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Palaeotemperature curve for the Late Cretaceous of the northwestern circum-Pacific

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In the northwestern circum-Pacific, two main trends in Late Cretaceous temperatures can be recognized. (1) In general, a recurrent warming trend is thought to have begun in the Turonian–Campanian, reaching temperature maxima in the early Late Santonian and early Late Campanian, and temperature minima in the earliest Santonian and perhaps early Campanian. (2) During the Maastrichtian, temperatures dropped sharply, with only a slight warming in the early Late Maastrichtian. The existence of a thermal maximum at the Coniacian–Santonian transition has previously been expected, but is not confirmed by new isotopic results.

KEY WORDS: K/T boundary; oxygen and carbon isotopes; palaeotemperatures; palaeoproductivity; molluscan diversity; Hokkaido; Sakhalin; Koryak Upland.

1. Introduction

Isotopic palaeotemperature trends for the Cretaceous of Western Europe and Svalbard were recognized by Lowenstam & Epstein (1954), Spaeth *et al.* (1971) and Ditchfield (1997), mainly on the basis of data from calcitic belemnite rostra. Palaeotemperatures for the Cretaceous of the Russian Platform and neighbouring areas were described by Teiss & Naidin (1973), who also used belemnite material for their analyses. Palaeotemperature curves for the Cretaceous and Cretaceous/Tertiary boundary transition of the Pacific, Atlantic and Antarctic Oceans, mainly on the basis of planktonic and benthic foraminiferal data, nannoplankton and limestones, were presented by Douglas & Savin (1971, 1973, 1975), Anderson & Schneidermann (1973), Coplen & Schlanger (1973), Boersma & Shackleton (1981), Barrera *et al.* (1987), Pirrie & Marshall (1990a, b), Stott & Kennett (1990) Alcala-Herrera *et al.* (1992), Ditchfield *et al.* (1994), Huber *et al.* (1995) and Jenkyns *et al.* (1995). Most of these authors found that the warmest Cretaceous temperatures were recorded for the Albian and cooling temperatures during the Late Cretaceous, especially in the Maastrichtian.

The purpose of our study is to present a palaeotemperature curve for the Late Cretaceous of the northwestern circum-Pacific using predominantly aragonitic material to check previous results based on data from calcitic material. This is because it is often difficult to determine the extent of diagenetic alteration in calcitic fossils, with the apparent exception of articulate brachiopods (Grossman *et al.*, 1991; Mii *et al.*, 1997).

2. Material and methods

Oxygen and carbon isotopes were determined mainly for Turonian–Maastrichtian ammonoids and inoceramid bivalve shells preserved as aragonite. They were mostly recovered from Hokkaido (Japan) and southern Sakhalin (Russia). Additional samples from well-preserved (silver-white in colour) Campanian and

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Maastrichtian brachiopods from south Sakhalin, Turonian aragonite ammonoid material from the Koryak Upland (Kamchatka region) and a single Middle Danian calcite bivalve shell from south Sakhalin were also analysed for comparative purposes.

Some years ago we proposed five stages in diagenetic alteration in aragonitic shells which could be used in the evaluation and careful selection of ammonoid or inoceramid aragonitic material prior to isotopic investigations (Zakharov *et al.*, 1975) as follows:

(1) Stage of weakening of the crystal lattice (characterized only by changes in the Sr content of different parts of the aragonitic shell): secondary calcite is usually absent or represented by a small portion (not more than 1–5%). Rogland *et al.* (1969) stated that changes in the Sr/Ca ratio may be connected with inorganic processes in shells just before recrystallization. Aragonitic material of this stage seems to preserve both its original oxygen and carbon isotopic compositions.

(2) Stage of slight recrystallization (characterized by lower Sr concentrations and appearance of a larger portion (5–30%) of secondary calcite). Material of this stage seems to preserve more or less primary crystal structure observable under the scanning electron microscope (SEM) and its original isotopic composition.

(3) Stage of significant recrystallization (shell material consists of approximately 30–50% of secondary calcite). Only a limited number of specimens show more or less original carbon and more rarely oxygen-isotopic composition.

