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Seasonal temperature fluctuations in the high northern latitudes during the Cretaceous Period: isotopic evidence from Albian and Coniacian shallow-water invertebrates of the Talovka River Basin, Koryak Upland, Russian Far East

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Abstract

Palaeotemperatures during the Albian–Coniacian in the northernmost Pacific have been determined on the basis of oxygen isotopic analysis of well-preserved brachiopod and molluscan shells from the Koryak Upland, Far East Russia. Those obtained from the calcitic brachiopod shells from the Albian range from 12.5 to 22.7 °C. The lower temperature level corresponds to winter seasons and the higher reflects summer temperatures. Probable winter isotopic palaeotemperatures, fluctuating from 10.9 to about 14.1 °C, were obtained from Coniacian bivalve shells. Presumed spring and autumn isotopic palaeotemperatures for the Coniacian, fluctuating from 14.1 to 17.7 °C, were obtained from rhynchonellid brachiopods and bivalves, all with calcitic shells, and ammonoids with aragonitic shells. Presumed summer isotopic palaeotemperatures varied between 18.5 °C to 22.4 °C. The new and previously published data suggest a short-term presence of polar ice during the Cretaceous (early Maastrichtian) only in the Southern Hemisphere on the Antarctic continent. Evidence pertaining to the Northern Hemisphere seems to suggest only occasional short-lived subfreezing conditions. These most probably occurred during polar winters in the early Valanginian, late Coniacian–early Santonian and early Maastrichtian. Temperatures in northern high latitudes during the course of even these winter seasons were probably not low enough for the formation of permanent sea ice. This may be a result of the lack of a continental massif in the North Pole area and a significant ameliorating effect of oceanic heat-transport poleward through the straits of Turgai and the Western Interior of North America.

Keywords: Cretaceous; Oxygen isotopes; Carbon isotopes; Seasonal palaeotemperatures; Palaeoproductivity; Palaeosalinity; Invertebrates; Talovka; Koryak Upland

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1. Introduction

According to Price (1999), throughout the Mesozoic Era high-latitude warmth was the norm, although limited polar ice at times is not a myth but was a reality. Barerra et al. (1987) and Barerra (1994) have provided proof of rather low late Campanian–Maastrichtian water temperatures for both the Seymour Island shelf (Antarctica) (ca. 4–9 °C) and the equatorial Pacific deep-sea sites (ca. 7–14 °C) based upon isotope data on benthic foraminifera. The existence of low temperatures in southern high latitudes during the early Maastrichtian was recently confirmed by the isotopic investigation of Huber et al. (1995) of planktic foraminifera [10 °C; pH effect on foraminiferal $\delta^{18}O$ (Zeebe, 2001) not taken into account]. Similar evidence has been obtained from Maastrichtian macrofauna of James Ross Island, Antarctica (Pirrie and Marshall, 1990): 9.32–14.84 °C (from bivalves), 10.61–14.81 °C (from nautiloids), 9.93–12.35 °C (from ammonoids: *Gunnarites*), 10.17 °C (from a belemnite rostrum).

Recently Miller et al. (1999) have established the coincidence of $\delta^{18}O$ increases in both Maastrichtian deep-water benthic foraminifera of the Antarctic, South Atlantic and Indian-Pacific basins, and Maastrichtian low-latitude surface-dwelling planktic foraminifera of the Pacific, by comparison with Late Campanian foraminifera. They put forward two interpretations to account for the coincidence of these events: (1) the development of a moderate-sized ice sheet during the early Maastrichtian, and (2) a global decrease in both deep and tropical sea-surface temperatures during this period. Since the events mentioned above correlate with a large (30–40 m), rapid, earliest Maastrichtian sea-level fall, inferred from the New Jersey sequence-stratigraphic record, they incline mainly to the first interpretation, supporting a glacio-eustatic cause for the sea-level lowering.

Lowermost isotopic palaeotemperatures for Cretaceous northern high latitudes (5.3–10.4 °C) (Ditchfield, 1997) have been obtained from early Valanginian belemnite rostra of Svalbard; relatively low isotopic palaeotemperatures for the Maastrichtian (10.2–16.9 °C) have been recently obtained by us from early Maastrichtian brachiopods of the western Koryak Upland (Zakharov et al., 2000).

We focus in this paper on palaeotemperature fluctuations in high latitudes of the Northern Hemisphere during the Albian–Coniacian to distinguish lowermost (winter) temperatures for this time interval.

2. Material and methods

Macrofossil samples for isotope analyses were collected by a Russian-Japanese Geological Expedition team in 1999 from the Talovka River Basin, western Koryak Upland, northern Kamchatka (Fig. 1). During the Barremian–Paleogene this basin was at a palaeolatitude of approximately 69° N (Spicer et al., 2002). Material used for isotopic analysis consisted of: (1) brachiopod shells with fibrous structure from the Albian Kedrovskaya Formation along the Melkaya River (6 samples); (2) aragonitic and calcitic inoceramid shell material from the Cenomanian Mamet Formation of the right bank of the Talovka River (10 samples); and (3) exceptionally well-preserved shells of brachiopods, bivalves, gastropods and diverse ammonoids from the Coniacian Penzhinskaya Formation exposed along the lower reaches of the Talovka River (87 samples). Some Coniacian mollusc shells from Hokkaido, which retain original mineralogy and microstructure, were also investigated.

Zolotarev et al. (1974) and Evseev et al. (1999) recognized seasonal layers in shells of the Recent bivalves *Swiftopecten swifti* (Bernardi) and *Mizuhopecten yessoensis* (Jay) from the Sea of Japan. Only a single cycle of temperature fluctuation was discovered within each annual shell layer of *Swiftopecten swifti*, indicated on the surface of the shell by steep ridges (Fig. 2). Zolotarev et al. (1974) determined that the formation of ridges in this species is initiated by increased (fairly warm) temperatures at the beginning of the summer (12–16 °C), and that the first stage in the formation of wide bands (growth increments) occur at the maximum temperature (25.5 °C). Maximum linear growth of shells under the influence of the highest summer temperatures is about 2 mm during 1–2 weeks. Subsequent formation of annual layers in the autumn and winter takes place under the gradual lowering of temperature (to 4.5 °C). No pronounced morphological indicators, corresponding to the coldest seasons, are present on the shell surface; completion of growth of each wide band takes place in the spring.

Samples for our isotopic analyses were carefully removed from the shells using a special method. Material was taken from narrow areas along growth striations on the surface of the shell that crossed all shell layers except the innermost, covering all living chambers in ammonoids and gastropods, and the inner surface of brachiopod and bivalve valves. This enabled shell material formed during different seasons of the year to be identified.

The following were used to determine diagenetic alteration in the organogenic carbonates investigated: (1) visual signs; (2) percentage of aragonite in a structure when analyzing shells originally composed of 100% aragonite; (3) degree of integrity of microstructure, determined under a scanning electron microscope (SEM) when ammonoid aragonite was investigated, and by a preliminary luminescent test using a JXA-5A microanalyzer when calcitic brachiopod shells were examined.

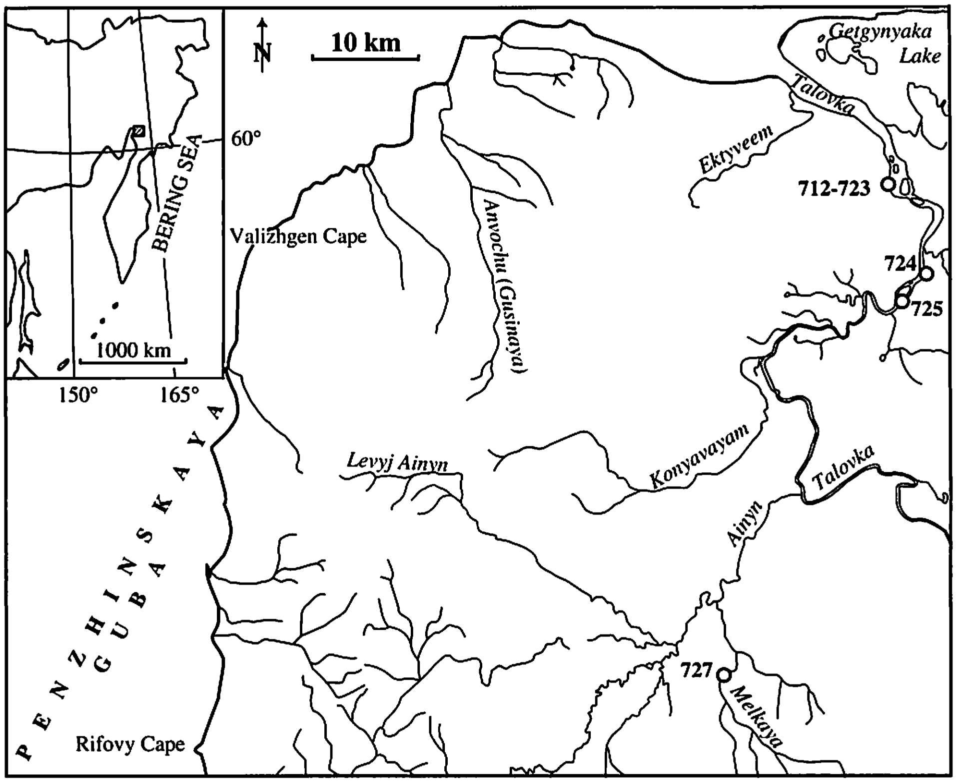

Fig. 1. Location of the Talovka River Basin, Koryak Upland. Localities: 727, Melkaya River (Kedrovskaya Formation, Albian); 725, 726, Bolshoy Vylgilveem Creek (Mamet Formation, Cenomanian); 724, Tyngyrginkuyul Creek (Mamet Formation, Cenomanian); 712, 723, lower reaches of the Talovka River (Penzhinskaya Formation, Coniacian).

Oxygen and carbon isotope measurements were made using a (German) Finnigan MAT-252 mass spectrometer at the Analytical Centre 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 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, since icecaps were not present during most of the Cretaceous Period, 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: those of Anderson and Arthur (Epstein et al., 1953; Craig and Gordon, 1965; Anderson and Arthur, 1983) for calcitic material and Grossman and Ku (1986) for aragonitic material.

X-ray analyses were carried out using a DRON-3 diffractor following the method of Davis and Hooper (1963). Ca and Mg contents in the carbonates investigated were determined using the method of complexometric titration (Berlin and Khabakov, 1966, 1968; Krasnov and Pozdnyakova, 1982; Cherbadzhi, 1984). Berlin and Khabakov (1968) made palaeotemperature determinations from belemnites using a Ca/Mg method, but it is more usual these days to cite Mg/Ca molar ratios rather than Ca/Mg ratios (Lear et al., 2002).

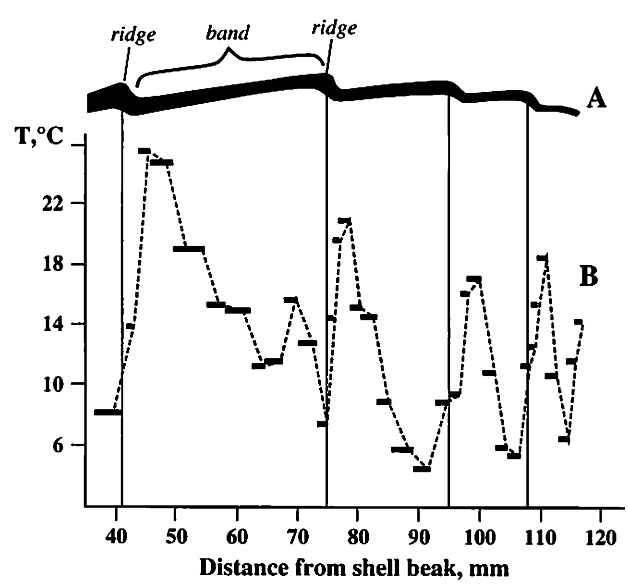

Fig. 2. Recent *Swiftopecten swifti* (Bernardi) shell from Japan sea. A, cross section. B, isotopic temperatures of growth (Zolotarev et al., 1974). Black rectangles and squares indicate the width of the areas along growth striations on shell surfaces from which material was taken for analysis.

