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Cretaceous climatic oscillations in the Bering area (Alaska and Koryak Upland): Isotopic and palaeontological evidence

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ABSTRACT

New isotopic palaeotemperatures, estimated from $\delta^{18}O$ values of Early Albian, latest Campanian and Early Maastrichtian ammonoid shells of Southern Alaska, as well as our previously published data on the Cretaceous of the Koryak Upland, have been used to reconstruct palaeonvironmental changes in the Bering area. Significant seasonal contrast, marked in Alaska and the adjacent area during the Early Albian, as well as the Coniacian, was partly connected apparently with the possible penetration of cooler waters from the polar area via the Strait of Alaska. Data suggest that the Bering Land Bridge existed during the post-Aptian Cretaceous, with the exception of the Early Albian and Coniacian. Both the stable isotope and the floral data on the post-Aptian Cretaceous of the Bering area suggest the existence of warm climatic conditions in the Late Albian, latest Cenomanian, Coniacian, Santonian to Early Campanian, latest Campanian, and also late Early Maastrichtian. Recurrent terrestrial cooling in northern Alaska, reflected in the composition of corresponding floras, took place possibly because of a barrier to poleward oceanic heat-transport via the Western Interior Seaway (WIS) of North America during the Turonian and Santonian through Early Campanian, then during the Late Maastrichtian through Danian.

The first data on seawater palaeotemperatures estimated from oxygen isotopic analyses on Cretaceous brachiopod, bivalve, gastropod and ammonoid shells of the Koryak Upland (Northern Kamchatka area) and Alaska, were reported by Zakharov et al. (1996, 1999, 2002a, b, 2004, 2005, 2006a,c, 2007). Information on Cretaceous plant and dinosaur remains from this area was given by many authors (e.g. Krassilov (1981), Nesov (1995, 1997), Herman (2004a,b, 2007a,b), Herman and Spicer (in press), Spicer and Herman (2001, in press)). Marine invertebrates assemblages of the Koryak Upland and Alaska have been investigated by Pergament (1961), Jones (1967), Vereschagin (1977), Pokhialainen (1985), Smirnova (1994), Alabushev (1995), and Shigeta et al. (1999). Some authors consider that narrow and very long meridional marine shallow-water basins connected Palaeoarctic basin with the Tethys, enabling poleward heat-transport, were among the favorable conditions to cross Cretaceous climatic barriers. These investigations are the following: the Western Interior Seaway (WIS) in North America and Turgai Strait–Western Siberian Sea system in Eurasia (Kauffman, 1984; Slingerland et al., 1996; Nesov, 1992, 1997; Tsujita and Westerman, 1998; Naidin, 2001, 2007; Baraboshkin, 2007; Scott, 2007; Oboh-Ikuenobe et al., 2007, 2008; Scott et al., 2009).

According to Sacks (1976), the Arctic was connected with the Pacific basin via narrow straits located in the Kolyma-Anadyr (northeast Russia) or MacKenzy-Yakutat (North America) areas during the Late Cenomanian and in the Kozebu-Norton area (western Alaska) during the Aptian to Albian. For an overview of some questions concerning permanent connections of the Palaeoarctic basin with the Pacific during the Cretaceous the reader is referred to other relevant but contradictory publications (e.g., Kitchell and Clark, 1982; Naidin et al., 1986; Hay et al., 1999; Zakharov et al., 2002a,b,c; Baraboshkin, 2007; Naidin, 2007).

This paper attempts to synthesize the isotopic data on the Cretaceous of the Koryak Upland–southern Alaska area (original and our previously published evidence) as well as the published palaeoclimatological data mainly from Late Cretaceous plant fossils of the Koryak Upland and northern Alaska, which presents an opportunity to examine both climatic oscillations in the Bering area and hydrological activity of the WIS during Cretaceous time.

1. Materials and methods

Early and Late Cretaceous mollusc shells for isotope analyses were collected by Y. Shigeta and H. Maeda in northern Alaska during 2004–2005. Original material from northern Alaska (Fig. 1) used for oxygen and carbon-isotope analyses this time consisted of: (1) aragonitic ammonoid shell material from the Lower Albian portion of the

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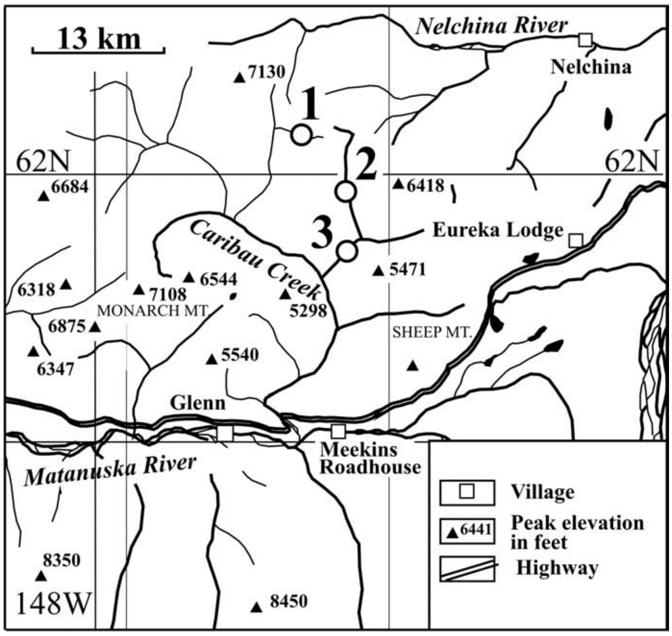


Fig. 1. Location of the investigated sections in the Matanuska River basin, southern Alaska. 1 — Ammonite Creek (Matanuska Formation, Unit A-2, the upper part of the Lower Albian, *B. hulense* Zone); 2 — Flume Creek (Matanuska Formation, Member 3, Lower Maastrichtian); 3 — Caribau-Alfred Creeks area (Matanuska Formation, uppermost Campanian).

Matanuska Formation (24 samples from a single, large shell), (2) aragonitic ammonoid and inoceramid bivalve shell material from the uppermost Campanian portion of the Matanuska Formation (4 samples from 4 mollusc shells), and (3) aragonitic ammonoid shell material from the upper Lower Maastrichtian portion of the Matanuska Formation (1 sample). Larger block of information on seasonal temperature fluctuations in the Koryak Upland during the Cretaceous Period, used in this paper, was obtained by us earlier (Zakharov et al., 2002a,b, 2005, 2006a) from data on isotopic composition of well-preserved brachiopod, bivalve, gastropod and ammonoid shells originated from the Lower Cretaceous (27 analyses), Cenomanian (37 analyses), Turonian (27 analyses), Coniacian (96 analyses), Campanian (21 analyses) and Lower Maastrichtian (4 analyses).

The following criteria were used in this study to determine diagenetic alteration: (1) visual signs; (2) percentage of aragonite in a structure when analyzing shells or their elements originally composed of 100% aragonite; (3) degree of integrity of microstructure, determined under a scanning electron microscope (SEM), (4) X-ray powder analyses to identify possible diagenetic admixtures (e.g. α-SiO_2).

We have recognized four stages in diagenic alteration of investigated ammonoid shells from southern Alaska and the Koryak Upland: 1st stage, where secondary calcite is absent (100% aragonite) or represented by a small portion, not more than 1–5%; 2nd stage, characterised by appearance of a larger portion (5–30% secondary calcite); 3rd stage, where shell material consists of approximately 30–50% secondary calcite; 4th stage, characterised by the presence of more than 50% secondary calcite and has a very pronounced change in isotopic composition (Zakharov et al., 1975, 2006c). However, in our case material of only the first stage seems to preserve more or less primary original isotopic composition.