(4) Stage of considerable recrystallization. This is apparently a very short-lived stage, characterized by the presence of more than 50% secondary calcite, and seems to be followed by a very pronounced change in both crystal structure and isotopic composition.

(5) Stage of complete recrystallization, during which the characteristic feature for shell material is represented by secondary calcite with lower Sr concentrations and high Mg and Fe content.

Material exhibiting stages 4 and 5 and part of stage 3 alteration seems to be unsuitable for distinguishing the true (original) isotopic record. The results of X-ray diffraction analyses and SEM observations reveal that most of the aragonitic ammonoid and inoceramid samples from the Upper Cretaceous of Hokkaido, Sakhalin and the Koryak Upland, carefully selected after visual inspection, correspond to the first two stages of diagenetic alteration and should have preserved both their original oxygen and carbon isotopic records. To find signs of alteration in well-preserved brachiopod shells from the Upper Campanian and Maastrichtian of the Naiba River Basin, south Sakhalin, a preliminary luminescent test was used, as recommended by Grossman *et al.* (1991).

Oxygen and carbon isotope measurements were made at the Far Eastern Geological Institute (FEGI), Vladivostok, using a modernized MI-1201B mass spectrometer, 'Iskra-1256'-PRM-2 complex. The laboratory gas standard was calibrated to V-SMOW and KH-2 standards. X-ray analyses were carried out using a DRON-3 diffractometer following the method of Davis & Hooper (1963). The laboratory standard used in the measurements was calibrated relative to calcite NBS (National Bureau of Standards) 19 and equals +3.98 ± 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 0.1‰.

In calculating the temperatures, it was assumed that Cretaceous seawater was free from icecaps and therefore a $\delta^{18}O$ of − 1.2‰ PDB (equivalent to − 1.0‰ SMOW) was thought to be appropriate (Savin, 1977).

3. Geological setting of samples

Turonian

Shells of Turonian age preserved as aragonite have not been discovered in Sakhalin, only in Hokkaido (K. Tanabe's collection) and the Koryak Upland (G.V. Guseva's collection). Cenomanian–Turonian sediments in Hokkaido are represented by the Mikasa and Saku Formations (upper Middle Yezo Group) (Hirano *et al.*, 1992). The former consists mainly of sandstone with intercalations of shelly material whereas the latter is rich in siltstone and mudstone. The samples for isotope analysis were taken from aragonitic ammonoid shells discovered in calcareous nodules from the Upper Turonian Saku Formation (upper Middle Yezo Group) in Nakafutamata Creek, Haboro area (Figure 1, Table 1).

In the Koryak Upland, an ammonoid preserved as aragonite belonging to *Mesopuzosia pacifica* Matsumoto was discovered in a nodule within the deep-water Vatym Group on the right bank of the Pakhacha River, 12 km above the mouth of Echviyam Creek (Table 2). The Vatym Group is characterized by the presence of a small portion of shallow-water sediments (in olistoliths) containing inoceramid bivalves and very rare ammonoid shells.

Coniacian

Aragonite-preserved ammonoids were discovered only in Hokkaido (K.Tanabe's collection) (Table 3). Isotopic analyses were carried out on shells of *Anagaudryceras limatum* (Yabe) recovered from calcareous