3. $\delta^{18}O$, $\delta^{13}C$ and Mg/Ca ratios in fossils from the Koryak Upland

In the Talovka River Basin, all material for isotopic investigation was obtained from the three levels: (1) Albian, Melkaya River, a tributary of the Ainyn River; (2) Cenomanian, Bolshoy Vylgilveem and Tynogyrgin-kuyul creeks area; (3) Coniacian, lower reaches of the Talovka River.

3.1. Kedrovskaya Formation (Albian)

The ammonoid assemblage in the Kedrovskaya Formation of the Ainyn River Basin has been described in detail by Avdeiko (1968) and briefly by Alabushev (1987, 1989a,b, 1995a,b), and Alabushev and Wiedmann (1994a).

On the left bank of the Melkaya River, about 10 km above its mouth, sediments of the formation are exposed in descending order, as follows:

5. Grey siltstone with small marly boulders of irregular shape (large boulders are rare)........................12–14 m
4. Greyish green siltstone with interlayers of mudstone and abundant of large marly boulders (727-1,1a, 4; 727-2-1–13)........................5.5 m
Yields brachiopods (*Penzhinothyris plana* Smirnova), bivalves (*Inoceramus* sp.), ammonoids (*Beudanticeras* sp., *Hulenites* sp.), and plant remains (*Metasequoia* sp.).
3. Greyish green siltstone with small, noticeably scarcer large marly boulders (727-1-2)........................15 m
Contains brachiopods (*Penzhinothyris plana* Smirnova).
2. Greyish green, fine-grained, greywacke sandstone........................0.12 m
1. Greyish green siltstone with small marly boulders........................2.3 m
Yields brachiopods, gastropods, and ammonoids (*Anagaudryceras* sp., *Marshallites*? sp., *Sciponoceras* sp.) in small boulders from talus (727-1-3).
The thickness of the formation in this section is 35–37 m.

Penzhinothyris plana shells with a well-preserved fibrous structure (727-2-1, 3, 6, 8) were used for isotopic analyses. The $\delta^{18}O$ and $\delta^{13}C$ values for calcitic brachiopod samples range from −2.5 to −0.1‰ (corresponding to palaeotemperatures of 12.5–22.7 °C) and from −2.0 to −1.3‰, respectively (Table 1), and Mg/Ca ratios in the shells range from 5.25 to 5.87 mmol mol^{-1}.

3.2. Upper Mamet Formation (upper Lower Cenomanian)

The Cenomanian ammonoid fauna from the Talovka River Basin has been described by Alabushev (1987, 1995a,b) and Alabushev and Wiedmann (1994b).

3.2.1. Bolshoy Vylgilveem

At the mouth of Bolshoy Vylgilveem Creek, 29.3 km above the mouth of the Talovka River (Litvinov et al., 1999), Cenomanian sediments of the Mamet Formation are exposed (Fig. 3) as follows:

4. Dark grey siltstone with large calcareous-marly boulders (725-5)........................35 m
Yields ammonoids (*Anagaudryceras* sp., *Marshallites* sp.).
3. Greyish green, fine-grained sandstone with lenses of coquinoid calcareous sandstone and rare interlayers of dark grey siltstone (725-3; 725-4-1–3)........................5.0 m
Contains bivalves (*Inoceramus pennatulus* Pergament).
2. Moderate-sized pebble conglomerate and coquinoid calcareous sandstone with large slumped blocks of sandstone........................3.0 m
Contains bivalves (*Inoceramus* sp.).
1. Greyish green, fine-grained, cross-bedded sandstone with thin interlayers of grey siltstone and lenses of coquinoid calcareous sandstone (725-1-1, 725-2,1a)........................2.5 m
Contains bivalves (*Bairostrina concentricus costatus* Nagao and Matsumoto, *Inoceramus pennatulus* Pergament).
The total thickness of the formation in this section is 46 m.

Both aragonitic elements of *Bairostrina concentricus costatus* (725-1-1) and calcitic prismatic layers of *Inoceramus pennatulus* (725-4-2, 3) shells from members

Table 1
Carbon and oxygen isotope analyses of Albian calcitic brachiopod shells (*Penzhinothyris plana* Smirnova) from the Kedrovka Formation of Melkaya River (L, length)

Sample	Location (L in mm)	Diagenetic alteration			$\delta^{13}C$ (PDB) (‰)	$\delta^{18}O$ (PDB) (‰)	T °C
		Shell structure	Cathodo-luminescence (by 25 kV)	Colour			
727-2-1	L = 15	Well preserved fibrous	Very weak	Silvery-white	−1.6	−0.1	12.5
727-2-2	L = 38	Well preserved fibrous	Very weak	Silvery-white	−4.5	−2.5	22.7
727-2-3	L = 35	Well preserved fibrous	Very weak	Silvery-white	−2.1	−1.6	18.6
727-2-6	L = 20	Well preserved fibrous	Very weak	Silvery-white	−1.3	−1.5	18.2
727-2-8	L = 20	Well preserved fibrous	Very weak	Silvery-white	−2.0	−1.6	18.6
727-2-9-1a	L = 10 (3 shells)	Well preserved fibrous	Very weak	Silvery-white	−1.8	−1.1	16.5

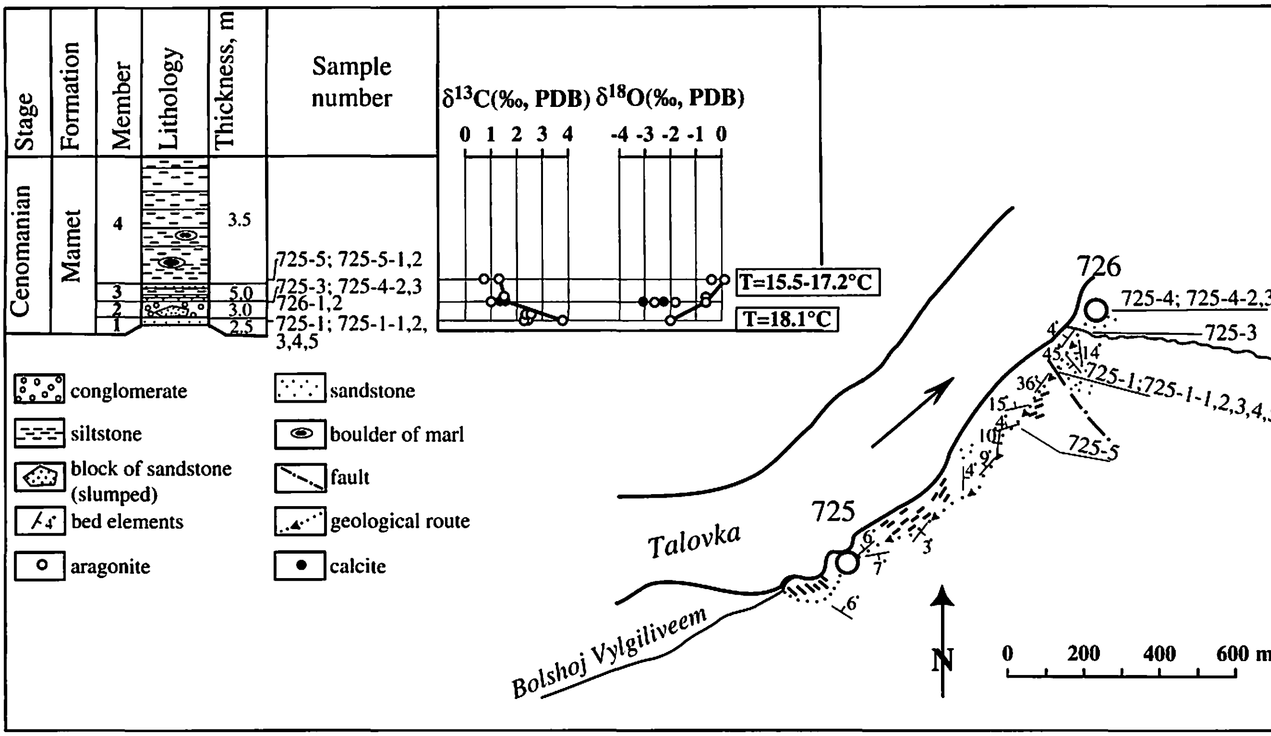

Fig. 3. $\delta^{18}O$ and $\delta^{13}C$ values in the aragonitic and calcitic elements of inoceramid shells from upper Lower Cenomanian strata of the Mamet Formation, Talovka River section (Bolshoy Vylgiliveem Creek), Koryak Upland.

1 and 3 were used for isotopic investigation. Rather low $\delta^{18}O$ values, ranging from −3.2 to −2.0‰, were derived from well-preserved *Inoceramus* when $\delta^{13}C$ values are positive (1.3–2.5‰) and aragonite content reaches 100% (Table 2). A single $\delta^{18}O$ value (−2.3‰), corresponding to a more-or-less reliable temperature (21.7 °C), was obtained from one fragment of the prismatic layer.

3.2.2. Tynogyrginkuyul

An exposure of the Mamet Formation located 25 km above the mouth of the Talovka River and 2 km above the mouth of Tynogyrginkuyul Creek (Litvinov et al., 1999) is represented by the two members (Fig. 4):

2. Dark grey siltstone with interlayers of greyish green sandstone containing prismatic inoceramid bivalve fragments .... 10 m
1. Greyish green, fine-grained sandstone with interlayers of sandy siltstone, and lenses and boulders of coquinoid calcareous sandstone (734-14, 15)7 .... 25.0 m
Yields bivalves (*Bairostrina concentricus costatus* Nagao and Matsumoto, *Inoceramus pennatulus* Pergament, *Nannonavis* sp.) and ammonoids [*Desmoceras* (*Pseudouhligella*) japonicum (Yabe), *Hypophylloceras* sp., *Marshallites* sp., *Puzosia*? sp.].

As for the previous section, the aragonitic *Bairostrina concentricus costatus* shells examined (724-10, 15; 724-12-4, 6) are characterized by rather low $\delta^{18}O$ values, fluctuating from −2.9 to −1.7‰, in spite of their high aragonite content (87–100%) and mainly positive $\delta^{13}C$ values (up to 2.8‰) (Table 2). Low $\delta^{18}O$ values (−3.0 and −3.1‰) were also encountered in calcite of fragments of prismatic layers from inoceramid bivalves; values of $\delta^{13}C$ vary between 0.3 and 1.1‰. Isotopic data on the aragonitic (95 ± 5%) ammonoid *Desmoceras* (*Pseudouhligella*) *japonicum* shell, however, show unusually high $\delta^{18}O$ values, changing from −0.9 to −0.1‰) and corresponding to palaeotemperatures of 15.9–17.7 °C. The Mg/Ca ratio in calcitic prismatic layer of an *Inoceramus* shell is 5.90 mmol mol^{-1}.

3.3. Upper Penzhinskaya Formation (Coniacian)

Cretaceous ammonoids (including *Eorhaeboceras*, *Hypophylloceras*, *Yokoyamaoceras*, *Yezoites*) and inoceramid bivalves (*Sphenoceramus naumanni* Yokoyama) from the lower reaches of the Talovka River were first investigated by Pokhialainen (1985), Alabushev and Alabusheva (Alabushev and Alabusheva, 1988; Alabushev, 1989a; Alabushev and Wiedmann, 1994a,b). They used E.S. Alekseev's collection (locality 152) and their own collections (locality 20) for this purpose. Inoceramid bivalves found here usually range through Coniacian–Campanian deposits in the Far East (Pokhialainen, 1985). They discussed the Santonian–Campanian strata exposed in the lower course of the Talovka River on the basis of ammonoid data (Alabushev and Alabusheva, 1988; Alabushev and Wiedmann, 1994c).

