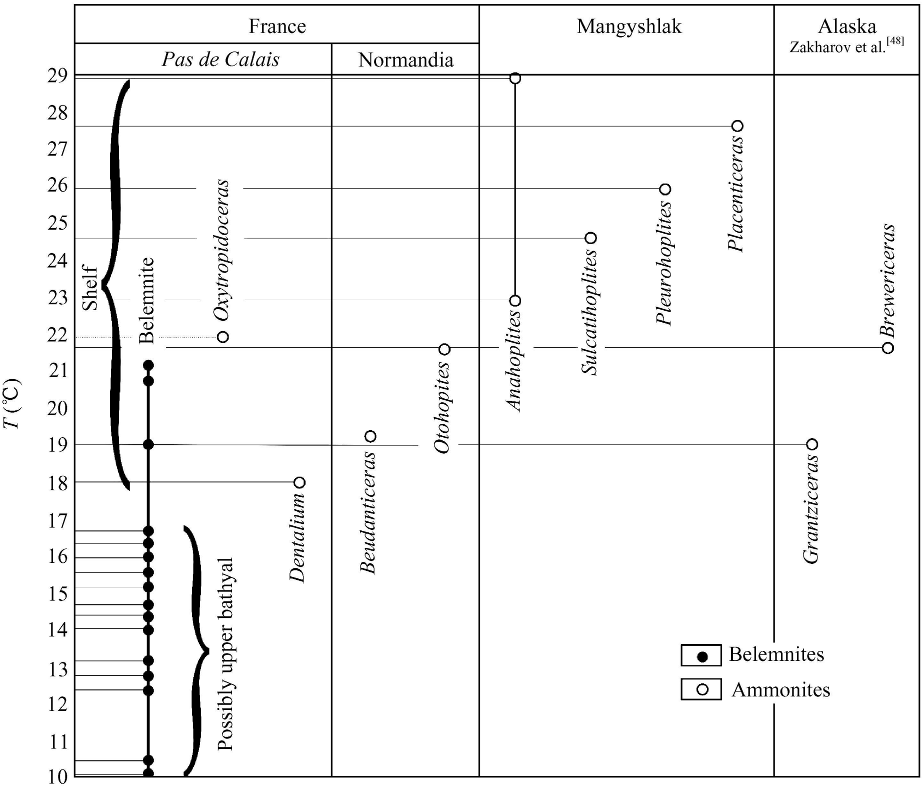

Fig. 4. Comparative growth temperatures for Albian belemnites and ammonites from samples in Europe, Middle Asia and North America.

3 Discussion

3.1 Jurassic

According to paleobotanical data[18], the climate cooled gradually just after the Late Triassic, and a minimum was reached in the Pliensbachian. This was followed by the Toarcian climatic optimum, then the late Toarcian cooling. The second climatic optimum occurred at the beginning of the Late Jurassic (Oxfordian)[18,19] after which warm conditions persisted for a long time. The next cooling, in Vakhrameev's opinion[18], began only in the earliest Berriasian. Published data on isotopic thermometry[10,20—31] and our new data on isotopic composition of some Early, Middle and Late Jurassic mollusc and brachiopod shells of the Russian Platform, Poland, Germany and England support Vakhrameev's idea[18] based on palaeobotany.

3.1.1 Early Jurassic The new data indicate a drop in the temperature from the early to late Pliensbachian. The isotopic composition of the ammonoids *Aegoceras* sp. and *Tragophylloceras loscombi* (Sowerby) from the lower Pliensbachian of England and *Pleuroceras costatus* Reinecke from the upper Pliensbachian of Germany shows paleotemperatures of 24.2, 23.1 and 20.7℃, respectively；Table 1).

Using belemnites from southern Germany,

Fritz[32] obtained paleotemperatures for the succeeding Early Sinemurian of 21.1—26.9℃，for the late Sinemurian of 16.7—26.4℃，for the early Pliensbachian of 21.2—22.6℃ and for the early Toarcian of 20.0—22.6℃. Comparatively high isotopic paleotemperature values（27—28℃）were also calculated for the Toarcian of western Europe by Pearson[22].