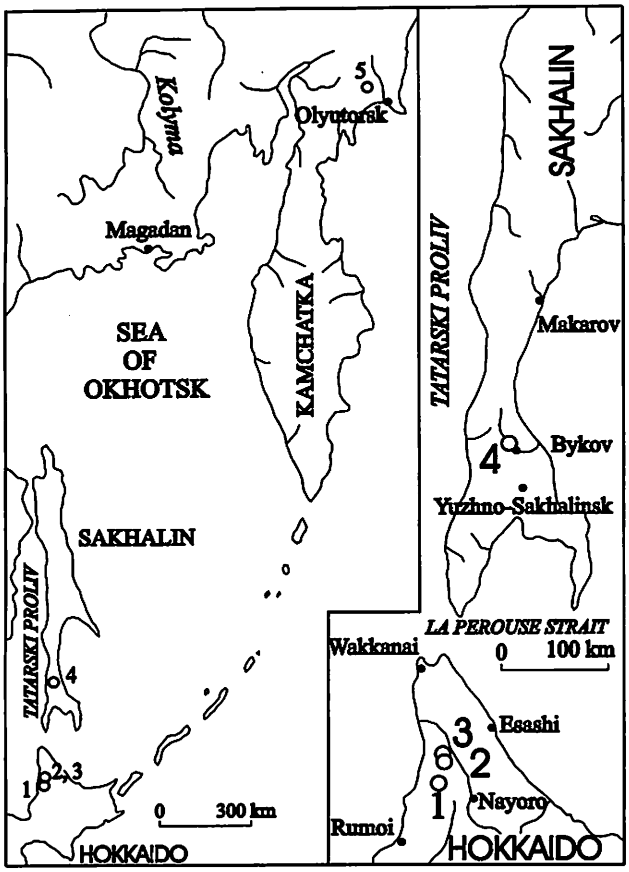

Figure 1. Location of the Nakafutamata Creek, Haboro area, Hokkaido (1, Turonian and Coniacian); Abeshinai River, Hokkaido (2, Santonian; 3, Campanian); Naiba River basin, South Sakhalin (4, Santonian-Danian); Pakhacha River basin, Koryak Upland (5, Turonian).

nodules embedded in Lower Coniacian silty mudstone (lower Upper Yezo Group) of Nakafutamata Creek in the Haboro area.

Santonian

Aragonitic shells of ammonoids and inoceramid bivalves were collected from the upper Bykov Formation (Lower Santonian, *Anapachydiscus naumanni* beds) of the Naiba River, south Sakhalin (Table 4) and Upper Yezo Group (upper *Inoceramus japonicus* Zone or lower *Inoceramus orientalis* Zone) of the Abeshinai River, Hokkaido (Table 5). Tanabe indicates herein a Late Santonian age for samples collected from the Upper Yezo Group, following the interpretation of Hirano *et al.* (1992). The upper Bykov Formation and Upper Yezo Group are represented mainly by mudstones with calcareous nodules (Zakharov *et al.*, 1981, Hirano *et al.* 1992). The samples for isotope analysis were taken from aragonitic material of inoceramid bivalves and ammonoid shells discovered in boulders.

Campanian

Aragonitic ammonite and inoceramid shell material was collected from the uppermost part of the Yezo Group of Early Campanian age along the Abeshinai River, Hokkaido (Table 5). Some well-preserved Upper Campanian brachiopods from the lower part of the Krasnoyarka Formation along the Naiba River, south Sakhalin, were also used for isotopic analysis (Table 6). The uppermost part of the Yezo Group consists mainly of mudstones containing calcareous nodules (Hirano *et al.*, 1992) whereas the lower Krasnoyarka Formation is represented by tuffaceous siltstones, tuffaceous sandstones, tuffs and siltstones with several coquina layers (Zakharov *et al.*, 1981, 1984).

Maastrichtian

The well-preserved Maastrichtian ammonites and brachiopods used for isotopic analyses were collected from the upper part of the Krasnoyarka Formation of the Naiba River basin, south Sakhalin. This is mainly composed of mudstones with calcareous nodules in the lower part (*Zelandites japonicus* beds) and mudstones, siltstones and tuffaceous sandstones in the upper part (*Pachydiscus-Pleurogrammatodon bykovensis* beds) (Zakharov *et al.*, 1984). Aragonitic ammonites and well-preserved brachiopod shells used for isotopic analyses were collected from nodules taken from several horizons (Tables 6, 7).

Danian

After a detailed investigation of bivalve, foraminiferal and palynologic assemblages of the Sinegorsk member in south Sakhalin, Kalishevich *et al.* (1981) concluded that the age of this member is early Palaeogene (Danian). The member mainly consists of siltstones with minor sandstones. No aragonitic shells have been found. As a result, we have no original information on Danian $\delta^{18}O$, only on $\delta^{13}C$ (on the basis of data from a single bivalve shell).

4. Results of isotopic analysis

Aragonite oxygen-isotope values become slightly lighter from the Turonian to the lower Coniacian in the shallow-water Hokkaido–south Sakhalin Basin

Table 1. Carbon and oxygen isotope analyses of aragonitic ammonoid shells from the Upper Turonian of Hokkaido and late Turonian palaeotemperatures for middle latitudes of the Northern Hemisphere (H, height; W, width).