Table 2
Carbon and oxygen isotope composition of Cenomanian aragonitic and calcitic mollusc shells (ammonoid and inoceramid bivalves) from the Mamet Formation of the Talovka River

Sample	Species	Locality (Creek)	Location (H and L in mm)	Diagenetic alteration				$\delta^{13}C$ (PDB) (‰)	$\delta^{18}O$ (PDB) (‰)	"T" °C	T °C
				Aragonite (%)	Primary calcite (%)	Admixture	Colour				
724-1-1	*Desmoceras* (*Pseudouhligella*) *japonicum* (Yabe)	Tynogyrginkuyul	H = 25	98 ± 2	0	–	Silvery-white	−0.2	−0.3	–	16.8
724-1-3	Same shell	Tynogyrginkuyul	H = 20	100	0	–	Silvery-white	−0.1	−0.5	–	17.7
724-1-4	Same shell	Tynogyrginkuyul	H = 19	100	0	–	Silvery-white	−0.9	−0.1	–	15.9
724-1-5	Same shell	Tynogyrginkuyul	H = 13	95 ± 5	0	–	Silvery-white	−0.9	−0.3	–	16.8
724-2-1	*Bairostrina concentricus costatus* Nagao and Matsumoto	Tynogyrginkuyul	H = 25	100	0	Ceolite (trace)	Silvery-white	4.2	−1.0	–	19.8
724-2-2	Same shell	Tynogyrginkuyul	H = 35	97 ± 3	0	Ceolite (trace)	Silvery-white	4.0	−1.6	–	22.4
724-3-3	*Inoceramus pennatulus* Pergament	Tynogyrginkuyul	H = 20	100	0	–	Cream	2.9	−0.5		17.7
724-5	*Bairostrina concentricus costatus*	Tynogyrginkuyul	H = 22	100	0	–	Silvery-cream	3.3	−0.8	–	19.0
724-7	*Bairostrina concentricus costatus*	Tynogyrginkuyul	H = 43	97 ± 3	0	–	Cream	3.8	−0.7	–	18.5
724-9	*Bairostrina concentricus costatus*	Tynogyrginkuyul	H = 25	90 ± 3	0	–	Cream	−1.6	−2.5	26.4	–
724-1	*Inoceramus* sp.	Tynogyrginkuyul	Prismatic layers	0	100	–	White	0.3	−3.1	25.4	–
724-10	*Bairostrina concentricus costatus*	Tynogyrginkuyul	H = 30	~100	0	–	Cream	−0.3	−1.7	22.9	–
724-12-1	*Bairostrina concentricus costatus*	Tynogyrginkuyul	H = 20	93 ± 3	0	Lamellar silicates (trace)	Silvery-cream	2.8	−1.8	23.3	–
724-12-4	*Bairostrina concentricus costatus*	Tynogyrginkuyul	H = 30	~100	0	–	White	2.8	−2.1	24.6	–
724-12-5	*Bairostrina concentricus costatus*	Tynogyrginkuyul	Prismatic layers	0	100	–	White	1.1	−3.0	25.0	–
724-12-6	*Bairostrina concentricus costatus*	Tynogyrginkuyul	H = 20	87 ± 3	0	–	Cream	0.1	−2.4	25.9	–
724-15	*Bairostrina concentricus costatus*	Tynogyrginkuyul	H = 16	96 ± 3	0	–	Light cream	0.3	−2.9	28.1	–
725-1	*Bairostrina concentricus costatus*	Bolshoi Vylgilveem	H = 30	93 ± 5	0		Silvery-cream	3.8	−2.1	24.6	–
725-1-1	*Bairostrina concentricus costatus*	Bolshoi Vylgilveem	H = 30	100	0		Light cream	2.5	−2.0	24.2	–
725-1-2	*Inoceramus pennatulus* Pergament	Bolshoi Vylgilveem	H = 30	100	0	–	Light cream	1.2	−21.2	25.1	–
725-1-3	Same shell	Bolshoi Vylgilveem	H = 124	100	0	–	Light cream	2.6	−1.5	–	22.0
725-1-4	Same shell	Bolshoi Vylgilveem	H = 157	100	0	–	Light cream	2.3	−0.6	–	18.1
725-1-5	Same shell	Bolshoi Vylgilveem	H = 188	100	0	–	Light cream	2.4	−0.6	–	18.1
725-4-2	*Inoceramus pennatulus*	Bolshoi Vylgilveem	Prismatic layers	0	100	–	White	1.3	−3.2	25.9	–
725-4-3	*Inoceramus pennatulus*	Bolshoi Vylgilveem	Prismatic layers	0	100	–	White	1.6	−2.3	–	21.7
725-5-1	*Anagaudyceras* sp.	Bolshoi Vylgilveem	H = 30	97 ± 3	0	α-SiO_2	Cream	1.3	0.1	–	15.1
725-5-2	Same shell	Bolshoi Vylgilveem	H = 13	98 ± 3	0	–	Cream	0.7	−0.4	–	17.2
726-1	*Inoceramus pennatulus*	Bolshoi Vylgilveem	H = 30	88 ± 5	0	Ceolite (little)	Light cream	1.0	−2.6	26.8	–
726-2	*Inoceramus pennatulus*	Bolshoi Vylgilveem	H = 25	100	0	$CaSO_4$ H_2O (trace)	Cream	1.5	−1.8	23.3	–

High $\delta^{18}O$ values might have been caused by freshening influence (H, height).

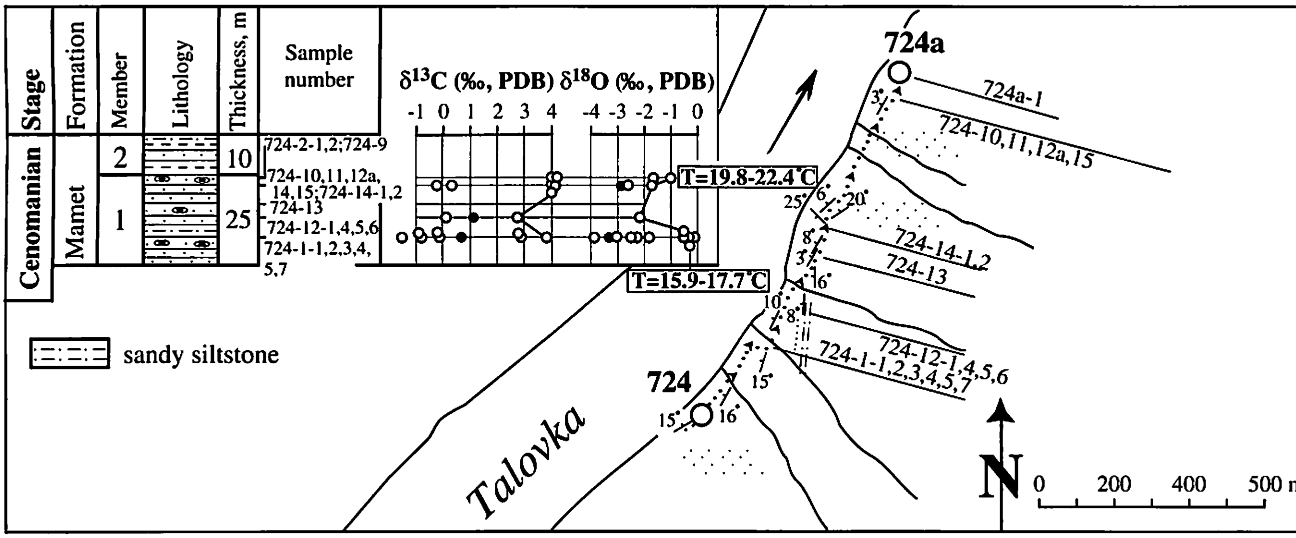

Fig. 4. $\delta^{18}O$ and $\delta^{13}C$ values for the aragonitic ammonoid *Desmoceras* (*Pseudouhligella*) *japonicum* (Yabe) and the aragonitic and calcitic elements of inoceramid shells from upper Lower Cenomanian strata of the Mamet Formation, Talovka River section (Vylgilveem Creek area), Koryak Upland. For key to lithologies, see Fig. 3.

The upper beds of the section in this area that we investigated, locality 719, are exposed about 12 km south-east of the mouth of the Talovka River; its lower beds (locality 723) are situated about 7 km to the north (west of the large islet near the sharp bend in the river). South of the locality, Cretaceous exposures are absent; therefore, we believe that the outcrops we have studied correspond to those of Alekseev and Alabushev.

Our re-examination of the mollusc assemblages mentioned above showed that the fauna of *Kossmaticeras japonicum* Matsumoto, *Mesopuzosia yubarensis* (Jimbo), micro- and macroconchs of *Yezoites pseudoaequalis* (Yabe) [microconch previously described as *Otoscaphites klamathensis* (Anderson)], and rare *Inoceramus uwajimensis* (Yehara) and *Sphenoceramus yokoyamai* (Nagao and Matsumoto), is known from the Coniacian of Hokkaido, suggesting that the upper Penzhinskaya Formation is of Coniacian age. It is appropriate to mention here that Alabushev (in Alabushev and Wiedmann, 1994c) apparently made an error when he included data on a massive conglomerate and a cross-stratified sandstone, now considered to be Oligocene, in his description of the Cretaceous section.

In separate exposures at the base of a high terrace we recorded the following units of the upper part of the Penzhinskaya Formation (Figs. 5, 6).

3.3.1. Upper member

7. Greyish green siltstone with abundant marly boulders (713-2–4; 713-4a; 713-5-1; 713-5-3; 713-5a-3; 713-5b; 713-6-1, 2; 713-6a-2; 713-6b–e; 713-6d-1, 2; 713-7-1–4; 713-13-1–4; 714-1; 721-1, 2, 4–8, 10, 11; 721-3-1, 2; 721-9-1; 723-5).. 22 m
Yields rhynchonellid brachiopods, bivalves [*Acila* (*Truncacila*) sp., *Grammatodon* sp., *Inoceramus* sp., *Nannonavis* sp.], gastropods (*Harpogodes* sp., *Semifusus* sp.), scaphopods (*Dentalium* sp.), ammonoids [*Baculites* sp., *Gaudryceras denseplicatum* (Jimbo), *Kossmaticeras japonicum* Matsumoto, *Mesopuzosia yubarenzis* (Jimbo), *Phyllopachyceras* sp., *Tetragonites glabrus* (Jimbo), *Yezoites* sp. *Yokoyamaoceras* sp.], and plant remains [*Metasequoia* sp. (dominant), *Ginkgo* sp.].
Covered interval about 20–25 m thick.
6. Greyish green siltstone with rare marly boulders (in talus) (713-1-1; 713-2-3) ....2–3 m exposed
Contains bivalves [*Acila* (*Truncacila*) sp., Nannonavis sachalinensis (Yokoyama)], ammonoids [*Gaudryceras denseplicatum* (Jimbo)].