Our new isotopic data from the ammonoids *Aegoceras* sp.，*Tragophylloceras loscombi*（Sowerby）and *Pleuroceras costatus* Reinecke show a drop in temperature from the early Pliensbachian of England（23.1 to 24.2℃）to the late Pliensbachian of Germany（20.7℃）.

3.1.2 Middle Jurassic During the late Bajocian-Bathonian paleotempratures in the western Europe dropped to 13.2—18.1℃，but higher paleotemperatures are known from the Bajocian of eastern Greenland（19.1—20.3℃）and South America（19.7—28.6℃，middle Bajocian）；paleotemperatures of 15.9℃ were calculated for the Middle Jurassic of Alaska[33].

Besides the Toarcian and Oxfordian（or Kimmeridgian-Oxfordian）climatic optima，determined by paleobotanical data and confirmed by the isotopical method[22,25,26,29,31,34,35]，a middle Callovian warming event has been suggested[10] and this is confirmed by our data：isotopic composition of the ammonoid *Kossmoceras* sp. from the lower part of the English middle Callovian shows a paleotemperature of 29.4℃（Table 1）. However，middle Callovian paleotemperatures obtained from belemnites of the Russian Platform[21,26]，Urals and Kazakhstan[21] are lower（10.3—18.4℃）.

We also obtained lower paleotemperatures for lower Callovian and lower-middle Callovian boundary beds of the Russian Platform via the early Callovian ammonoid *Kepplerites gowerianus* Sowerby from the Mikhailovsky Mine（17.2—18.1℃），the middle early Callovian ammonoids *Cadoceras elathmae* Nikitin and *Cadoceras* sp.（13.3—20.7℃），the middle early Callovian belemnite rostrum（11.9℃），and the brachiopod *Praecyclothyris badensis*（Oppel）（9.8—16.7℃）from lower-middle Callovian boundary beds of the Kineshma area. Results obtained are similar to Early Callovian paleotemperatures estimated from isotopic data on belemnites from Poland（14.5—20.8℃）and Pechera River Basin，Russia（16.7—19.7℃）[21].

According to our new data late Callovian ammonoids from Europe also show moderate paleotemperatures：17.2℃（from *Quenstedtoceras* sp.，Poland），21.0℃（from *Kossmoceras aculatum* Michailow，Russian Platform），comparable with the maximaumtemperature value（19.4℃）obtained from Late Callovian belemnites in Poland and the Ryazan area[21].

3.1.2 Late Jurassic Bowen[35,36] provided isotopic evidence for an Oxfordian climatic optimum（24.4—26.7℃）from data obtained in Switzerland，England，and north Caucasus，which was supported recently by new isotopic data on aragonitic ammonoid（*Kossmoceras*）shells（16—28℃），calcitic belemnite rostra（10.6—19.0℃），aragonitic and calcitic bivalve shells（15.8—16.9℃），and phosphatic vertebrate teeth and other skeletal elements（20—29℃）from the Peterborough Member of the Oxford Clay，England[24]. Oxfordian belemnites of the Russian Platform also yielded paleotemperature values of 7—18℃[27,37].

Kimmeridge-Tithonian paleotemperatures（13.6—16℃）for shallow marine basins of low and middle paleolatitudes calculated from belemnites of the Ammonitico Rosso Formation of Mallorca[25] seem to be unrealistically low，taking into account the higher paleotemperatures（20.4 and 14.8—27.2℃，respectively）obtained from brachiopod shells and aptychi from the same locality[2]. We calculated a paleotemperature of 16.8℃ for a belemnite rostrum from the late Tithonian *Strajevskia* Beds of the Yatria River Basin，Subpolar Urals at a significantly higher paleolatitude（about 50—55°N）.