Microstructure of the largest ammonoid shell (*Grantziceras*) from southern Alaska was investigated, using SEM (JEOL model, JSM-5310) at National Museum of Nature and Science, Tokyo. Before SEM observation a small fragment was taken from the shell wall and without etching was coated with gold using an ion coater. The SEM photograph of Albian *Grantziceras* shell (Fig. 2) shows that this skeleton fulfills diagenetic screening criteria and was therefore considered suitable for isotopic analysis. It was confirmed by results of the X-ray analysis that shows the lack of secondary admixtures, including α-SiO_2 (analyses were carried out using a DRON-3 diffractometer at FEGI (Vladivostok), following the method of Davis and Hooper, 1963).

Isotope samples for our new investigation were taken from narrow transects along growth striations on the surface of the shell that crossed all shell layers except the innermost. In an ammonoid shell, for instance, the innermost layer covers the entire living chamber and therefore is inadequate for detailed analyses.

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

In this paper we use the form proposed by Grossman and Ku (1986) to convert the oxygen isotope composition of the Cretaceous molluscs from southern Alaska into seawater temperatures:

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

where T (°C) is the ambient temperature, $\delta^{18}O_{\mathrm{aragonite}}$ (‰) is the oxygen isotope ratio of the aragonite (versus VPDB), and δ_{w} (‰) is the $\delta^{18}O$ of ambient water (versus VSMOW). A δ_{w} of $-1.0‰$ VSMOW is thought to be appropriate for an ice-free world (Shackleton and Kennet, 1975; Hudson and Anderson, 1989; Pirrie and Marshall, 1990; Price et al., 1998; Price, 1999; Price and Hart, 2002; Huber et al., 2002).

According to our calculation, the correlation coefficient (R) for $\delta^{18}O$ and $\delta^{13}C$ values obtained for *Grantziceras* ammonoid shells from the Lower Albian of southern Alaska (Fig. 3) is only 0.54. However, the general trend of this positive correlation is somewhat stronger than that ($R = 0.41$), obtained by us for Recent *Nautilus pompilius* Linne from the Philippines (Zakharov et al., 2006b), therefore it cannot be considered as an established fact (based this time on isotopic

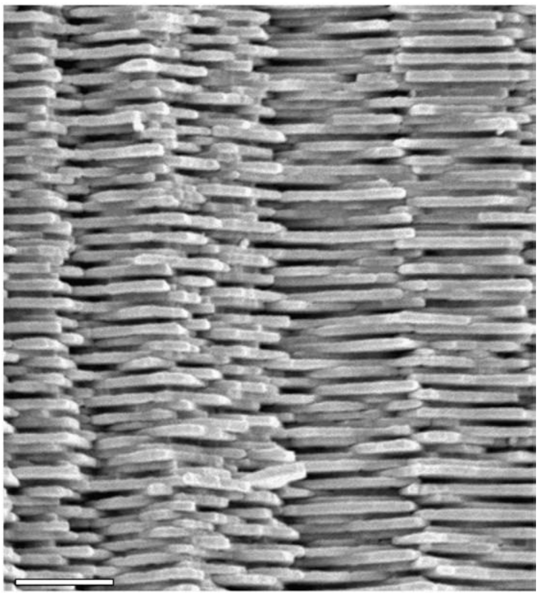


Fig. 2. Scanning electron micrograph of the ammonoid *Grantziceras affine* (A-1), fragment of the shell whorl at $H = 51.0$ mm showing microstructure of nacreous layer in cross-section, bar = 3 μm; lower Albian portion of the Matanuska Formation, Member 6; Ammonite Creek, southern Alaska.

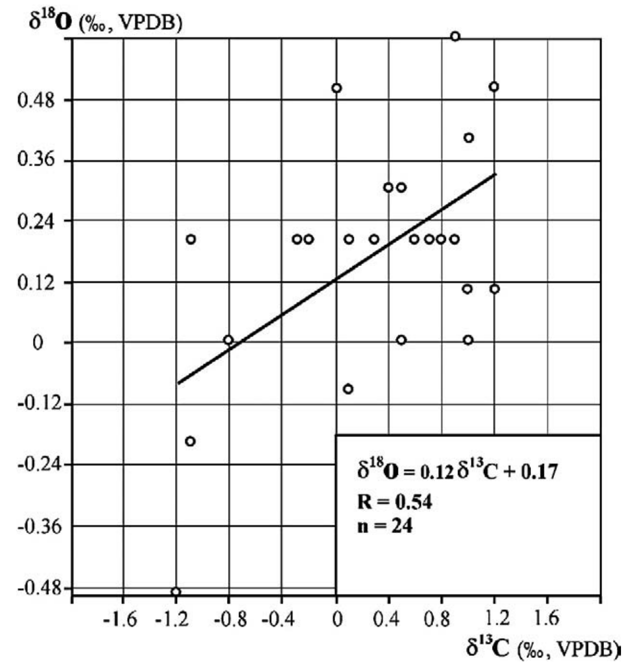


Fig. 3. Scatter plot and regression line for the *Grantziceras affine* shell A-1 from the upper part of the Lower Albian, Ammonite Creek (it was constructed with use of the PAST program (Hammer et al., 2001)). *R* — correlation factor (coefficient), *n* — number of measurements.

composition) in favor of any diagenetic alteration for the *Grantziceras* shell, investigated in detail (Table 1).

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

As was written earlier (Smyshlyaeva et al., 2002; Moriya et al., 2003; Zakharov et al., 2003, 2004, 2005, 2006b, 2007), Cretaceous ammonoid shells were most likely secreted near the bottom of shallow marine basins where the animals spent most of their life. Therefore, probably all palaeotemperatures calculated from isotopic composition of ammonoids, as well as of benthic invertebrates, mainly reflect near-bottom environments of the shelf. To determine sea-surface palaeotemperatures of shallow-water basins we suggested to apply a small correction about 2.0–2.5 °C to bottom temperatures (Zakharov et al., 2007).

2.1. Lower Albian (Ammonite Creek, Alaska)

The Lower Albian *Brewericeras hulense* Zone (Matanuska Formation, Unit A-2) in Alaska is 73 m thick and is represented by yellowish brown siltstone with fossil wood at the base and light-olive-grey silty claystone containing fossiliferous limestone concretions in the middle and upper parts (Jones, 1967).

Small portion of late Early Albian aragonitic ammonoid material from the Talkeetna Mountains, Southern Alaska, has been investigated by us earlier as a reconnaissance (Zakharov et al., 2004). From investigated shells at that time *Grantziceras affine* (Whiteave) (sample Al-1) was found most useful for analyses because it is characterised by minor diagenetic alterations and consists solely of aragonite — 100%, without any admixtures. The δ^{18}O value of aragonite in the mentioned shell equals −0.8‰, which corresponds to a temperature of 19.0 °C; δ^{13}C value reaches 0.6‰. *B. hulense* (Anderson) shell (Al-3) contains only 65% aragonite and has a trace of α-SiO_2. Its δ^{18}O value equals −1.4‰, which corresponds to 21.6 °C, and the δ^{13}C value is negative (−3.58‰). Investigated *Freboldiceras singulare* Imlay shell (Al-2), contained 69% aragonite, and a trace of α-SiO_2, and is characterised by a positive δ^{13}C value (2.0‰), but its δ^{18}O value (−8.4) is unusually low, and the specimen seems to be unsuitable for distinguishing an original isotopic record.