Shells of three ammonoid species from the lower portion of the Upper member were analyzed: *Gaudryceras denseplicatum* (713-1-1, 97% aragonite), *Kossmaticeras japonicum* (95%), and *Baculites* sp. (713-5, 90%). An aragonitic gastropod shell, *Semifusus* sp. (ca. 100% aragonite, with only small portion α-SiO_2), and a calcitic bivalve shell, *Nannonavis* sp., were also studied. $\delta^{18}O$ values in the ammonoid shells fluctuate from −1.6 to −0.3‰ ($\delta^{13}C$ values range from −0.9 to 0.2‰); $\delta^{18}O$ values in the *Nannonavis* shell range from −1.1 to −0.7‰ ($\delta^{13}C$ = 1.1–1.2‰) and the Mg/Ca ratio fluctuates from 5.44 to 5.85 mmol mol^{-1}; the $\delta^{18}O$ value in the *Semifusus* shell is −0.9‰ ($\delta^{13}C$ = 0.1‰) (Table 3).

The shells of three ammonoid species from the middle portion of the upper member were analyzed: *Baculites* sp. (713-5a-3, 89% aragonite), *Mesopuzosia yubarensis* (713-6d-2, 100%) and *Kossmaticeras japonicum* (713-7-1, 96% aragonite; 713-7-2, 91%; 713-7-3, 97%; 713-7-4, 95%; 713-13-1, 95%; 713-13-2, 87%; 713-13-3, 95%, 713-13-4, 93%). $\delta^{18}O$ and $\delta^{13}C$ values in them vary between −1.6 and −0.8‰ and −3.6 and −0.8‰, respectively (Table 5). The $\delta^{18}O$ value for a single fragment of

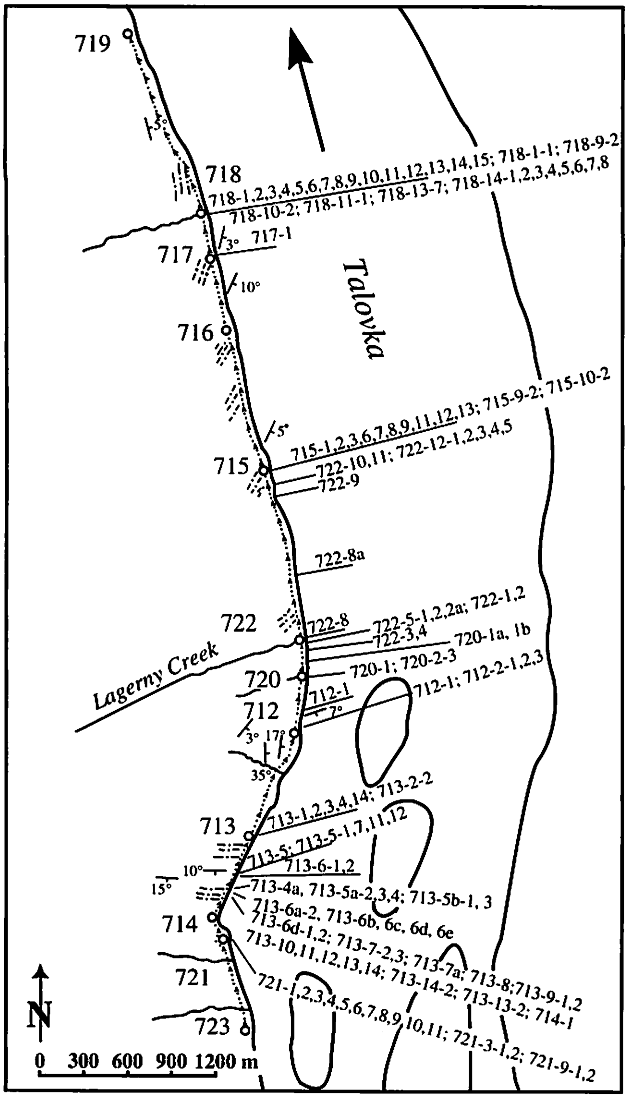

Fig. 5. Sketch map showing Coniacian outcrops in the Talovka River Basin. For key to lithologies, see Fig. 3.

an aragonitic inoceramid shell is −0.2‰ ($\delta^{13}C = 0.0$‰); $\delta^{18}O$ values in the calcitic bivalve *Acila* and *Nannonavis* shells range from −0.9 to 0.1‰ ($\delta^{13}C = 0.2$–1.2‰) and for the rhynchonellid brachiopod shell the value is −1.4‰ ($\delta^{13}C = 1.6$‰). The Mg/Ca ratio in calcitic bivalves changes from 5.08 to 5.80 mmol mol^{-1}.

From the upper portion of the upper member the aragonitic shells of four ammonoid species, *Mesopuzosia yubarensis* (97% aragonite), *Yesoites* sp. (aragonite bearing, with a small admixture of α-SiO_2 and $MnCO_3$), *Gaudryceras denseplicatum* (81% aragonite, with traces of α-SiO_2 and $MnCO_3$) and *Kossmaticeras japonicum* (90–95% aragonite, with traces of α-SiO_2 and clinoptilolite), and a gastropod *Harpogodes* sp. (100% aragonite) were analyzed. $\delta^{18}O$ values in the former fluctuate from −1.1 to −0.2‰ ($\delta^{13}C$ values fluctuate from −2.8 to 0.1‰); the $\delta^{18}O$ value in the gastropod shell is −0.1‰ ($\delta^{13}C = 1.3$‰) (Table 3). Primary calcitic material isotopically investigated was taken from shells of the bivalves *Acila* and *Nannonavis*: $\delta^{18}O$ and $\delta^{13}C$ values fluctuate from −1.8 to −0.7‰ and from 0.2 to 1.6, respectively; Mg/Ca ratios change from 5.16 to 5.55 mmol mol^{-1}.

The lowest palaeotemperatures determined from calcitic and aragonitic invertebrate shells of the upper member are 11.7 and 16.4 °C, respectively; the highest are 19.5 and 22.4 °C. Average palaeotemperatures from 32 calcitic and 21 aragonitic samples are 15.5 and 19.2, respectively.

3.3.2. Middle member

5. Greyish green siltstone with lenses of dark grey calcareous sandstone and large boulders of marl (712-1,1a; 712-2-1–3) .... 3.0 m
Contains remains of sponge colonies, bivalves (*Nannonavis* sp.), scaphopods (*Dentalium* sp.), ammonoids [*Gaudryceras* sp., *Mesopuzosia jubarensis* (Jimbo), *Mesopuzosia* sp.].
Covered interval about 15–20 m thick.

4. Dark grey, sandy siltstone with small calcareous-marly boulders (in talus) (720-1, 1a, 1b; 720-2-3; 722-1–4, 8; 722-3-4; 722-5-1, 2, 2a)................. less than 2–3 m
Contains bivalves [*Acila* (*Truncacila*) sp., *Inoceramus* sp., *Nannonavis* sp.], gastropods, ammonoids [*Anagaudryceras* sp., *Gaudryceras* sp., *Hypophylloceras* sp., *Kossmaticeras japonicum* Matsumoto, *Scalarites* sp., *Tetragonites popetensis* Yabe, *Yokoyamaoceras katoi* (Jimbo)], and plant remains (*Metasequoia* sp.). Apparently from this portion of the section rare specimens of *Inoceramus uwajimensis* (Yehara) and micro- and macroconchs of *Yezoites pseudoaequalis* (Yabe) were collected by H. Maeda.
Covered interval about 40–55 m thick.

3. Dark grey sandy siltstone with abundant lenses and large boulders of marl (715-1–3, 8, 9, 11, 13; 715-10-2; 722-10, 11; 722-12-1–4) .... about 5 m
Yields bivalves (*Nannonavis* sp.), gastropods, scaphopods (*Dentalium* sp.), ammonoids (*Gaudryceras* sp., *Kossmaticeras japonicum* Matsumoto, *Tetragonites popetensis* Yabe) and plant remains (*Ginkgo* sp., *Metasequoia* sp.).
Covered interval about 80–85 m thick.

Analysis of the lower portion of the middle member involved the use of aragonitic shells of three ammonoid species: *Kossmaticeras japonicum* (715-1, 95% aragonite; 715-2, 93%; 715-3, 95%; 715-6, 97%), *Gaudryceras* sp. (715-10-2, 78%, with a trace of α-SiO_2; 715-11, 100%; 722-12-1, 93%, with traces of α-SiO_2, clinoptilolite and lamenar silicates; 722-12-2, 93%; 722-12-3, 93%) and *Tetragonites popetensis* (aragonite preserved, with traces of $MnCO_3$ and lamellar silicates). $\delta^{18}O$ values in them vary between −1.5 and 0.0‰, and $\delta^{13}C$ values range from −3.6 to 1.2‰ (Table 4). Mg/Ca ratios in calcitic bivalve shells change from 5.47 to 5.79 mmol mol^{-1}.

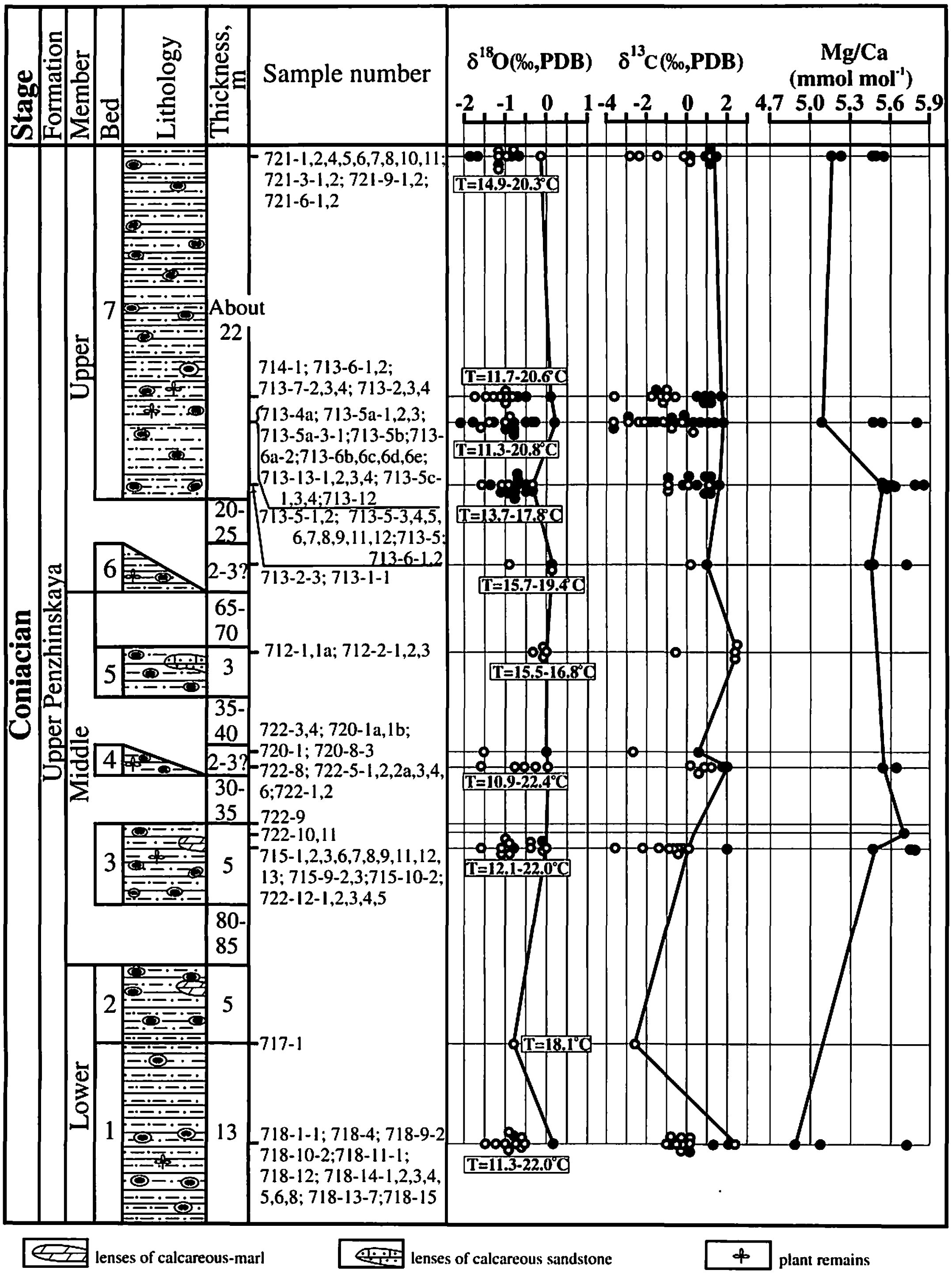

Fig. 6. $\delta^{18}O$ and $\delta^{13}C$ values in the aragonitic ammonoid and gastropod and calcitic brachiopod and bivalve shells from Coniacian sediments of the Penzhinskaya Formation, left bank of the lower reaches of the Talovka River; see Figs. 3 and 4 for further information.