Judging from the mean annual isotopic paleotemperatures for the near-polar Timan-Pechera area[21,31]，Falkland Plateau[25] and New Zealand[26]，comparatively high paleotemperatures were also experienced in the Kimmeridgian and in the beginning of the Tithonian. This agrees with data from the Russian Platform.[27,38]

Late Jurassic subpolar regions experienced temperatures of 17.58—23.27℃（Early Kimmeridgian），17.89—22.28℃（Late Kimmeridgian），and 17.98—22.05℃（Early Volgian）[21,31]. However，paleotemperatures obtained from Early Kimmeridgian and Volgian belemnite rostra of the Sosva River of the Subpolar Urals were substantially cooler（10.1—12.2℃）[2,37]. Palaeotemperatures of about 17℃

were obtained for the Kimmeridgian and Volgian of the Russian Platform[27]. Oxfordian-early Kimmeridgian and middle Oxfordian-early Kimmeridgian palaeotemperatures of the Falkland Plateau (ODP Sites 330 and 511) were calculated as 15.77—18.97℃ and 15.99—19.74℃, respectively[25]. A slightly higher value was calculated for the Kimmeridgian of New Zealand (18℃)[26] and a slightly lower value (14.7℃)[39].

Gröcke et al.[29] interpreted a warming through the Oxfordian-Kimmeridgian, cooler paleotemperatures within the Tithonian and gradual warming across the Jurassic-Cretaceous boundary. They considered that the large variability seen in the $\delta^{18}O$ values in Oxfordian and Kimmeridgian belemnites from New Zealand was a consequence of localized variations in the isotopic composition of the seawater resulting from a reduction in ice and/or snow-sheet volume and associated increased runoff[29,41]. For the middle Tithonian of New Zealand Gröcke et al.[29] calculated a low paleotemperature value (~11℃) comparable with Tithonian-Valanginian paleotemperatures (5—10℃) obtained from high-latitude belemnites of Spitsbergen[41] and James Ross Island[39].

Paleotemperature data for the Latest Jurassic is incomplete and contradictory. In particular, the results of Gröcke et al.[29], Ditchfield[41] and Ditchfield et al.[39] show palaeotemperatures fluctuating from 12.0 to 24.6℃, and do not agree with isotopic data from Greenland, Spain, the Russian Platform, North Siberia, south Urals (Orenburg area), and Kazakhstan[2,20,21,27,29]. Kimmeridgian-Tithonian paleotemperatures (13.6—16℃) for low-middle paleolatitudes obtained from belemnites of the *Ammonitico Rosso* Formation of Mallorca (Balearic Islands)[25] seem to be underestimated, considering that higher paleotemperatures (20.4 and 14.8—27.2℃) were obtained from the isotopic composition of brachiopod shells and aptyhus from the same formation[2]. We calculated a late Tithonian paleotemperature of 16.8℃ for significantly higher paleolatitude shells (50—55℃) of the Northern Hemisphere (Yatria River Basin, subpolar Urals).

3.2 Neocomian

Data on Neocomian isotopic paleotemperatures are restricted to near-equatorial regions of the Pacific[42—44], England[45], Spitsbergen[41], subpolar Urals[21,46], north Siberia[21,23,33,47] and high latitudes of the Russian Far East[48].

Paleotemperatures calculated from the isotopic composition of belemnites from upper Volgian and lowermost Ryazanian stages (lower Berriasian) of the subpolar Urals are 11.8—14.9℃[46]. For the Late Berriasian of north Siberia (Boyarka River and Anabar River Basin) relatively high paleotemperatures (not lower than 18.1—23.6℃) have been obtained and these significantly differ from early Berriasian temperatures of the same region, Boyarka River (11.8—14.9℃)[21].

Paleotemperatures obtained from early Valanginian and earliest Hauterivian belemnites of England are relatively cool: *c*. 12—15℃ and >9℃, respectively[45], and perhaps even cooler from late Valanginian-early Hauterivian belemnites of the subpolar Urals (2—14℃)[46]. Paleotemperatures calculated from the isotopic composition of numerous belemnites from the early-middle Volgian of Spitsbergen are also cool, not higher than 10.9℃[41]; but the coolest Cretaceous isotopic paleotemperatures fluctuated from −1 to 5℃ were recorded from Valanginian belemnites of Australia[49].

Paleotemperatures calculated from the isotopic composition of early Hauterivian inoceramid prismatic layers from Penzhinskaya Guba are significantly higher (21.0—21.3℃), as are those derived from the Middle Barremian bivalve *Aucellina* sp. of the same region (24.5℃)[48]. Relatively high isotopic paleotemperatures (16.2—20.9℃) were also obtained for the early Hauterivian of the subpolar Urals[21]. Tropical surface water temperatures during the coldest interval of the Neocomian (Valanginian) seem to be consistently high (not lower than 25℃)[44].