Additionally, we investigated 24 samples from another shell (A-1, 96–100% aragonite) of the ammonoid *G. affine* (Whiteave), which was recently collected by Y. Shigeta from the Matanuska Formation (Member 6) of Ammonite Creek, Talkeetna Mountains. δ^{18}O values vary between −0.5 and 0.6‰, and the δ^{13}C values fluctuate from −1.2 to 1.2‰ (Table 1).

New isotopic evidence show that marine late Early Albian faunas in Southern Alaska inhabited conditions of marked seasonal contrast. According to our interpretation, based on evidence from the late Early Albian ammonoid *G. affine* (Whiteave) shell (Fig. 4), investigated in detail, and another ammonoid shell of the same species (Zakharov et al., 2004), presumed summer temperature values of near-bottom waters for the late Early Albian of southern Alaska fluctuated from 16.4 to 19.0 °C, and presumed winter temperature values from 12.9 to 14.6 °C (intermediate temperatures corresponds apparently to spring–autumn values).

From the large ammonoid *G. affine* shell (Al-2) samples for our isotopic analyses were taken from its last ontogenetic stage which, judging from our version on Early Albian seasonality, possibly corresponds to two-year interval (Fig. 4).

2.2. Uppermost Campanian (Caribau-Alfred Creeks area, Alaska)

Among the fossils recently collected by H. Maeda from uppermost Campanian siltstone of the Matanuska Formation (Member 3) at Caribau Creek near the mouth of Alfred Creek only *Baculites* sp. (sample AF-1001-5) is characterised by almost 100% (95 ± 3%) aragonite without any admixtures (Zakharov et al., 2007). Its δ^{18}O and δ^{13}C values are −0.9 and −3.2‰, respectively. A more or less well-preserved *Inoceramus* sp. shell AF-1001-4 (88% aragonite) has a significantly higher δ^{13}C value (1.8‰); its δ^{18}O value is −2.3‰. Both results were used for palaeotemperature calculation (19.4–25.5 °C) (Table 1). Other fossils from the same locality show significant diagenetic alteration: *Inoceramus* sp., sample AF-10013 (69% aragonite) and *Pachydiscus kamishakensis* Jones, sample AF-1001-2 (47% aragonite) and therefore have not been used for palaeotemperature calculation.

2.3. Lower Maastrichtian (Flume Creek, Alaska)

A single well-preserved late Early Maastrichtian ammonoid *Pachydiscus* sp. shell (M-1-1, 88% aragonite) from the Matanuska Formation (Member 3) on the upper course of Flume Creek has a δ^{18}O value of −0.6‰, which corresponds to a palaeotemperature of 18.1 °C; its δ^{13}C value is −1.5‰ (Table 1).

3. Discussion

3.1. Late Early Albian interval

It is reasonable to expect that a marked seasonal contrast in both southern Alaska (original data) and the Koryak Upland (Zakharov et al., 2004, 2005) during the Early Albian was caused by penetration of cooler polar waters to the northern part of the Boreal-Pacific Province via the strait located apparently in western Alaska (Kozebu-Norton area) (Fig. 5). This is supported by the finding of Arctic mollusks (ammonite *Arctohoplites* and belemnite *Neohibolites*) in Lower Albian Member KJ5 of the Kamiji Formation, Yezo Group, in the Nakagawa area of northern Hokkaido (Iba and Tanabe, 2007). Late Early Albian marine fauna (ammonoids *G. affine* and others) of the Koryak Upland, in contrast, apparently originated from North America (Shigeta et al., 1999). The latter fauna was able to migrate to higher latitudes (Koryak Upland) apparently via the Boreal-Pacific Province.

Our knowledge of the reliable late Early Albian flora (Kukpowruk?) (Figs. 5 and 6) of Northern Alaska remains limited because of

Table 1
Carbon and oxygen isotope analyses of aragonitic ammonoid shells and inoceramid bivalve elements from the upper part of the Lower Albian, uppermost Campanian and Lower Maastrichtian portions of the Matanuska Formation in northern Alaska.

Sample	Species (locality)	Zone, member (unut)	Location (*H* and *D* in mm)	Diagenetic alterations				$\delta^{13}C$ (VPDB), ‰	$\delta^{18}O$ (VPDB), ‰	*T*, °C
				Diagenetic stage	Aragonite, %	Admixture, %	Colour			
M-1-1	Pachydiscus sp. (Flume Creek)	Lower Maastrichtian (Member 3)	*H* = 81.0	2nd	88 ± 3	0	Silvery-cream	−1.5	−0.6	18.1
AF-1001-5	Baculites sp.(Alfred-Caribau)	Uppermost Campanian (Member 3)	*D* = 6.0	1st	95 ± 3	0	Cream	−3.2	−0.9	19.4
AF-1001-4	Inoceramus sp.(Alfred-Caribau)	Same level	*H* = 20.0	2nd	88 ± 3	0	White	1.8	−2.3	[25.5][a]
AF-1001-3	Inoceramus sp.(Alfred-Caribau)	Same level	*H* = 25.0	3rd	69 ± 3	0	White	0.4	−3.7	[31.4][a]
AF-1001-2	Pachydiscus kamishakensis Jones (Alfred-Caribou)	Same level	*H* = 53.0	4rd	47 ± 5	Ceolite (trace)	Cream	−7.1	−2.4	[25.9][a]
Al-1(Zakharov et al., 2006c)	Grantziceras affine (Ammonite Creek)	Lower Albian *Brewericeras hulense* (Unit A-2)	*H*>25		100	0	Silvery-cream	−0.8	0.6	19.0
A-1-1	Grantziceras affine (Ammonite Creek)	Same level	*H* = 51.0	1st	99 ± 1	0	Cream	−0.8	0.0	15.5
A-1-2	Same shell	Same level	*H* = 51.5	1st	99 ± 1	0	Cream	−1.1	−0.2	16.4
A-1-3	Same shell	Same level)	*H* = 52.0	1st	98 ± 2	0	Cream	−1.2	−0.5	17.7
A-1-4	Same shell	Same level	*H* = 52.3	1st	98 ± 2	0	Cream	−0.2	0.2	14.6
A-1-5	Same shell	Same level	*H* = 53.0	1st	98 ± 2	0	Cream	0.1	0.2	14.6
A-1-6	Same shell	Same level	*H* = 53.2	1st	99 ± 1	0	Cream	−0.3	0.2	14.6
A-1-7	Same shell	Same level	*H* = 53.3	1st	100	0	Cream	0.3	0.2	14.6
A-1-8	Same shell	Same level	*H* = 54.0	1st	99 ± 1	0	Cream	0.4	0.3	14.2
A-1-9	Same shell	Same level	*H* = 55.0	1st	100	0	Cream	0.1	−0.1	15.9
A-1-10	Same shell	Same level	*H* = 55.3	1st	99 ± 1	0	Cream	0.6	0.2	14.6
A-1-11	Same shell.	Same level	*H* = 55.4	1st	99 ± 1	0	Cream	0.9	0.2	14.6
A-1-12	Same shell	Same level	*H* = 55.5	1st	97 ± 3	0	Cream	1.0	0.4	13.3
A-1-13	Same shell	Same level	*H* = 55.6	1st	98 ± 2	0	Cream	0.7	0.2	14.6
A-1-15	Same shell	Same level	*H* = 56.5	1st	96 ± 3	0	Cream	1.2	0.5	13.3
A-1-16	Same shell	Same level	*H* = 58.0	1st	99 ± 1	Ceolite (trace)	Cream	1.0	0.1	15.1
A-1-17	Same shell	Same level	*H* = 59.0	1st	98 ± 2	0	Cream	0.5	0.0	15.5
A-1-18	Same shell	Same level	*H* = 60.0	1st	99 ± 1	0	Cream	0.5	0.3	14.2
A-1-19	Same shell	Same level	*H* = 60.5	1st	99 ± 1	0	Cream	0.5	0.3	14.2
A-1-20	Same shell	Same level	*H* = 60.8	1st	100	0	Cream	0.8	0.2	14.6
A-1-210-9	Same shell.	Same level	*H* = 61.0	1st	100	0	Cream	1.0	0.0	15.5
A-1-22-3	Same shell	Same level	*H* = 61.2	1st	99 ± 1	0	Cream	1.2	0.1	15.1
A-1-24-7	Same shell.	Same level	*H* = 30.0 (septum)	1st	96 ± 3	0	Cream	−1.1	0.2	14.6
A-1-25-5	Same shell.	Same level	*H* = 108.0 (septum)	1st	98 ± 2	0	Cream	0.9	0.6	12.9
A-1-26-3	Same shell	Same level	*H* = 30.0	1st	99 ± 1	0	Cream	0.0	0.5	13.3
Al-2(Zakharov et al., 2006c)	*Freboldiceras singulare* (Ammonite Creek)	Same level	*H* = 23.0	3rd	69 ± 3	Trace	Cream	2.0	−8.4	[51.0]
Al-3 (Zakharov et al., 2006c)	*Brewericeras hulense* (Ammonite Creek)	Same level	*H*>25	3rd	65 ± 3	Trace	Silvery-white	−3.5	−1.4	21.6