In the middle portion of the middle member the shells of five ammonoid species were analyzed: *Tetragonites popetensis* (722-8, aragonite preserved, with traces of α-SiO_2, $MnCO_3$ and clinoptilolite), *Scalarites* sp. (722-5-1, 96% aragonite; 722-5-2a, 94%), *Anagaudryceras* sp. (722-1, 97%; 722-2, 93%) and *Yokoyamaoceras katoi* (720-2-3, 93%, with a trace of α-SiO_2). $\delta^{18}O$ and $\delta^{13}C$ values in them fluctuate from −1.6 to 0.1‰ and from −2.7 to 1.2‰, respectively (Table 4). $\delta^{18}O$ values in the shells of the calcitic bivalves *Acila* and *Nannonavis* range from −0.6 to 0.0‰; $\delta^{13}C$ values fluctuate from −0.5 to 2.0‰. Mg/Ca ratios in the bivalves range from 5.54 to 5.64 mmol mol^{-1}.

$\delta^{18}O$ values in the shells of two ammonoid species, *Gaudryceras* sp. (712-1a, 96% aragonite) and *Mesopuzosia* sp. (712-2-1, 100%; 712-2-2, 98%, with a trace of

Table 3
Carbon and oxygen isotope analyses of Coniacian calcitic and aragonitic mollusc shells from the upper Penzhinskaya Formation (upper member) of the lower reaches of the Talovka River and Lower Haborogawa Formation of Hokkaido (Yutakazawa River) (H, height, D, diameter, L, length)

Sample	Species	Location (H, L and D in mm)	Diagenetic alteration				$\delta^{13}C$ (PDB) (‰)	$\delta^{18}O$ (PDB) (‰)	T °C
			Aragonite (%)	Primary calcite (%)	Admixture	Colour			
713-1-1	*Gaudryceras denseplicutum* (Jimbo)	H = 18	97 ± 3	0	α-SiO_2 (trace)	Silvery-white	0.2	−0.9	19.4
713-2-1	*Acila (Truncacilla)* sp.	H = 11	0	100	–	Silvery-white	1.1	−0.8	15.3
713-2-2	Same shell	H = 7.5	0	100	–	Silvery-white	1.2	0.1	11.7
713-2-2a	Same shell	H = 7.6 m	0	100	–	Silvery-white	−1.5	−0.5	14.1
713-2-3	*Nannonavis sachalinensis* (Yokoyama)	H = 13	0	100	–	White	0.9	−0.9	15.7
713-3a-2	Rhynchonellida	L = 5	0	100	–	Silvery-white	1.6	−1.4	17.8
713-5a-1	*Inoceramus* sp.	Fragment	~100	0	–	Silvery-white	0.0	−0.2	16.4
713-5-1	*Kossmaticeras japonicum* Matsumoto	H > 10	95 ± 5	0	Mn CO_3 (small)	Cream	−0.8	−0.3	16.8
713-5	*Baculites* sp.	H = 7 (septum)	90 ± 5	0	α-SiO_2 (trace), clinoptilolite (small)	Silvery-white	−0.9	−1.6	22.4
713-5a-3	*Baculites* sp.	D = 7	89 ± 3	0	Clinoptilolite (small)	Silvery-white	−0.7	−1.6	22.4
713-5a-2	*Nannonavis* sp.	H = 8	0	100	–	White	0.2	−0.7	14.9
713-5a-4	Same shell	H = 30	0	100	–	White	0.3	−0.,3	13.3
713-5-2	*Nannonavis* sp.	D = 47	0	100	–	White	1.2	−0.7	14.9
713-5-3	Same shell	H = 42	0	100	–	White	1.1	−1.1	16.3
713-5-4	Same shell	H = 40	0	100	–	White	1.2	−0.7	14.9
713-5-6	Same shell	H = 33	0	100	–	White	0.9	−0.4	13.7
713-5-7	Same shell	H = 21	0	100	–	White	1.0	−0.9	15.7
713-5-8	Same shell	H = 17	0	100	–	White	1.0	−0.9	15.7
713-5-9	Same shell	H = 14	0	100	–	White	0.8	−0.8	15.3
713-5-11	Same shell	H = 5	0	100	–	White	0.4	−0.5	14.1
713-5-12	Same shell	H = 2	0	100	–	White	−0.1	−1.4	17.8
713-5-5	*Nannonavis* sp.	H = 37	0	100	–	White	1.1	−0.5	14.1
713-6-2	Gastropod (*Semifusus* sp.)	H = 30	100	0	α-SiO_2 (small)	White	0.1	−0.9	19.4
713-6b	*Nannonavis* sp.	H = 26	0	100	–	White	−0.7	−0.9	15.7
713-6f	*Nannonavis* sp.	H = 20	0	100	–	White	−1.4	−2.1	20.8
713-6d-2	*Mesopuzosia yubarensis* (Jimbo)	H = 95	100	0	–	Cream	−0.8	−0.8	19.0
713-6e	*Acilla* (*Truncacilla*) *hokkaidoensis* (Nagao)	H = 5	0	100	–	Silvery-white	2.3	0.2	11.3
713-7-1	*Kossmaticeras japonicum* Matsumoto	H = 25	96 ± 4	0	–	Silvery-white	−1.1	−1.2	20.6
713-7-2	Same shell	H = 20	91 ± 5	0	Clinoptilolite (trace)	Silvery-white	−3.5	−1.0	19.8
713-7-3	Same shell	H = 11	97 ± 3	0	–	Cream	−1.0	−1.0	19.8
713-7-4	*Kossmaticeras japonicum*	H = 26	95 ± 5	0	Clinoptilolite (small)	Silvery-white	−1.7	−1.1	20.3
713-12	*Acila* (*Truncacila*) sp.	H = 11	0	100	–	White	1.3	−0.2	12.9
713-13-1	*Kossmaticeras japonicum*	H = 50	95 ± 5	0	α-SiO_2 (small), ceolite (trace)	Silvery-white	−2.5	−1.0	19.8
713-13-2	Same shell	H = 42	87 ± 5	0	α-SiO_2 (small)	Silvery-cream	−3.5	−1.4	21.6
713-13-3	Same shell	H = 40	95 ± 5	0	α-SiO_2 (small) $BaCO_3$(?)	Silvery-cream	−2.3	−1.6	22.4
713-13-4	Same shell	H = 25	93 ± 5	0	α-SiO_2 (small), ceolite (trace)	Silvery-cream	−3.6	−0.9	19.4
721-2	*Mesopuzosia yubarensis* (Jimbo)	H > 60	97 ± 3	0	–	Light-cream	−0.1	−0.8	19.0
721-3-1	Gastropod (*Harpogodes* sp.)	H = 10	100	0	–	Light-cream	1.3	−1.0	19.8
721-4	*Nannonavis* sp.	H = 25	0	100	–	White	0.2	−1.7	19.1

721-5	*Nannonavis* sp.	H = 40	0	100	–	White	1.1	−1.8	19.5
721-6-1	*Nannonavis* sp.	H = 20	0	100	–	White	1.2	−0.7	14.9
721-6-2	Same shell	H = 5	0	100	–	White	1.3	−1.2	16.9
721-8	*Yesoites* sp.	H = 3.5	–	0	α-SiO_2 $MnCO_3$	Silvery-white	−2.8	−1.1	20.3
721-9-1	*Anagaudryceras denseplicatum* (Jimbo)	H = 12	81 ± 5	0	α-SiO_2 $MnCO_3$	Silvery-white	−1.5	−1.1	20.3
721-9-2	*Kossmaticeras japonicum* Matsumoto	H = 60?	90 ± 3	0	–	Silvery-white	−2.5	−0.2	16.4
721-10	*Acila (Truncacila)* sp.	H = 12	0	100	–	Pinky-cream	0.9	−0.9	15.7
721-11	*Kossmaticeras japonicum*	H > 35	95 ± 5	0	α-SiO_2 (trace), clinoptilolite (small)	Cream	0.2	−1.1	20.3
S - 19 (Hokkaido)	*Yokoyamaoceras* sp.	H > 45	90 ± 5	0	Clinoptilolite (small)	Goldish-cream	−1.5	−1.4	21.6
(Hokkaido)	*Inoceramus* sp.	H > 35	100	0	–	Cream	5.4	−2.2	25.1

α-SiO_2; 712-2-3, 100%, with traces of α-SiO_2 and $MnCO_3$) from the upper portion of the middle member fluctuate from −0.3 to 0.0‰; $\delta^{13}C$ values range from −0.6 to 2.5‰ (Table 4).

The lowest palaeotemperatures calculated from calcitic and aragonitic invertebrate shells from the middle member are 10.9 and 15.1 °C, respectively; the highest are 16.5 and 22.4 °C. Average palaeotemperatures from seven calcitic and 21 aragonitic samples are 13.6 and 18.3 °C, respectively.

3.3.3. Lower member

2. Dark grey sandy siltstone with lenses and small boulders of marl and rare interlayers of fine-grained sandstone (717-1).. 5 m
Contains ammonoids (*Gaudryceras* sp.).

1. Dark grey sandy siltstone with lenses and large boulders of marl (718-1-1; 718-4; 718-10-2; 718-11-1; 718-14-1–6, 8).. 3.0 m
Contains bivalves (*Bairostrina concentricus costatus* Nagao and Matsumoto, *Goniomya* sp., *Inoceramus tenuistriatus* Nagao and Matsumoto, *Nannonavis* sp.,), ammonoids [*Gaudryceras denseplicatum* (Jimbo), *Kossmaticeras japonicum* Matsumoto, *Scalarites* sp., *Tetragonites glabrus* (Jimbo), *Yokoyamaoceras* sp.), and plant remains (*Ginkgo* sp.).

From the middle part of the lower member the shells of four ammonoid species were investigated: *Kossmaticeras japonicum* (718-4, 88% aragonite), *Tetragonites glabrus* (718-10-2, 78%, with traces of α-SiO_2 and lamellar silicate), *Gaudryceras denseplicatum* (718-14-1, 98%, with a trace of α-SiO_2; 718-14-2, 100%; 718-14-3, 95%, with a trace of α-SiO_2; 718-14-4, 94%, with a trace of α-SiO_2; 718-14-5, 100%; 718-14-6, 100%) and *Scalarites* sp. (718-14-8, ca. 100%, with traces of α-SiO_2 and clinoptilolite). Their $\delta^{18}O$ values fluctuate from −1.5 to −0.5‰, and $\delta^{13}C$ values vary between −1.0 and 2.3‰ (Table 5). $\delta^{18}O$ values from *Nannonavis* and *Goniomya* shells range from −1.0 to 0.2‰; $\delta^{13}C$ values range from 0.2 to 2.1‰ and Mg/Ca ratios fluctuate from 4.88 to 5.72 mmol mol^{-1}.