The paleobotanical data[50,51] recorded the domination of cycadophytes in both the Matijsky (Okhotsk-Chukotka area) and the Solonijsky (Bureya River Basin) floristic assemblages; and the palynological data[52] indicated a reduction of *Classopolis* in the Valanginian of the Russian Far East. It is assumed that the climatic optimum at the very beginning of the Neocomian was followed by cooling during the Valanginian. Data from the Ozhoginsky floristic assemblage of north-east Asia[53] and the Chemchukinsky assemblage of the Bureya River Basin[51], together with data from nannoplakton of the Barents Sea[54] favour interpretation of warm humid climates in north Eurasia during the Hauterivian-Barremian, with the possible exception at the beginning of the middle Hauterivian.

Fossil plant indicators (*Nilssonia*, *Podozamites* and *Cladophlebis*) from the Berriasian Taukhe Formation of South Primorye[18,52], Barremian palynological assemblages from the Chegdamyn Formation of the Bureya Coal Basin[55], and Barremian plant remains from the Starosuchanskaya Formation of the Suchan Coal Basin in South Primorye[18,55] confirm the presence of thermophilic and hygrophilous Neocomian floras in the southern Far East. However, the palynological data on the Solonijskaya Formation of the Bureya Coal Basin characterized by the reduction of *Classopolis* demonstrates alternatively a cooling during the Valanginian[55].

One global peculiarity of the Neocomian is the lack of an equatorial humid belt, which characterizes other Cretaceous stages (Albian-Maastrichtian), and the development of a subtropical arid belt[56—58].

3.3 Aptian-Albian

Few isotopic paleotemperatures are available for Aptian shallow water marine basins. We determined unusually high paleotemperatures on the basis of isotopic analysis of well preserved ammonoids *Deshayesites dedhayesi* d'Orbigny and *Aconeceras* (*Sinzovia*) *trautscholdi* (Sinzow) from the lower Aptian (28.9—33.2℃) and *Acanthoplites* sp. and *Aconeceras* (*Sinzovia*) sp. from the upper Aptian (25.4—28.4℃) of Ulyanovsk region. These results are similar to palaeotemperatures obtained for the Aptian of France (19.2—28.0℃)[33,35,59] but somewhat higher than paleotemperatures we calculated[60] from early Aptian ammonoids *Tetragonites* sp., *Cheiloniceras* sp. and also a huge undetermined ammonite of Polkovnichya Ravine, north Caucasus (17.9—23.9℃). Marked cooling in that region (to 13.1℃) was recognized around the end of the early Aptian based on theisotopic composition of another aragonitic ammonoid (*Hypophylloceras* sp.) collected in the upper level of the same formation[60].

A well preserved bivalve *Aucellina aptiensis* (d'Orbigny) from the upper Karmalivayam Formation of the Koryak Upland provides additional evidence confirming an early Aptian climatic optimum (paleotemperatures of 18.6—25.9℃)[48].

Minimum paleotemperature values estimated from the isotopic composition of belemnite rostra[61] and benthic foraminifera[4,62] from low paleolatitudes of the Southern Hemisphere for the Early Albian are 6.1℃, and for the late Albian ~10℃. Annual average Aptian (apparently late Aptian) isotopic paleotemperatures for southern high latitudes (New Zealand) were determined by Stevens and Clayton as 15℃[40].

Maximum paleotemperature values calculated from early Albian planktic foraminifera of ODP Hole 463, equatorial Pacific, (25.2℃)[3], are noticeably lower than those obtained from late Albian planktic foraminifera of the same hole (28.2℃) and significantly lower than those determined from late Albian planktic foraminifera of Blake Nose, paleolatitude 30°N (32.5℃)[4,63,64]. In comparison, comparatively high isotopic paleotemperatures were obtained from early Albian brachiopods of the Koryak Upland (12.5—22.7℃) and late early Albian ammonoids of South Alaska (up to 21.6℃)[48], and from the outer layers of some belemnite rostra from the *Pas de Calais* area (21.2℃). Albian surface marine water paleotemperatures (15.9—17.2℃) of the Moderate-Warm Zone of the Southern Hemisphere[4,62] are comparable to those demonstrated above, although warmer paleotemperatures have been calculated for the middle-upper Albian of New Zealand (16.7—28.3℃)[40]. Judging from original isotopic results on late Albian ammonoids from Mangyshlak, near bottom water paleotemperatures of shallow marine basins in middle latitudes of the Northern hemisphere during the Late Albian were also very warm (22.9—28.9℃).