				Diagenetic alterations						
Sample	Species	Group, locality	Location (H & W, in mm)	Diagenetic stage	Aragonite (%)	α-SiO_2 (%)	Colour	$\delta^{13}C$ (PDB) (‰)	$\delta^{18}O$ (PDB) (‰)	T°C
H3403p-1	*Scalarites* sp. cf. *mihoensis* Wright & Matsumoto	Upper Middle Yezo; Tanabe's loc. H3403p; Habaro area, Nakafutamata Creek	H=19.0	1st	96 ± 3	0	Cream	+1.57	−0.09	15.8[a] (12.3)[b]
H3403p-2	Same shell	Upper Middle Yezo; Tanabe's loc. H3403p; Habaro area, Nakafutamata Creek	H=20.0	2nd	89 ± 3	0	Cream	+0.87	−0.29	16.6 (13.1)
H3403p-5	Undetermined ammonoid	Upper Middle Yezo; Tanabe's loc. H3403p; Habaro area, Nakafutamata Creek	H=13.0	1st	97 ± 3	0	Cream	+1.17	−0.09	15.8 (12.3)
H3403p-4	Same shell	Upper Middle Yezo; Tanabe's loc. H3403p; Habaro area, Nakafutamata Creek	H=14.0	1st	95 ± 3	0	Cream	+0.47	0.00	15.4 (12.0)
H3403p-3	Same shell	Upper Middle Yezo; Tanabe's loc. H3403p; Habaro area, Nakafutamata Creek	H=15.0	2nd	91 ± 3	Trace	Cream	−0.03	+0.19	14.5 (11.2)
H3403p-6	*Tragodesmoceroides* sp.	Upper Middle Yezo; Tanabe's loc. H3403p; Habaro area, Nakafutamata Creek	H=6.0 W=6.5	2nd	85 ± 3	0	Cream	−0.13	+0.77	12.0 (9.0)

[a]Grossman & Ku (1986); [b]Anderson & Arthur (1983).

(Tables 1, 3). The heaviest values for the Late Cretaceous occur in the lowest Santonian. The lightest aragonite oxygen-isotopic values seem to be in the lower part of the Upper Santonian. They become heavier again in the uppermost Santonian–Lower Campanian. The relatively light inoceramid aragonite and brachiopod calcite isotopic values for the Upper Campanian through the lower part of the Lower Maastrichtian become significantly heavier in the middle and upper part of the Lower Maastrichtian. Values then drop off slowly through the lower part of the Upper Maastrichtian (data from calcitic benthic shells).

$\delta^{13}C$ values are higher in general in the Upper Turonian, Lower Coniacian, Upper Campanian, lower part of the Upper Maastrichtian, and especially (+2.47‰) in the lower part of the Upper Santonian. They are lower through the lowest Santonian and Lower Maastrichtian, which agrees more or less with the diversity of the mollusc faunas of south Sakhalin (Zakharov *et al.*, 1996).

5. Palaeotemperature estimation

As shown above, previous oxygen-isotope data indicate the following trends in temperature change: after the Albian temperature maximum, cooling occurred in general during the Late Cretaceous, a minimum being reached in the Maastrichtian.

Very important results on shallow-water temperatures in high latitudes of the Southern Hemisphere have been presented by Barrera *et al.* (1987). They discovered high $\delta^{18}O$ values in late Campanian–Maastrichtian shells of benthic foraminifera from the Antarctic shelf near Seymour Island, corresponding to comparatively low temperatures (about 4–9°C). These high-latitude, shallow-water temperatures are similar to those inferred from the isotopic ratios of Late Cretaceous deep-water foraminifera from lower latitudes in the Pacific, indicating that the shallow continental shelves of Antarctica were probably a source of cold deep water during the Late Cretaceous, as at present.