[a] Unreal paleotemperatures (because of diagenetic alteration) are placed in brackets.

the great depositional facies variability of the most ancient plant-bearing Nanushuk Formation of this area (Mull et al., 2003). The exact location of its beds with plant fossils within the Albian interval seems to be a matter of question now.

In conclusion we would like additionally to note that the palaeotemperatures obtained from Early Barremian and Early Aptian bivalves of the Koryak Upland (18.4–24.5 and 16.4–25.9 °C, respectively) (Fig. 6) are relatively warmer than those from the Early Albian brachiopod *Penzhinothyris* of the same area (Fig. 6), which seems to be evidence that no connection existed between the Arctic ocean and the Boreal-Pacific Province prior to the Albian (at least during the Early Barremian and Early Aptian), which is consistent with the interpretation of other authors (e.g., Baraboshkin, 2007).

3.2. Early to middle Late Albian interval

In the early–middle Late Albian, the Bering Land Bridge seems to be formed between Asia and North America again because there is no evidence, showing influence of cooler waters from the Arctic Ocean in the northern part of the Boreal-Pacific Province. Furthermore, both the early Late Albian Lower Ginter flora in the Koryak Upland and Albian Kukpowruk flora in northern Alaska are thermophilous (Figs. 6 and 7). The Bering Land Bridge enabled to plant interchanges (Herman, 2007a). The plant reproductive bodies could not be transported in the main across narrow marine waters in case of its reality.

The *Cycadophytes*-bearing Kukpowruk flora, determined from the lower-middle part of the Nannushuk Formation (Mull et al., 2003), is the most ancient Cretaceous flora in northern Alaska (Spicer and Herman, 2001; Herman and Spicer, 2002; Herman, 2007a,b). It is characterised by predominance of Early Cretaceous plant ferns and cycadophytes and the presence of ancient conifers (*Podosamites*) and rare angiosperms (Herman, 2007a,b). It seems to be thermophilous because of possible climatic influence of a warm current, kept more likely via the WIS (Fig. 7).

Baraboshkin (2007) following Hancock et al. (1993) and Yacobucci (2004), according to whom the Albian–Cenomanian boundary within the Mowry Shale is located at the base of the *Neogastroplites cornutus* Zone (judging from Obradovich's et al. (2002) argon–argon data from Japan), concludes that the WIS did not exist as early as Early Cretaceous.

Newly published dinoflagellate data (Oboh-Ikuenobe et al., 2007, 2008; Scott, 2007; Scott et al., 2009) support the original correlation of the Albian–Cenomanian boundary with the 97.2 Ma Clay Spur

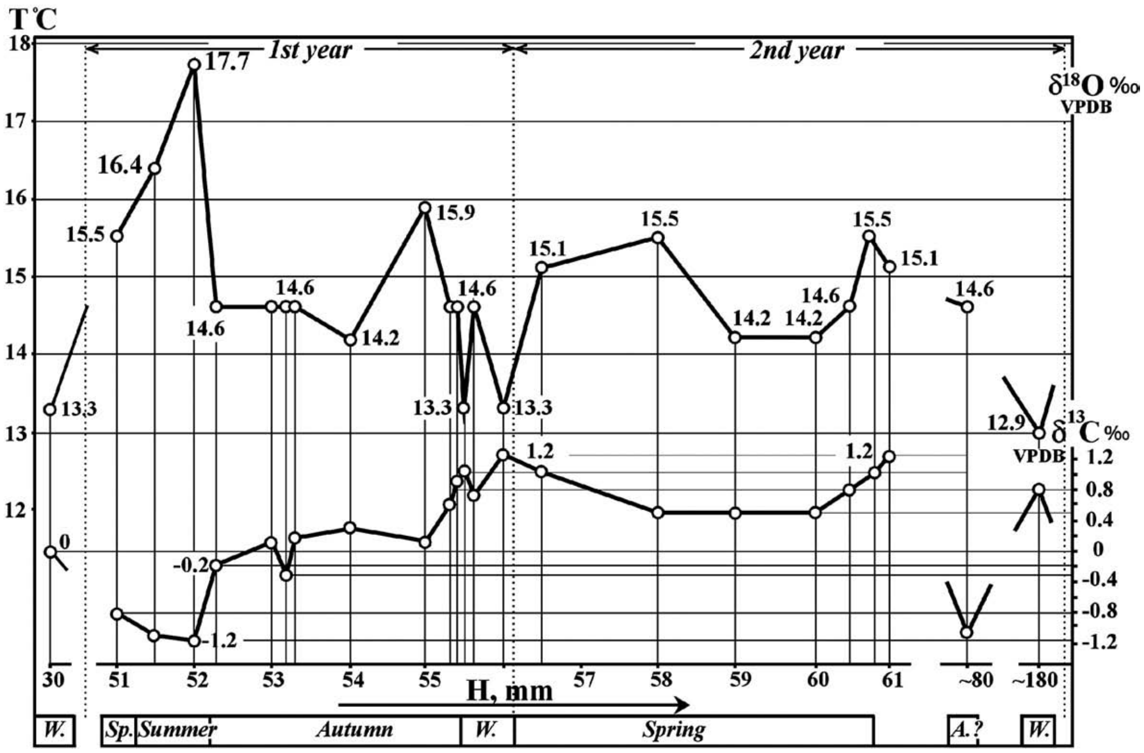


Fig. 4. Seasonal growth temperatures (upper curve) and carbon isotope (lower curve) for the aragonitic ammonoid *Grantziceras affine* (shell A-1 from the upper part of the Lower Albian, Ammonite Creek, Matanuska River basin, southern Alaska) (late part of the adult ontogenetic stage, with a prospective duration of about two years inferred from the $\delta^{18}O$ isotopic signature). Abbreviations: W. — winter, Sp. — spring, A. — autumn, H — whorl height.