For the isotopic investigation of the upper portion of the lower member a shell of *Gaudryceras* sp. (717-1, 100% aragonite, $\delta^{18}O = -0.6‰$; $\delta^{13}C = -2.6‰$) was used (Table 5).

Judging from the data obtained, the lowest palaeotemperatures calculated from the calcitic and aragonitic invertebrate shells of the lower member of the Coniacian succession are 11.3 and 17.7 °C, respectively; the highest are 16.1 and 22.1 °C, averaging 14.1 and 19.0 °C (from three calcitic and ten aragonitic samples).

Overall, isotopic palaeotemperatures calculated from Coniacian invertebrates of the Talovka River section fluctuate from 10.9 to 22.4 °C, with an average value of 17.2 °C (from 42 calcitic and 52 aragonitic samples). Unusually low $\delta^{18}O$ values recognized in the aragonitic

Table 4
Carbon and oxygen isotope analyses of calcitic and aragonitic mollusc shells from the upper Penzhinskaya Formation (middle member) of the lower reaches of the Talovka River (H, height, D, diameter)

Sample	Species	Location (H in mm)	Diagenetic alteration				$\delta^{13}C$ (PDB) (‰)	$\delta^{18}O$ (PDB) (‰)	T °C
			Aragonite (%)	Primary calcite (%)	Admixture	Colour			
715-1	*Kossmaticeras japonicum* Matsumoto	H = 27	95 ± 3	0	–	Cream	0.3	−0.9	19.4
715-2	Same shell	H = 25	93 ± 5	0	–	Cream	−0.9	−0.9	19.4
715-3	Same shell	H = 23	95 ± 5	0	–	Cream	−0.4	−1.5	22.0
715-6	Same shell	H = 20	97 ± 3	0	–	Cream	0.1	−1.1	20.3
715-10-2	*Gaudryceras* sp.	H = 8	78 ± 5	0	α-SiO_2 (trace)	Cream	−2.3	−1.1	20.3
715-11	*Gaudryceras* sp.	H = 7	100	0	–	Cream	−1.4	−1.0	19.8
722-12-1	*Gaudryceras* sp.	H = 27	93 ± 5	0	α-SiO_2 (trace), clinoptilolite (small)	Silvery-cream	−0.2	0.0	15.5
722-12-2	Same shell	H > 24	93 ± 5	0	Lamellar siliceous (trace)	Silvery-cream	−0.7	−0.4	17.2
722-12-3	Same shell	H > 22	93 ± 3	0	–	Silvery-cream	−0.5	−0.4	17.2
722-12-4	*Tetragonites popetensis* Yabe	H = 8	–	0	$MnCO_3$ (trace), lamellar siliceous (trace)	Silvery-cream	−3.6	−0.1	15.9
722-12-5	*Acila* (*Truncacila*) sp.	H = 6	–	100	–	Silvery-white	−0.5	0.0	12.1
722-5-1	*Scalarites* sp.	H > 22	96 ± 3		–	Silvery-cream	0.6	0.1	15.1
722-5-2a	*Scalarites* sp.	H = 13	94 ± 5		–	Cream	1.2	−0.1	15.9
722-5-3	*Nannonavis* sp.	H = 12	0	100	–	White	1.2	−0.6	14.5
722-5-6	*Acila* (*Truncacila*) sp.	H = 8	0	100	–	White	1.5	0.3	10.9
722-8	*Tetragonites popetensis* Yabe	H = 6	–	0	α-SiO_2 (trace), $MnCO_3$ (trace), Clinoptilolite and amphibole (small)	Silvery-white	1.2	−1.6	22.4
715-9-2	*Nannonavis sachalinensis* (Yokoyama)	D = 5	0	100	–	White	0.4	−0.8	15.3
722-1	*Anagaudryceras* sp.	H = 11	97 ± 3		–	Cream	0.3	−0.5	17.7
722-2	*Anagaudryceras* sp.	H = 15	93 ± 3		–	Cream	0.7	−0.6	18.1
720-2-3	*Yokoyamaoceras katoi* (Jimbo)	H = 5	93 ± 5		α-SiO_2 (trace), $MnCO_3$ (trace)	Silvery-cream	−2.7	−1.6	22.4
720-2-3a	Small bivalve (in association with *Yokoyamaoceras katoi*)	H = 4.5	0	100	–	White	0.6	0.0	12.1
712-1a	*Gaudryceras* sp.	H = 25	96 ± 3		–	Silvery-cream	−0.6	−0.3	16.8
712-2-1	*Mesopuzosia* sp.	H = 80 (septum)	100		–	Silvery-cream	2.4	−0.1	15.9
712-2-2	Same shell	H = 79 (septum)	98 ± 2		α-SiO_2 (trace)	Silvery-cream	2.4	0	15.5
712-2-3	Same shell	H = 78 (septum)	100		–	Cream	2.5	−0.1	15.9

Table 5
Carbon and oxygen isotope analyses of calcitic and aragonitic mollusc shells from the upper Penzhinskaya Formation (lower member) of the lower reaches of the Talovka River (H, height)

Sample	Species	Location (H in mm)	Diagenetic alteration				$\delta^{13}C$ (PDB) (‰)	$\delta^{18}O$ (PDB) (‰)	T °C
			Aragonite (%)	Primary calcite (%)	Admixture	Colour			
718-4	*Kossmaticeras japonicum* Matsumoto	H = 11	88 ± 3	0	–	Cream	−1.0	−1.3	21.1
718-9-2	*Nannonavis sachalinensis* (Yokoyama)	H = 5	0	100	–	White	1.3	0.2	11.3
718-10-2	*Tetragonites glabrus* (Jimbo)	H = 9.5	78 ± 5	0	Laminar silicates α-SiO_2 (trace)	White	−0.5	−1.5	22.0
718-12	*Goniomya* sp.	H = 13	0	100	–	Cream	2.1	−0.7	14.9
718-14-1	*Gaudryceras denseplicatum* (Jimbo)	H = 32	98 ± 2	0	α-SiO_2 (trace)	Silvery-cream	−0.3	−0.6	18.1
718-14-2	Same shell	H = 27	100	0	–	Silvery-cream	−0.5	−0.7	18.5
718-14-3	Same shell	H = 24	95 ± 3	0	α-SiO_2 (trace)	Silvery-cream	−0.8	−0.9	19.4
718-14-4	Same shell	H = 21	94 ± 3	0	α-SiO_2 (trace)	Silvery-cream	−0.3	−0.9	19.4
718-14-5	Same shell	H = 16	100	0	–	Silvery-cream	0.2	−0.5	17.7
718-14-6	Same shell	H = 12	100	0	–	Silvery-cream	0.3	−0.6	18.1
718-14-8	*Scalarites* sp.	H = 10	100	0	α-SiO_2 (trace), clinoptilolite	Silvery-cream	2.3	−0.5	17.7
718-15	*Nannonavis* sp.	H = 45	0	100	–	White	0.2	−1.0	16.1
717-1	*Gaudryceras* sp.	Fragment	100	0	–	Cream	−2.6	−0.6	18.1

Table 6
Carbon and oxygen isotope composition of Coniacian calcitic and aragonitic mollusc shells from the upper Penzhinskaya Formation of the lower reaches of the Talovka River (changed under conditions of freshening or diagenetic alteration) (H, height)

Sample	Species	Member	Location (H in mm)	Diagenetic alteration				$\delta^{13}C$ (PDB) (‰)	$\delta^{18}O$ (PDB) (‰)	"T" °C
				Aragonite (%)	Primary calcite (%)	Admixture	Colour			
713-4-1	*Grammatodon* sp.	Upper	H = 10	–	Undetermined	Undetermined	White	−4.5	−6.9	40.9
713-4	*Nannonavis* sp.	Upper	H = 23	–	Undetermined	Undetermined	Greyish-cream	−6.7	−6.7	44.6
716-6e	Gastropoda	Upper	H = 20	Undetermined	–	Undetermined	White	−14.2	−9.2	54.6
718-1-1	*Inoceramus tenuistriatus* Nagao and Matsumoto	Lower	H = 20	90 ± 5	0	α-SiO_2 (trace $MnCO_3$, very small)	Cream	2.1	−2.9	28.9
718-10-1	*Tetragonites glabrus* (Jimbo)	Lower	H = 8	45 ± 5	0	–	Silvery-cream	−1.5	−1.9	23.7
718-11-1	*Bairostrina concentricus costatus* Nagao and Matsumoto	Lower	H = 35	86 ± 3	0	–	Cream	4.7	−3.2	29.4
718-11-2	*Inoceramus* sp.	Lower	H = 38	96 ± 4	0	–	Cream	3.3	−3.9	32.4
718-13-7	*Kossmaticeras* sp.	Lower	H = 30	88 ± 5	0	α-SiO_2 (trace)		−0.6	−2.3	25.5
722-5-2	*Scalarites* sp.	Middle	H = 16	94 ± 5	0	–	Cream	−0.9	−3.2	29.4
722-5-2a	*Inoceramus* sp.	Middle	Prismatic layers	0	100	–	White	3.7	−2.6	23.1
722-11	*Tetragonites popetensis* Yabe	Middle	H = 6	87 ± 5	0	–	Silvery-cream	−3.6	−2.1	24.6

Table 7
Seasonal contrast range in isotopic temperature in high latitudes of the Northern Hemisphere: Koryak Upland, Talovka River, during the Albian (Kedrovka Formation) and Coniacian (Upper Penzhinskaya Formation)

Formation (member)	Lowermost temperature (°C)		Uppermost temperature (°C)		Seasonal temperature contrast (°C)	Average temperature, °C (number of analyzed specimens)	
	Calcite	Aragonite	Calcite	Aragonite		Calcite	Aragonite
Upper Penzhinskaya (upper member)	11.7	16.4	19.5	22.4	10.7	15.5 (32 specimens)	19.2 (21 specimens)
Upper Penzhinskaya (middle member)	10.9	15.1	16.5	22.4	11.5	13.6 (7 specimens)	18.1 (20 specimens)
Upper Penzhinskaya (lower member)	11.3	17.7	16.1	22.1	10.8	14.1 (3 specimens)	19.0 (10 specimens)
Kedrovskaya	12.5	–	22.4	–	9.0	17.9 (6 specimens)	–

elements of some specimens of *Inoceramus tenuistriatus* (718-1-1, −2.9‰) and *Bairostrina concentricus costatus* (718-11-1, −3.2‰; 718-11-2, −3.9‰, 90% and 86–90% aragonite, respectively) (Table 6), although one fragment of *Inoceramus* sp. is characterized by a "normal" $\delta^{18}O$ value (713-5a-1, −0.2‰). Comparatively low $\delta^{18}O$ values were also found in a few ammonoid shells, but most of these have undergone diagenetic alteration (Table 7); this material was not used in our determinations of palaeotemperatures.