Thus, there is evidence of more or less pronounced climatic zonation in the Albian; some cooling occurred during the early Albian followed by a climatic optimum in the late Albian.

On the basis of the isotopic paleotemperatures we conclude that the tropical-subtropical climatic zone during the Albian was extended (Fig. 1). In the late Albian, and during the following Cretaceous stages, the equatorial zone was represented by a humid belt[48,56,57].

Paleobotanical evidence for the Aptian climatic optimum have been provided by many of the authors[18,51,53,55,65—68]. These evidences include a high diversity of flora from the lower part of the Severosuchanskaya Formation of the Suchan Coal Basin, South Primorye[18,55,65,69]. Chumakov[56,57] and Zakhrov et al.[48] also provided evidence of expansion of the

Aptian arid belt from paleolatitudes 30—40°N to 45°S.

Early Albian cooling is confirmed by additional paleobotanical data: reduction of cycadophytes and domination of conifers in the Topanskaya flora (northeast Russia)[53]; this trend persists into the middle Albian as evidenced by the composition of the Emanrisky (Khabarovsk area) flora[51]. The late Albian-early Cenomanian Armanskaya flora from an upland region of northeast Russia (Okhotsk-Chukotsk area) and Grebenkinskaya flora from a coastal lowland site differ from the preceding Topanskaya flora by an increase in total diversity and more specifically an increase in the diversity of cycadophytes and large-leafed platanoid angiosperms and a corresponding decrease in the role of conifers. This suggests a trend towards warmer and more humid environments during the Early-Late Cretaceous transition[5,53,70,71]. The palynological data from southern Far East[55] suggests a thermal maximum in the Aptian, followed by falling temperatures in the early Albian, with only a slight warming in the late Albian

4 The problem of vertical migrations in fossil cephalopods

It is evident that the paleotemperature calculated from a Callovian belemnite of the Russian Platform is lower than that from ammonites found in the same calcareous nodule. For the adult stage of middle-late Albian belemnites from the *Pasde-Calais* area in north France we calculate paleotemperatures of 15.2—21.2℃, but for their juvenile stage only 12.4—16.4℃. In contrast, a well-preserved ammonoid *Oxytropidoceras* sp., found together with the studied late Albian belemnite rostra yielded a palaeotemperature of 21.9℃ and the middle-late Albian ammonoids *Otohoplites raulinianus* d'Orbigny, and *Beudanticeras beudanti* Brongjart derived from Normandy provided temperatures of 19.3—21.6℃. The ammonoid data seem to agree with paleotemperatures obtained from the adult stage of belemnites (Fig. 4).

According to new evidence from Coniacian and Campanian ammonoids of the Far East (Koryak Upland, Sakhalin and Hokkaido)[72—75] and Campanian of California[76] (Fig. 5), Late Cretaceous ammonoids were living in near-bottom conditions of relatively shallow marine basins. Similar life modes appear to have characterized Jurassic and Early Cretaceous ammonoids also.