bentonite and show that during deposition of the Mowry Shale (depositional Skull Creek Cycle) two intermediate minor late Albian connections with the Carribian developed. A full connection was ~100–102 Ma (Late Albian *Hysteroceras orbigni* Subzone) (R.W. Scott' pers. com.). These finding support the hypothesis (e.g., Kauffman, 1984; Nesov, 1992; Naidin, 2001, 2007) that the WIS was an active migration route for marine faunas during the post-Early Albian Cretaceous, except during regressive phases, such as the latest Albian to earliest Cenomanian, when the restricted epeiric Mowry Sea was a southward extension of the Arctic Ocean covering much of the Canadian WIS and extending as far south as central Colorado (Reeside and Cobban, 1960; Kauffman, 1984; Pokhialainen, 1985; Williams and Stelck, 1975; Naidin, 2001, 2007). On this evidence only late Albian warm currents might have influenced the formation of the thermophilous Kukpowruk flora in northern Alaska.

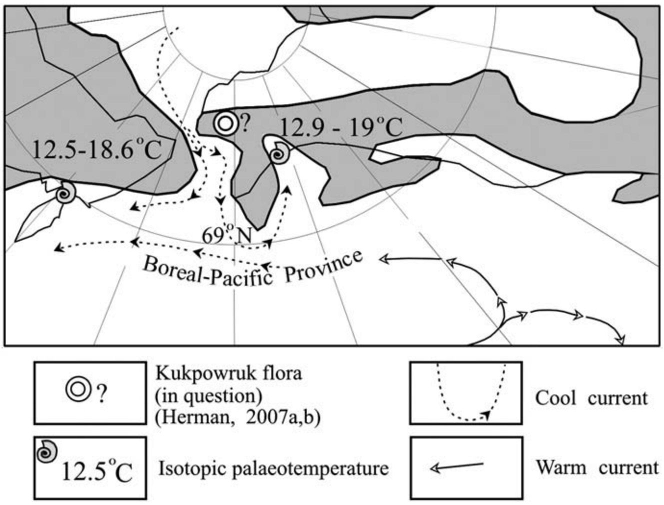


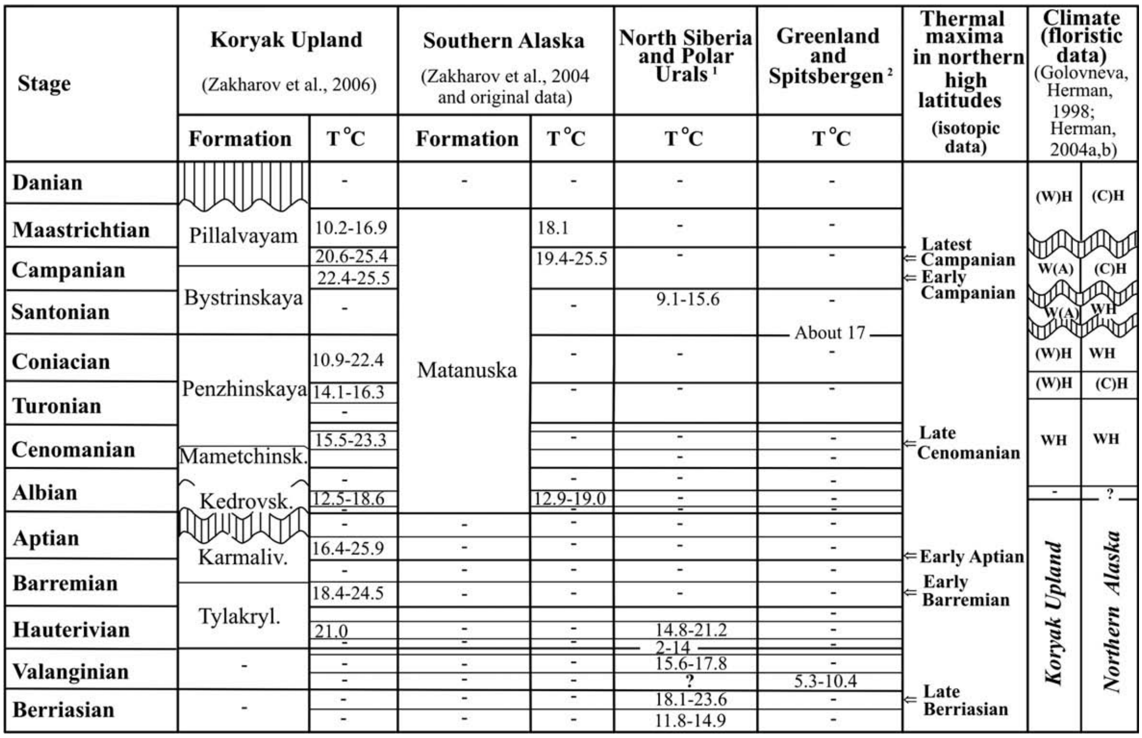
Fig. 5. Map showing palaeotemperatures determined on the basis of oxygen isotopic analysis (Zakharov et al., 2005 and original data), and some palaeofloristic data for the late part of the Early Albian (~107 Ma), Alaska–Koryak Upland area.

3.3. Early to Late Cenomanian interval

The Bering Land Bridge existed apparently during the Cenomanian through Turonian, enabling active exchange between the thermophilous latest Albian–middle Cenomanian Niakogon flora and latest Albian through Turonian Grebenka flora in northern Alaska and the Koryak Upland, respectively (Figs. 6 and 8). No evidence shows influence of cooler waters of the Arctic Ocean in the marine Boreal-Pacific Province. Both Early and Late Cenomanian palaeotemperatures calculated from isotopic composition of brachiopod and inoceramid bivalve shells of the Koryak Upland, in contrast, are comparatively warm, fluctuating from 15.5° to 22.4 °C and from 20.4° to 23.3 °C, respectively (Figs. 6 and 8) (Zakharov et al., 2006c).

3.4. Turonian interval

Palaeotemperatures in the marine Boreal-Pacific province cooled during Cenomanian to Late Turonian based on isotopic composition of early Late Cenomanian brachiopod and bivalve shells (20.4–23.3 °C) and a late Turonian ammonoid shell (14.1–16.3 °C) from the Koryak Upland (Fig. 6). Furthermore, the Turonian Kaolak flora in northern Alaska became cool-temperate possibly because of poleward oceanic heat-transport via the WIS of North America was blocked (Fig. 9). However, late Early Turonian–Late Turonian Penzhina flora from the Koryak Upland was intermediate between thermophilous and cool-