4. Seasonal aspects of temperature fluctuation in northern high latitudes during the Albian and Coniacian

As was shown above, our data on seasonal aspects of temperature fluctuation in the northern Kamchatka area during Late Cretaceous were obtained from the isotopic composition of semipelagic forms (ammonoids) and typically benthic invertebrates (brachiopods, bivalves and gastropods). According new evidence from Campanian ammonoids and bivalves of Hokkaido and Sakhalin (Krilyon) (Smyshlyaeva et al., 2002; Zakharov et al., 2003, 2004) and Campanian ammonoids, bivalves, gastropods and benthic and planktic foraminifera also of Hokkaido (Moriya et al., 2003), Late Cretaceous ammonoid shells were most likely secreted in near-bottom conditions where the animals spent most of their life in shallow marine basins. The general similarity between the isotopic temperature estimates for Campanian ammonoids, benthic molluscs and foraminifera of Hokkaido, and the fact that none of the ammonoids displays calcification temperatures equivalent to those of coexisting planktic foraminifera, suggest that, unlike Recent *Nautilus*, Late Cretaceous ammonoids did not

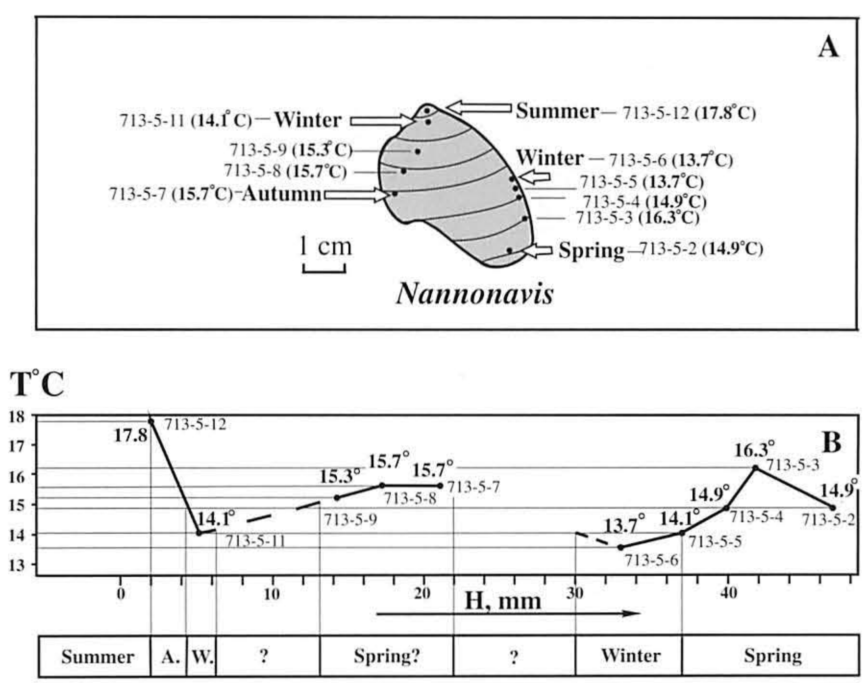

Fig. 7. Seasonal growth temperatures for the calcitic bivalve *Nannonavis* sp. from the Coniacian Penzhinskaya Formation, left bank of the lower reaches of the Talovka River.

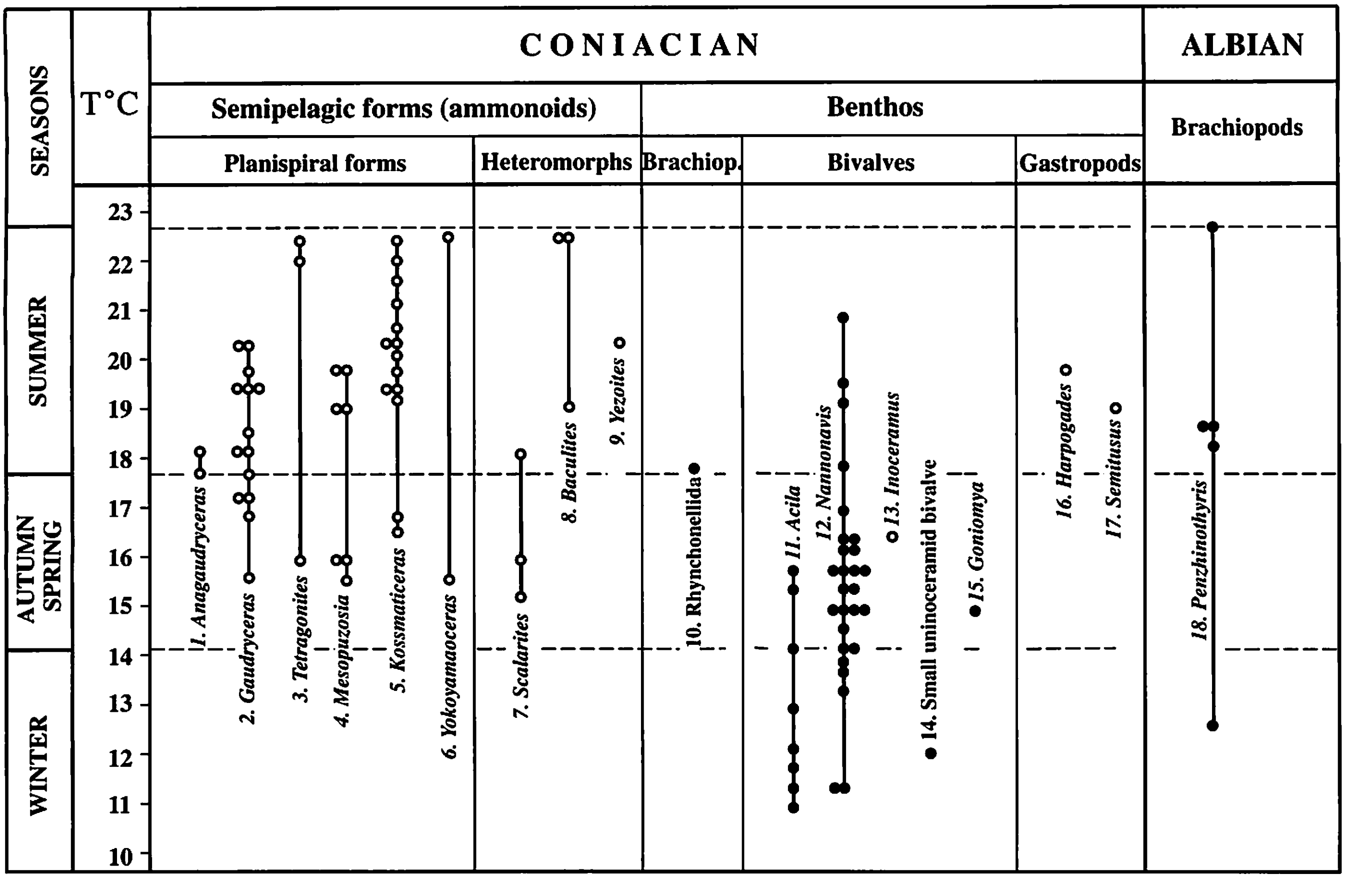

Fig. 8. Seasonal growth temperatures for calcitic benthic and semipelagic shells from the Albian (Kedrovskaya Formation) and Coniacian (Penzhinskaya Formation) of the Talovka River Basin (observations from 89 specimens).

engage in significant short-term vertical migrations in the water column (Moriya et al., 2003).

Isotopic palaeotemperatures obtained from shells of the brachiopod *Penzhinothyris plana* from the Albian Kedrovskaya Formation fluctuate fairly widely, from 12.5 to 22.4 °C ($\delta^{18}O$ values vary between −2.5 and −0.1‰); we assume that the lower temperature level corresponds to winter months and the higher to the summer season.

A similar picture is apparent from the more representative sampling of biogenic carbonates from the Coniacian strata of the Penzhinskaya Formation (Figs. 7, 8). Isotopic palaeotemperatures interpreted as winter values obtained from *Acila* (*Truncacila*) sp. and *Nannonavis sachalinensis* shells fluctuate from 10.9 to 14.1 °C ($\delta^{18}O$ values change from −0.5 to 0.3‰).

It is important to note that comparatively low isotopic palaeotemperatures from aragonitic ammonoids associated locally with the bivalves mentioned above have not been obtained in spite of the highly representative sampling (Fig. 9). This is apparent in both ammonoids with regular convoluted shells and heteromorphs and may be a result of a slow-down in the growth of their shells during Arctic winter seasons when temperatures were low and there was little or no sunlight for a long period of time. However, rare occurrences of more or less active growth of some Callovian (*Cadoceras*) (Zakharov et al., 2004), Turonian (*Tragodesmoceras*) (Zakharov et al., 1999), early Santonian (*Eupachydiscus*) (Zakharov et al., 1999) and Campanian–Maastrichtian (*Gunnarites*, Pachidiscidae) (Pirrie and Marshall, 1990) ammonoids that inhabited different latitudes at temperatures ranging from 3.7 (Sakhalin) through 9.9 (James Ross Island, Antarctica) to 13.3 °C (Russian Platform) are known; hence, it is difficult to generalise about the environmental influences on growth.

Isotopic palaeotemperatures for presumed spring and autumn seasons during the Coniacian in the Koryak Upland fluctuated from 14.1 to 17.7 °C according to data obtained from both the calcite of the bivalves *Acila* (*Truncacila*) sp., *Goniomya* sp., *Inoceramus* sp. and *Nannonavis sachalinensis* ($\delta^{18}O$ values vary between −1.4 and −0.5‰), and aragonite of the ammonoids *Anagaudryceras* sp., *Gaudryceras* sp., *Kossmaticeras japonicum*, *Mesopuzosia* sp., *Scalarites* sp. and *Tetragonites popetenis* ($\delta^{18}O$ values fluctuate from −0.7 to 0.1‰).

Presumed summer isotopic palaeotemperatures for the Coniacian period fluctuate from 17.7 to 22.4 °C

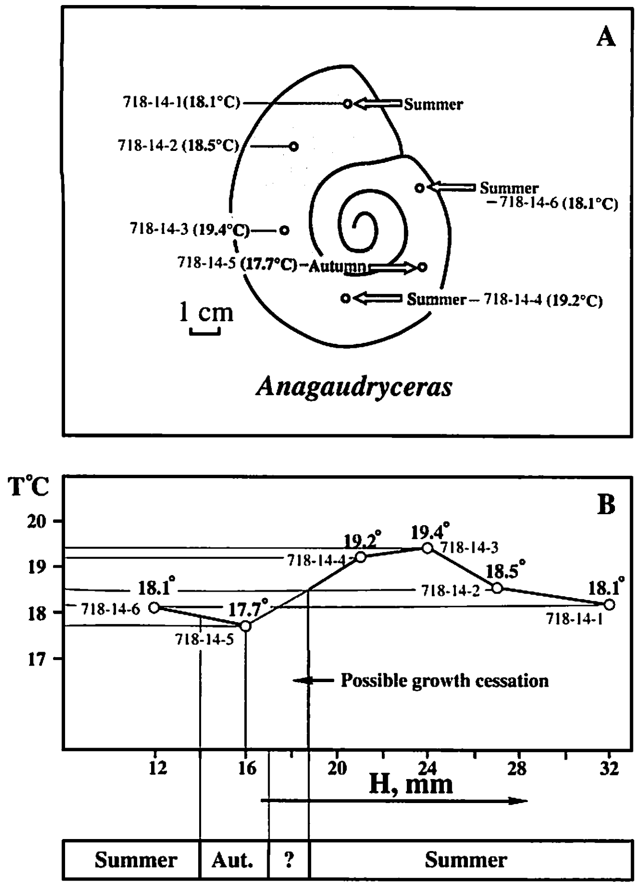

Fig. 9. Seasonal growth temperatures for the aragonitic ammonoid *Gaudryceras denseplicatum* (Jimbo) shell from the Coniacian Penzhinskaya Formation, lower reaches of the left bank of the Talovka River.

according to the calcite of the shells of a rhynchonellid brachiopod ($\delta^{18}O = -1.4‰$) and the bivalve *Nannonavis* ($\delta^{18}O$ values fluctuate from −2.1 to −0.5‰), and the aragonite of the ammonoids *Anagaudryceras*, *Baculites*, *Gaudryceras*, *Kossmaticeras*, *Mesopuzosia*, *Tetragonites*, *Yezoites* and *Yokoyamaoceras* ($\delta^{18}O$ values fluctuate from −1.6 to −0.5‰) and gastropod shells ($\delta^{18}O = -0.9‰$).