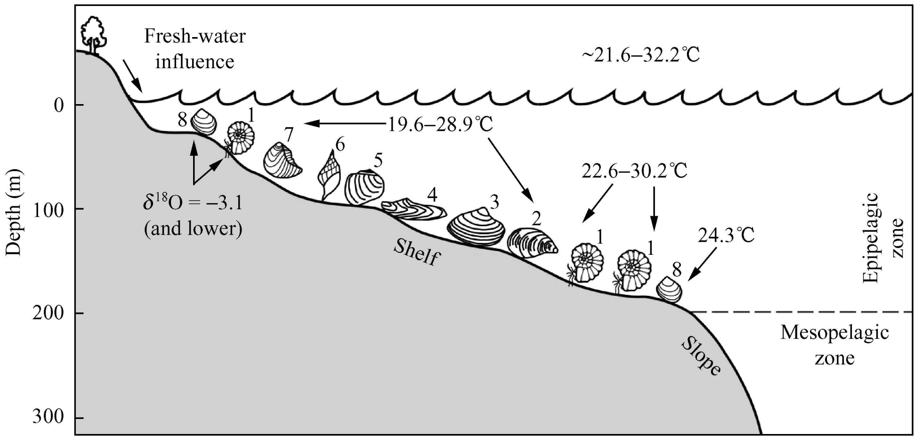

Fig. 5. Early Campanian paleotemperatures for a marine basin in California based on analysis of invertebrates. 1, ammonoid *Submartoniceras*; 2, inoceramid bivalve; 3, mactretid bivalve; 4, bakevellid bivalve; 5, gastropod *Tylostoma*; 6, gastropod *Anomalfusus*; 7, trigoniid bivalve; 8, nuculid bivalve.

New data on Jurassic and Early Cretaceous belemnites of the Russian Platform and *Pas de Calais* area (North France) suggest that, like modern *Nautilus*, most middle-late Mesozoic adult belemnites lived during their spawning in shallow waters, but at least juvenile individuals engaged in significant short-term vertical migrations in the water column, reaching colder upper bathyal waters (Fig. 6).

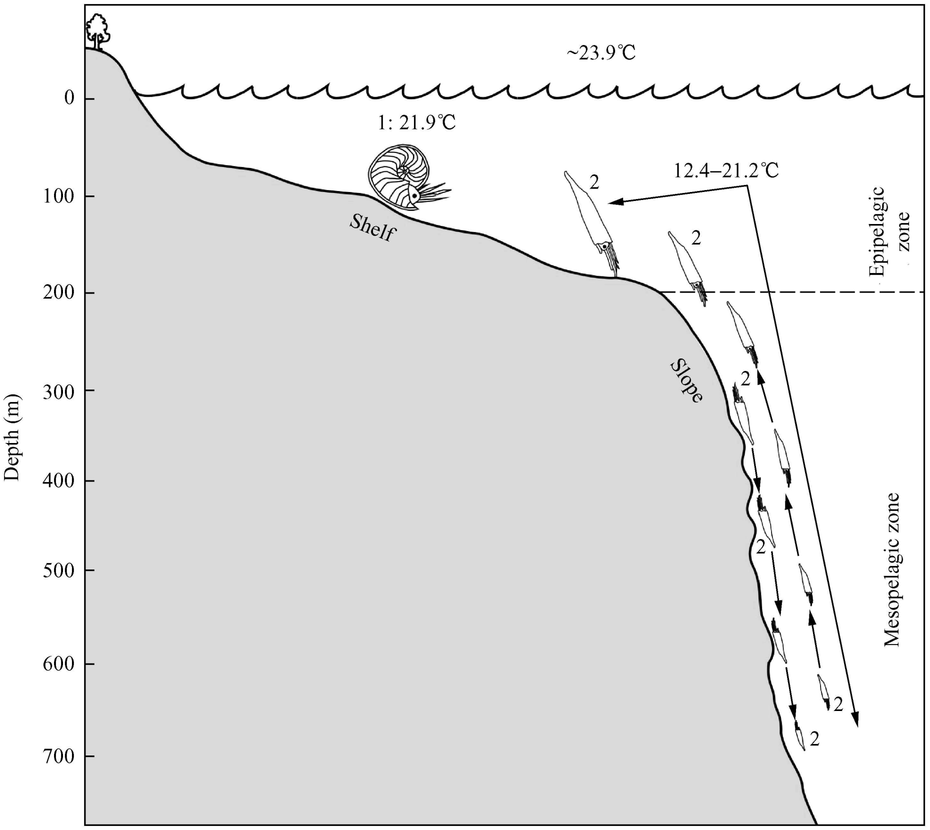

Fig. 6. Mode of life some Albian belemnites ; Blanc Nez, north France.