Stage	Koryak Upland (Zakharov et al., 2006)		Southern Alaska (Zakharov et al., 2004 and original data)		North Siberia and Polar Urals [1]	Greenland and Spitsbergen [2]	Thermal maxima in northern high latitudes (isotopic data)	Climate (floristic data) (Golovneva, Herman, 1998; Herman, 2004a,b)	
	Formation	T °C	Formation	T °C	T °C	T °C			
Danian		-	-	-	-	-		(W)H	(C)H
Maastrichtian	Pillalvayam	10.2-16.9	Matanuska	18.1	-	-			
Campanian		20.6-25.4 22.4-25.5		19.4-25.5	-	-	⇐ Latest Campanian ⇐ Early Campanian	W(A)	(C)H
Santonian	Bystrinskaya	-		-	9.1-15.6	-		W(A)	WH
Coniacian	Penzhinskaya	10.9-22.4		-	-	About 17 -		(W)H	WH
Turonian		14.1-16.3 -		-	-	-		(W)H	(C)H
Cenomanian	Mametchinsk.	15.5-23.3		-	- -	- -	⇐ Late Cenomanian	WH	WH
Albian	Kedrovsk.	- 12.5-18.6		- 12.9-19.0	- -	- -		-	?
Aptian	Karmaliv.	- 16.4-25.9	- -	- -	- -	- -	⇐ Early Aptian	Koryak Upland	Northern Alaska
Barremian		- 18.4-24.5	- -	- -	- -	- -	⇐ Early Barremian		
Hauterivian	Tylakryl.	21.0 -	- -	- -	14.8-21.2 2-14	- - -			
Valanginian	-	- -	- -	- -	15.6-17.8 ?	- 5.3-10.4			
Berriasian	-	- -	- -	- -	18.1-23.6 11.8-14.9	- -	⇐ Late Berriasian		

Fig. 6. Cretaceous palaeotemperatures and thermal maxima in northern high latitudes: isotopic evidence from southern Alaska, Koryak Upland, northern Siberia-Polar Urals area, Spitsbergen and Greenland. Climate (palaeobotanical evidence): (C)H — cool-temperate humidic, WH — warm humidic, (W)H — warm-temperate humidic, W(A) — warming with a weak aridity. Abbreviations (formations): Mametchinsk. — Mametchinskaya, Kedrovsk. — Kedrovskaya, Karmaliv. — Karmalivayamskaya, Tylakryl. — Tylakrylskaya. Other references: [1]Teiss and Naidin (1973); Golbert (1987); Teiss et al. (1968); Berlin and Khabakov (1970); Price and Mutterlose (2004). [2]Lowenstam and Epstein (1959); Ditchfield (1997).

temperate, containing only rare thermophilous elements (*Cycadophytes*). The Bering Land Bridge apparently continued to exist during at least the main part of the Turonian, favoring an active exchange between local floras of that time (Herman, 2007a,b).

The presence of a Turonian belemnite rostrum in the Koryak Upland (T.A. Jagt-Yasykova and L.I. Doguzhaeva's pers. com.) may be a result of possible short-term migration of the Arctic belemnite fauna via the Strait of Alaska which occurred at the very end of the Turonian.

3.5. Coniacian interval

The development of the thermophilous Coniacian Tuluvak flora in northern Alaska (Fig. 6) indicates poleward oceanic heat-transport via the WIS in Coniacian time. As in the late Early Albian, a marked seasonal contrast in the Koryak Upland is documented by $\delta^{18}O$ isotopic signature (Zakharov et al., 2005). Cooler Polar marine waters penetrated south via the Strait of Alaska (Fig. 10). These geochemical patterns are consistent with a significant reduction of thermophilous elements in the Coniacian

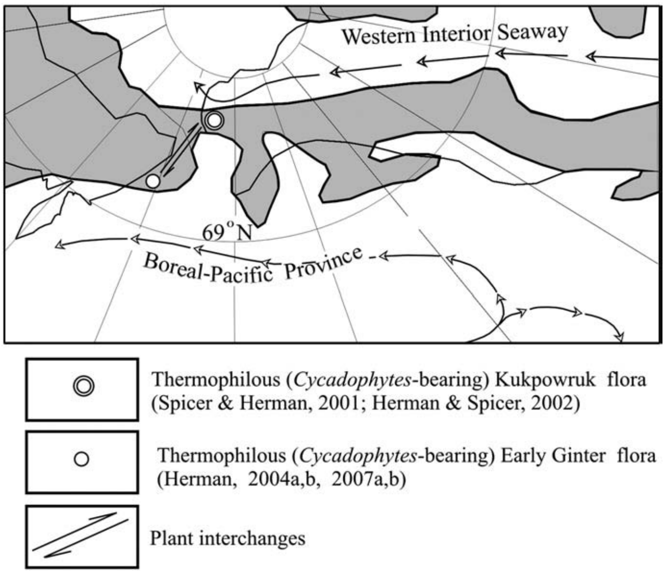


Fig. 7. Map showing some palaeofloristic data for the early–middle part of the Late Albian (~100 Ma), Alaska–Koryak Upland area. Other designation as in Fig. 5.

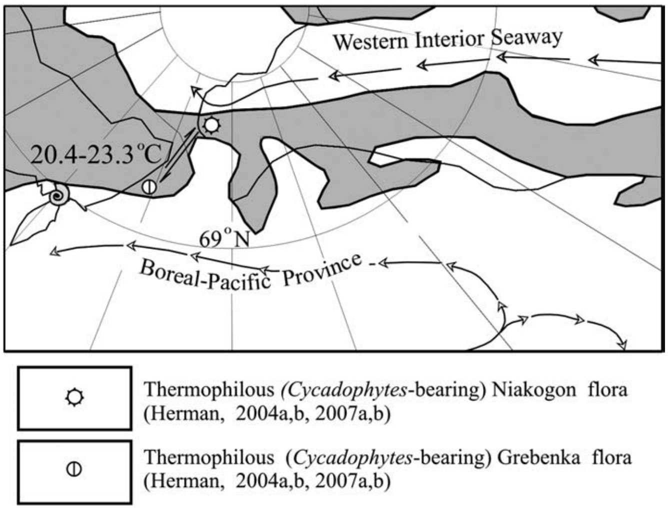


Fig. 8. Map showing palaeotemperatures, determined on the basis of oxygen isotopic analysis (Zakharov et al., 2004, 2006c), and some palaeofloristic data for the Early–Late Cenomanian (~94–99 Ma), Alaska–Koryak Upland area. Other designation as in Fig. 4.

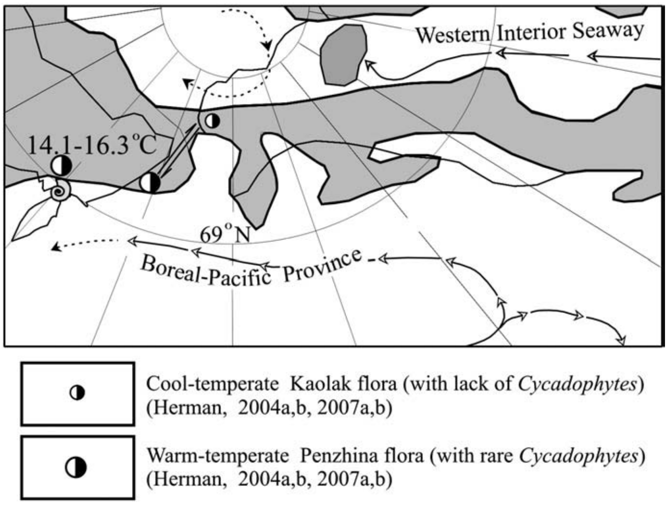


Fig. 9. Map showing palaeotemperatures, determined on the basis of oxygen isotopic analysis (Zakharov et al., 1996, 2006c), and some palaeofloristic data for the Late Turonian (~90 Ma), Alaska–Koryak Upland area. Other designation as in Fig. 4.