Results of our oxygen isotopic investigation of well-preserved calcitic and aragonitic invertebrate shells from the Coniacian succession appear, therefore, to indicate comparatively high summer temperatures in shallow water basins at this time, but average annual temperatures for the Koryak Upland do not appear to have exceeded 14.9 °C (calculated only from calcitic bivalves inhabiting environments of normal salinity in which steady growth was more or less possible throughout the year).

On the basis of leaf-physiognomy, Herman and Spicer (1996) expected somewhat lower temperatures for Alaska and Kamchatka during the Coniacian than we have calculated: cold and warm month temperatures about 5.7 and 0.0 °C and 20.0 and 18.6 °C, respectively; mean annual temperatures about 12.5 and 9.0 °C. This may be because water temperature indications are higher than those for the atmosphere. Contrary to Li and Keller's (1999) opinion, we suggest that oceanic heat transportation poleward prevailed during the Late Cretaceous.

At the present stage of our investigation, Coniacian palaeotemperatures for the Koryak Upland generally seem to be 3–4 °C lower than those for the early Coniacian of Hokkaido. Our data tie in with palaeobotanical results on the development of magnolias and the domination of large-leafed plants in Kaivayam flora of north-west Kamchatka in connection with a relative warming and increase in humidity during the Mid and Late Coniacian (Herman and Lebedev, 1991; Herman, 1996; Golovneva, 1998; Golovneva and Herman, 1998). At the same time there were pronounced seasonal variations during the deposition of the Talovka River section, the lowest calculated palaeotemperatures for the lower, middle and upper members of exposed Coniacian strata being 11.3 °C (the difference between winter and summer temperatures ca. 10.8 °C), 10.9 °C (seasonal difference ca. 11.5 °C) and 11.7 °C (the seasonal difference being ca. 10.7 °C) (Table 7). Strata exposed in the lower reaches of the Talovka River are probably latest Coniacian in age, taking into account both the seasonal contrasts noted above and the general fall in temperature in the Far East at the beginning of Santonian (Zakharov et al., 1999).

5. Local freshening in Cenomanian and Coniacian

It is known that a mid-Cretaceous global climatic optimum was achieved at some point between the Cenomania/Turonian transition and the mid Turonian (Jenkyns et al., 1994; Clarke and Jenkyns, 1999; Huber et al., 1999). Huber et al. (2002) suggested that global climate changed from a warm greenhouse state during the late Albian–late Cenomanian to a hot greenhouse phase during the latest Cenomanian–early Campanian, and then cooled from the mid-Campanian to the Maastrichtian.

The high palaeotemperatures obtained from some well-preserved Cenomanian (Fig. 10) and Coniacian (Fig. 11) inoceramid shells from the Koryak Upland seem unlikely. In the Cenomanian Mamet Formation (Tynogyrginkuyul and Bolshoy Vylgilveem creek sections) some of the well-preserved shells of the bivalve *Baiostrina concentricus costatus* are composed almost entirely of aragonite (96–100%), which implies only diagenetic alteration. This suggests that comparatively low $\delta^{18}O$ values in both the aragonite of inoceramid bivalves and calcite of their prismatic layers, varying between −3.2 and −2.0‰, might be a result of freshening of the environment, reflecting local freshwater input. The presence of ammonoid shells with

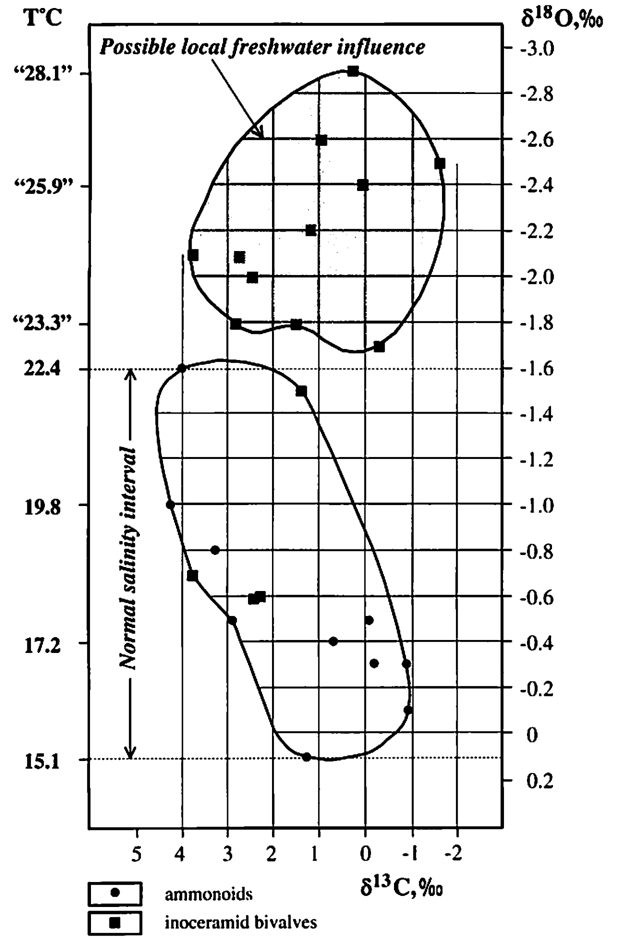

Fig. 10. Plots of $\delta^{18}O$ and $\delta^{13}C$ data for aragonitic ammonoid and inoceramid bivalve shells from the upper Lower Cenomanian portion of the Mamet Formation, Talovka River Basin.

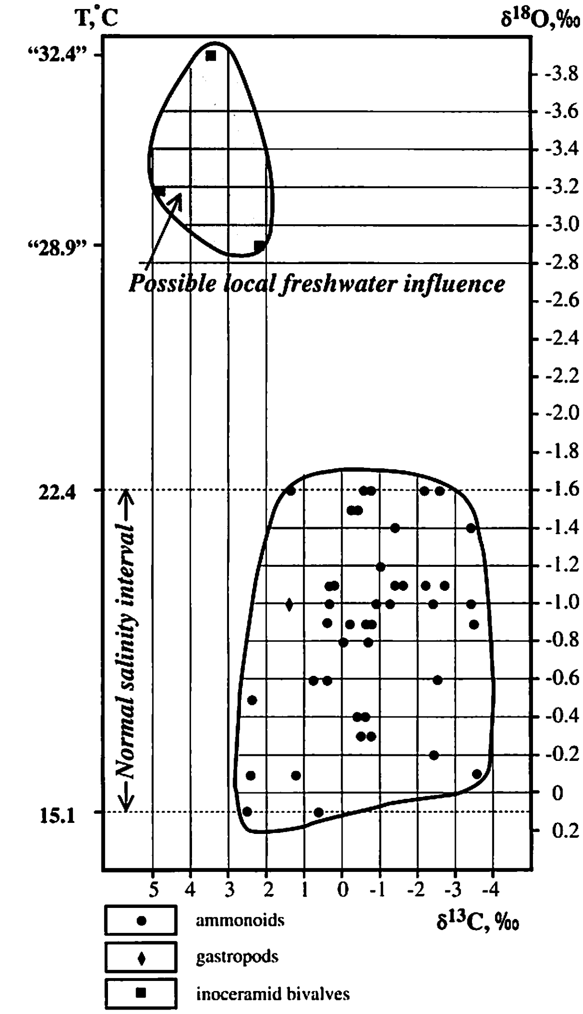

Fig. 11. Plots of $\delta^{18}O$ and $\delta^{13}C$ data for aragonitic ammonoid, gastropod and inoceramid bivalve shells from the upper Lower Cenomanian portion of the Mamet Formation, Talovka River Basin.

"normal" $\delta^{18}O$ values, fluctuating from −0.5 to 0.1‰ suggests that the Cenomanian ammonoids and some inoceramids in the north Kamchatka region inhabited biotopes of differing local salinity.

Some well-preserved Coniacian inoceramid shells from the Koryak Upland (three examples with 86–90% aragonite) are characterized by very low $\delta^{18}O$ values (up to −3.9‰) that correspond to improbably high isotopic paleotemperature; the animals concerned seem to have inhabited estuarine parts of basins or gulfs containing fresher water. The likely freshening of the Koryak Upland basin seems to have been more marked in the Cenomanian–Turonian (Zakharov et al., 2004) than during the Coniacian.

6. Biological productivity of near-polar seas during the Albian, Cenomanian and Coniacian

Anomalously high $\delta^{13}C$ values, reflecting high biological productivity (Alcala-Herrera et al., 1992), were encountered in a few mollusc shells from the upper Lower Cenomanian (4.2‰) and Coniacian of the Talovka River section and Hokkaido. High values (5.4‰ and 4.7‰ respectively) were recorded from an aragonitic *Inoceramus* sp. from the Yutakazawa River, Hokkaido (Zakharov et al., 2001), and an aragonitic *Inoceramus* shell (86 ± 3%) from the lower member Penzhinskaya Formation. $\delta^{13}C$ values for three other *Inoceramus* shells from the same section are 2.1, 3.3 and 3.7‰. In many aragonitic ammonoid shells from the section $\delta^{13}C$ values reach 2.5‰ but the average value from 50 samples is only −0.4‰. The $\delta^{13}C$ value for a calcitic rhynchonellid brachiopod shell is 1.6‰, and for the calcitic bivalves *Acila* and *Nannonavis* and an aragonitic gastropod shell they are about 1.5 and 0.1‰, respectively.

Following Norris (1996), some authors think that a strong positive size-related shift in $\delta^{13}C$ values of 0.5‰ or more, $\delta^{18}O$ values that are more negative than in coexisting taxa, and relatively small size-related changes in $\delta^{18}O$ values in some fossil planktic foraminifera, indicate an association with algal photosymbionts

(Houston and Huber, 1998; Houston et al., 1999; Pearson et al., 2001). MacLeod and Hoppe (1992) thought that inoceramid bivalve species were also photosymbiotic. However, we prefer another explanation for the unusual isotopic composition of inoceramid shells.

An association with symbiotic organisms to explain unusually high $\delta^{13}C$ but low $\delta^{18}O$ values in the shells of Cenomanian and Coniacian inoceramids from the Koryak Upland seems unlikely because representatives of the same species in other assemblages are characterized by "normal" values. The "isotopic effect" in inoceramid bivalves of the Koryak Upland is most probably a result of freshwater influence connected with a humid climate in the region during the Cenomanian–Turonian (Zakharov et al., 2004). Inoceramids yielding low $\delta^{18}O$ and high $\delta^{13}C$ values seem to have dwelt in fresher habitats, as noted above.

7. Conclusions

Albian–Cenomanian and Coniacian isotopic palaeotemperatures obtained from calcitic brachiopod shells from the Kedrovskaya Formation and aragonitic-calcitic invertebrate material from the Mamet and Penzhinskaya formations of the Koryak Upland are 12.5–22.4 °C, 15.9–21.7 °C and 11.3–22.4 °C, respectively. Seasonal contrast seems to have been marked during the Albian and particularly the Coniacian in northern high latitudes. Growth of both planispiral and heteromorphic ammonoids apparently slowed down during unfavourable winter months in the Coniacian whereas coexisting benthic organisms contain all seasonal growth phases in their shells. Available stable isotopic data and information on the earliest Maastrichtian sea-level fall (Ditchfield, 1997; Miller et al., 1999; Zakharov et al., 1999, 2000) allow us to assume a short-term existence of Cretaceous polar ice only during the early Maastrichtian in the Southern Hemisphere on the Antarctic continent. Short-lived, subfreezing conditions occurred occasionally in the Northern Hemisphere, most probably during polar winter months in the early Valanginian, late Coniacian–early Santonian and early Maastrichtian, but it was probably never sufficiently cold for long enough for permanent sea ice to form. This was possibly because of both the lack of a continent in the North Pole region and a significant ameliorating effect of oceanic heat-transport poleward, mainly via the straits of Turgai and the Western Interior of North America.

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