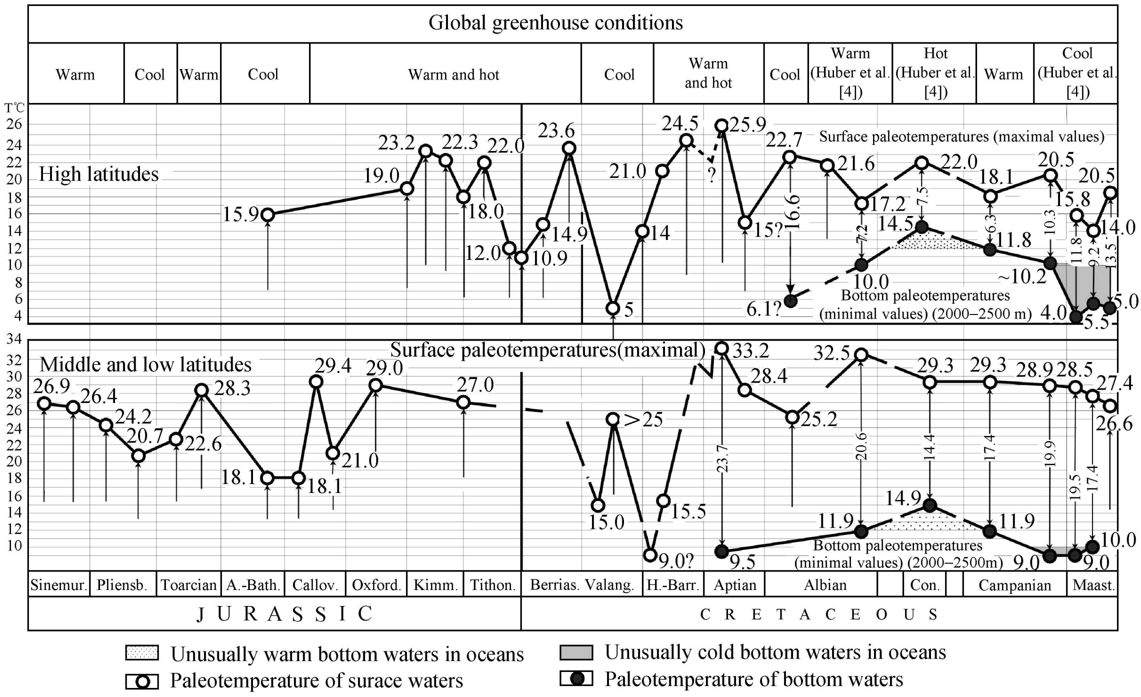

Fig. 7. Reconstruction of Jurassic-Cretaceous climatic conditions from isotopic data.

5 Conclusions

New oxygen stable isotopic data from marine invertebrate shells generally support global palaeotemperature interpretations for the middle-late Mesozoic based on previous isotopic and paleobotanical data. These data suggest the following trends in global temperature change during the middle-late Mesozoic：after possible Hettangian-Sinemurian cooling[34] about 13 temperature maxima can be recognized（Fig. 7），only three of which fall in the Jurassic-Toarcian[22]，Callovian[10] and Oxfordian[36]. At least ten temperature peaks are recorded in the Cretaceous：late Berriasian[21]， ? middle Barremian[31]， early Aptian[33,59]，late Albian[63]，late Cenomanian[48]，early Turonian[77]，Coniacian[44]，middle Santonian[78]，early Campanian[74,76]， and ? middle Maastrichtian[79]. These data show that，although both the Jurassic and Cretaceous climates were generally very warm，the Jurassic climate seemed to be somewhat less variable.

We agree with Huber et al.[4] that a pronounced greenhouse phase dominated the mid- to Late Cretaceous. Additional new evidence supplemented by previous research on the Jurassic[2,20—22,25,26,29,31,32,35—40] and Cretaceous[4,33,35,48,59,61,80] suggests the occurrence of twelve stages of global climate fluctuation during the Sinemurian to the Maastrichtian intervals，viz. Sinemurian-Early Pliesbachian warm phase；middle-late Pliensbachian cool phase；Toarcian warm phase；Aalenian ?/Bajocian-early Callovian cool phase；middle Callovian-Berriasian warm phase；Valanginian cool phase；Hauterivian-early Aptian warm/hot phase；late Aptian-early Albian warm to cool phase；late Albian-early Cenomanian warm phase；late Cenomanian-early Campanian hot phase；early Campanian-early late Campanian warm phase；and late Campanian-Maastrichtian cool phase.

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