Kaivayam flora of the Koryak Upland (Herman, 2007a,b). The Coniacian ammonoid fauna of the Koryak Upland includes *Kossmaticeras japonicum* Matsumoto, *Tetragonites glabrus* (Jimbo), *Tetragonites popetensis* Yabe, *Gaudryceras denseplicatum* (Jimbo), *Yokoyamaoceras katoi* (Jimbo), *Mesopuzosia yubarenis* (Jimbo), and *Yezoites pseudoaequalis* (Yabe) and has a great affinity with that from Hokkaido but is less diverse.

3.6. Santonian–Late Campanian interval

The Coniacian thermophilous, *Cycadophytes*-bearing, flora was replaced by the cool-temperate, latest Santonian–early Late Campanian Lower Kogosukruk flora in northern Alaska (Herman, 2007a,b). Perhaps poleward oceanic heat-transport via the WIS of North America was blocked during much of the Campanian.

The cool-temperate latest Santonian–early Late Campanian Lower Kogosukruk flora of northern Alaska was considerably different from the thermophilous Santonian–early Late Campanian Barykov flora of the Koryak Upland (Figs. 6 and 11). Moreover, higher palaeotemperatures are indicated by isotopic data of Early Campanian ammonoids from the Koryak Upland (Zakharov et al., 2006c). Both the palaeofloristic and the isotopic evidence from the Koryak Upland demonstrate the existence of the Bering Land Bridge and therefore the absence of cool-water influence in the Boreal-Pacific province at least during early Campanian time (Fig. 11).

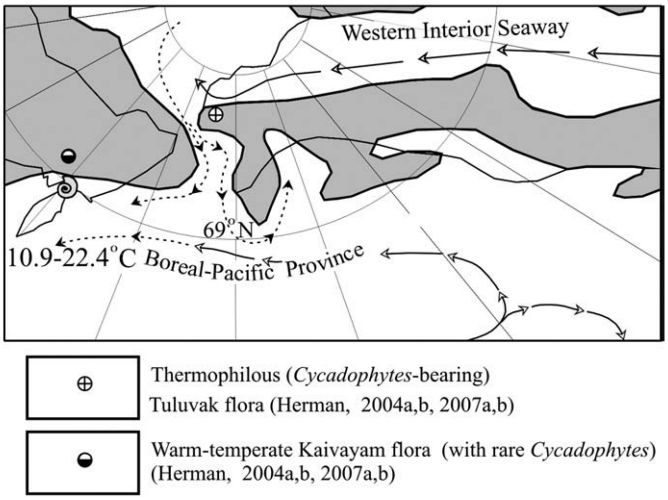


Fig. 10. Map showing palaeotemperatures, determined on the basis of oxygen isotopic analysis (Zakharov et al., 2004, 2006c), and some palaeofloristic data for the Coniacian (~87 Ma), Alaska–Koryak Upland area. Other designation as in Fig. 4.

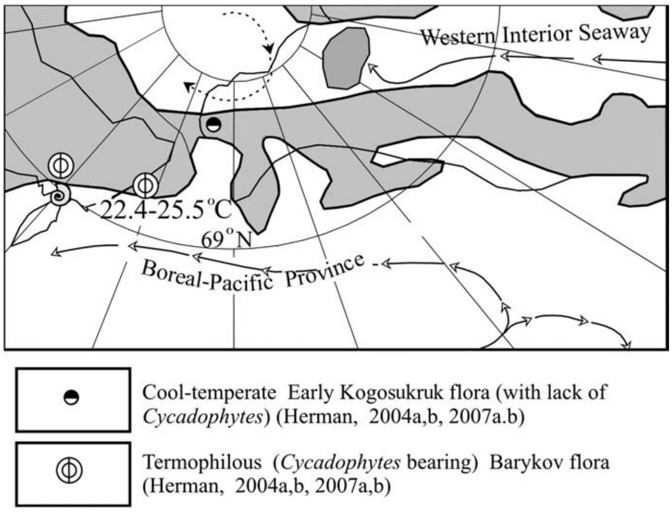


Fig. 11. Map showing palaeotemperatures, determined on the basis of oxygen isotopic analysis (Zakharov et al., 2004, 2006c), and some palaeofloristic data for the Early Campanian (~78 Ma), Alaska–Koryak Upland area. Other designation as in Fig. 4.

3.7. Latest Campanian interval

The latest Campanian palaeoenvironmental situation was very similar to that for the Early Campanian in the Boreal-Pacific Province (Koryak Upland and southern Alaska) and in northern Alaska (Figs. 6 and 12). Comparatively high palaeotemperatures are calculated from ammonoids of both the Koryak Upland (20.6–25.4 °C) (Zakharov et al., 2006c) and southern Alaska (19.4–25.5 °C). The cool-temperate

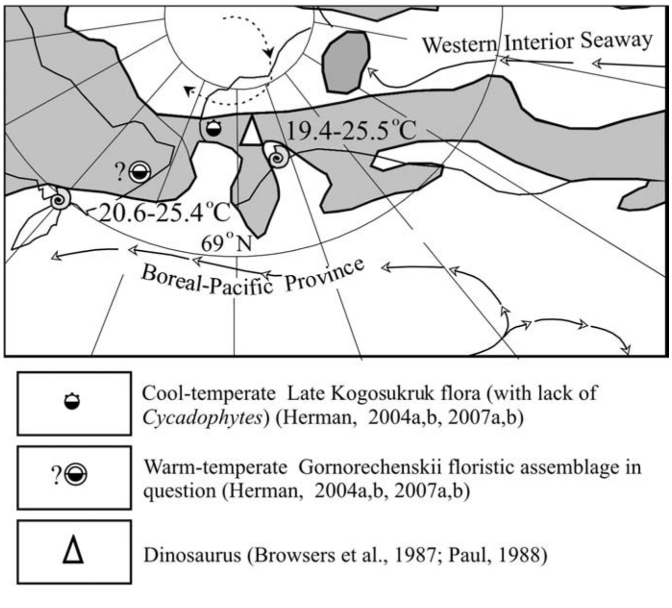


Fig. 12. Map showing palaeotemperatures, determined on the basis of oxygen isotopic analysis (Zakharov et al., 2004 and original data), and some palaeofloristic and dinosaur data for the latest Campanian (~71 Ma), Alaska–Koryak Upland area. Other designation as in Fig. 4.

late Late Campanian–Maastrichtian Upper Kogosukruk flora existed in northern Alaska and the thermophilous late Late Campanian–Early Maastrichtian Gornorechenskij flora was in the Koryak Upland (Fig. 6).

3.8. Maastrichtian interval

As was mentioned above, cool-temperate Upper Kogosukruk and thermophilous Gornorechenskij floras continued to exist in the northern Alaska–Koryak Upland area during the Early–Late Maastrichtian and Early Maastrichtian, respectively (Herman, 2007a,b). Floristic evidence of cool-water influence in the Boreal-Pacific Province (Koryak Upland) is absent possibly because of northern a land barrier separating this area from the Arctic Ocean at that time. Early Early Maastrichtian palaeotemperatures calculated from isotopic data from southern Alaska (18.1 °C) and the Koryak Upland (10.2–16.9 °C) (Fig. 6) are lower than those calculated for the Campanian of the Koryak Upland (Fig. 13). This may be due to the effect of a global climatic shift. The latter is confirmed by the isotopic data from some Early Maastrichtian middle latitude areas (e.g., Zakharov et al., 2006c).

3.9. Latest Maastrichtian to Danian interval

According to the Herman's (2007a,b) data, an active connection between the Sagvon-1 flora in northern Alaska and the Koryak flora in the Koryak Upland was interrupted in the Campanian to Early Maastrichtian and was renewed in latest Maastrichtian–Danian time. However, *Cycadophytes* were not found in either floras in latest Maastrichtian–Danian time. At the end of the Cretaceous only the late Early Maastrichtian Kakanaut flora of the Koryak Upland was *Cycadophytes*-bearing, thermophilous (Krassilov, 1981; Krassilov et al., 1990). Information on the dinosaur migration seems to be important for Cretaceous palaeogeography (Colbert, 1964; Béland and Russel, 1978; Browsers et al., 1987; Paul, 1988; Nesov, 1995). However, discovery of Late Maastrichtian North American dinosaurs (Nesov, 1995) is especially important, as their occurrence in the Bering region of the Koryak Upland (Nesov, 1995) seems to be an additional strong evidence that the Bering Land Bridge existed during Late Maastrichtian to Danian time (Fig. 14).

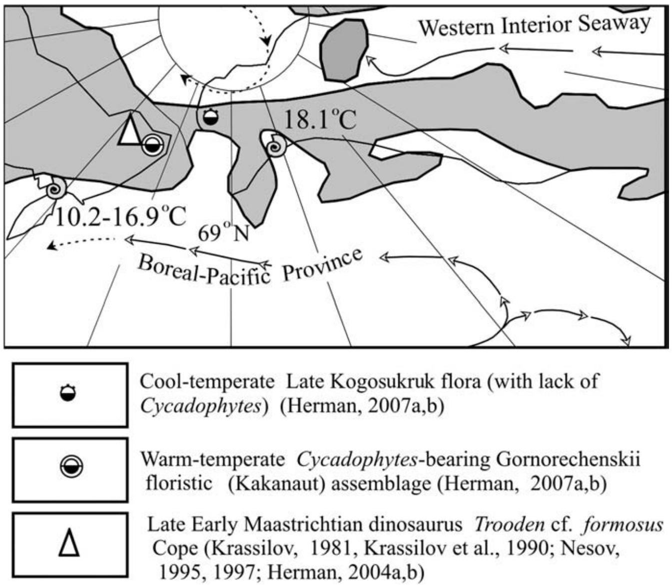


Fig. 13. Map showing palaeotemperatures, determined on the basis of oxygen isotopic analysis (Zakharov et al., 2004 and original data), and some palaeofloristic and dinosaur data for the late part of the Early Maastrichtian (~68–70 Ma), Alaska–Koryak Upland area. Other designation as in Fig. 4.

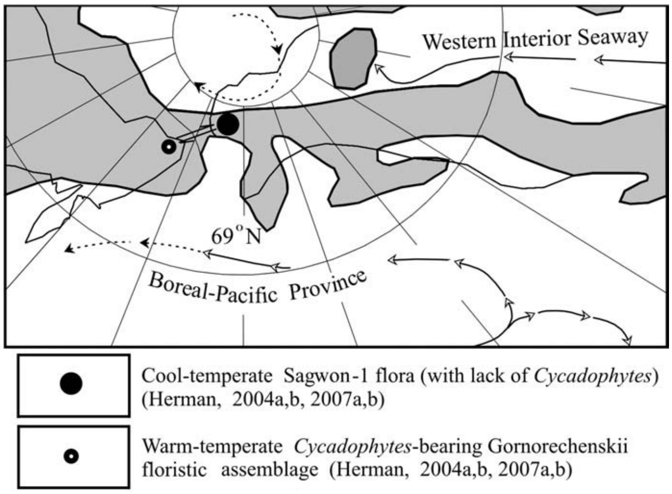


Fig. 14. Map showing some palaeofloristic data for the latest Maastrichtian–Danian (~65–66 Ma), Alaska–Koryak Upland area. Other designation as in Fig. 4.

3.10. Preliminary correlation of the Lower Albian using $\delta^{13}C$ data

Information on post-Aptian Cretaceous biological productivity in high-latitude seas of southern Alaska, based on carbon isotopic data, are very limited: the main data are reported from the aforementioned late Early Albian interval. 18 samples from 24 taken from the well-preserved Early Albian ammonoid *G. affine* shell show positive $\delta^{13}C$ values, with an average value of 0.07‰. Only in a couple of them $\delta^{13}C$ value reaches 1.2‰. Heaviest $\delta^{13}C$ values (>3‰) for the Albian in Italy have been discovered about 4.5 m above the base of the Albian at Piobbico (Erbacher, 1994). This level was referred by Erbacher (1994) as OAE1b. Because a positive carbon-isotope anomaly has not been recognized within the Lower Albian *B. hulense* Zone in southern Alaska, this interval more likely corresponds to the upper Lower Albian interval overlying the OAE1b in Italy.

4. Conclusions

1. Significant seasonal contrast marked the Alaska–Koryak Upland area during the late part of the Early Albian, as well as in the Coniacian (Zakharov et al., 2005). Seasonality was possible partly because of the penetration of cool waters via the Strait of Alaska during the late Early Albian and the Coniacian. Relatively cool Maastrichtian palaeotemperature estimated from oxygen isotopic analyses on calcite of late Early Maastrichtian brachiopods from the Koryak Upland and aragonite of ammonoids from southern Alaska might have been a response to a global Early Maastrichtian climatic shift.
2. In the Bering area Albian through Late Cretaceous warm climatic conditions are inferred from stable isotope and the palaeobotanical data (Herman, 2007a,b) during 1) Late Albian (terrestrial warming in the north Alaska–Koryak Upland area), 2) Cenomanian (terrestrial and marine warming in the northern Alaska and Koryak Upland, respectively), 3) Coniacian (terrestrial warming in northern Alaska), 4) Santonian–Early Campanian (both the terrestrial and the marine warming in the Koryak Upland), 5) latest Campanian (marine warming in the southern Alaska–Koryak Upland area), and 6) late Early Maastrichtian (terrestrial warming in the Koryak Upland) (Fig. 6).
3. Recurrent terrestrial cooling of northern Alaska took place possibly because of poleward oceanic heat-transport via the WIS of Northern America was blocked in the Turonian and Santonian to Danian. During the very end of the Maastrichtian terrestrial cooling in north Alaska may have been intensified by the ensuing global climate shift. Available stable isotopic data (Ditchfield, 1997;

Zakharov et al., 2006c) and palaeontological evidence (Herman and Spicer, 1997; Herman et al., 2004a; Jenkyns et al., 2004; Spicer and Herman, 2009) allow us to assume only a short-lived existence of subfreezing conditions that occurred occasionally in the Northern Hemisphere probably during polar winter months in the early Valanginian, late Coniacian–earliest Santonian and Early Maastrichtian. However, it was probably never sufficiently cold for longer period to allow the formation of sea ice. 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 via the WIS (during early–middle Late Albian, Cenomanian–Turonian, Coniacian and early–middle Campanian) and some other straits, including the Turgai.

4. The high-latitude isotopic and palaeontological records provide evidence of the fact that the Bering Land Bridge enabled biotic migration between North America and Eurasia during the latest part of the Early Cretaceous to Danian except during the late part of the Early Albian and Coniacian. A similar situation is suggested also for the Early Barremian and Early Aptian (Fig. 6), taking into account polar warmth through these times (at least for the Koryak Upland area) (Zakharov et al., 2006c).

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