Based on analyses of belemnite rostra, Lowenstam & Epstein (1954) obtained very warm palaeotemperatures for the Coniacian–Santonian transition in northwestern Europe. Coplen & Schlanger (1973) also obtained anomalously warm oceanic floor temperatures for the same interval in the central Pacific on the basis of data on carbonate sediments from the Magellan Rise ($\delta^{18}O = -2.8$‰). They believed the warming to represent a worldwide climatic event, but as will be shown later, this is not confirmed by palaeobotanical data. Douglas & Savin (1975) were

Table 2. Carbon and oxygen isotope analyses of a Turonian aragonitic ammonoid shell (*Mesopuzosia pacifica* Matsumoto) from the Koryak Upland and Turonian palaeotemperatures for high latitudes of the Northern Hemisphere (D, diameter; H, height).

			Diagenetic alterations						
Sample	Series, locality	Location (D & H) (mm)	Diagenetic stage	Aragonite (%)	α-SiO_2 (%)	Colour	$\delta^{13}C$ (PDB) (‰)	$\delta^{18}O$ (PDB) (‰)	T°C
940-1	Turonian block in deep-sea Vatym Series, mouth of right bank of the Pakhacha River (12 km above the Echviyam Creek)	Septa (D=79; H=31)	2nd	91	0	Cream	− 2.5	+0.1	14.9[1] (11.6)[b]
940-3	Turonian block in deep-sea Vatym Series, mouth of right bank of the Pakhacha River (12 km above the Echviyam Creek)	Dorsal wall	1st	95	0	Cream	− 6.0	+0.3	14.1 (10.8)
940-4	Turonian block in deep-sea Vatym Series, mouth of right bank of the Pakhacha River (12 km above the Echviyam Creek)	Lateral wall (D=71.6; H=27.8)	1st	95	0	Cream	− 4.1	0.0	15.4 (12.0)
940-5	Turonian block in deep-sea Vatym Series, mouth of right bank of the Pakhacha River (12 km above the Echviyam Creek)	Dorsal wall (D=71.6; H=27.8)	2nd	91	0	Cream	− 8.1	+0.1	14.9 (11.6)
940-6	Turonian block in deep-sea Vatym Series, mouth of right bank of the Pakhacha River (12 km above the Echviyam Creek)	Lateral wall (D=32.5; H=14.0)	2nd	90	0	Cream	− 5.9	− 0.2	16.3 (12.7)
940-7	Turonian block in deep-sea Vatym Series, mouth of right bank of the Pakhacha River (12 km above the Echviyam Creek)	Lateral wall (D=31.0; H=13.0)	2nd	84	0	Cream	− 7.8	+0.2	14.5 (11.2)
940-8	Turonian block in deep-sea Vatym Series, mouth of right bank of the Pakhacha River (12 km above the Echviyam Creek)	Lateral wall (D=28.9; H=12.0)	2nd	92	0	Cream	− 7.3	0.0	15.4 (12.0)
940-2	Turonian block in deep-sea Vatym Series, mouth of right bank of the Pakhacha River (12 km above the Echviyam Creek)	Ventro-lateral part (D=79; H=31)	4th	15	Trace	Cream and brown	− 11.4	− 1.0	"T"C= 19.7 (16.0)

[a]Grossman & Ku (1986); [b]Anderson & Arthur (1983).

unable to test this conclusion on either the Shatsky or the Hess Rises in the north Pacific Ocean. In their investigation, however, the pelagic limestones from the central Caribbean (Atlantic Ocean) showed that deep-water sediments, in common with those that accumulate in shallow water, can change their original isotope composition through diagenetic processes. Unlike Coplen & Schlanger (1973), they suggested that the very negative $\delta^{18}O$ values (− 3.45– − 5.68‰) of the pelagic limestones from the Coniacian–Santonian transition of the central Caribbean are a diagenetic artefact, the result of recrystallization and cementation during a period of high temperature in the sediments, such as during a time of abnormally high heat flow.

Some palaeoclimatic reconstructions have shown the existence of phytoclimatic maxima during the Turonian (Krassilov, 1985, 1989; Herman & Spicer, 1996, 1997; Herman & Lebedev, 1991), Santonian (Goldberg, 1987; Wolfe & Upchurch, 1987; Herman

Table 3. Carbon and oxygen isotope analyses of aragonitic ammonoid shells from the Lower Coniacian of Hokkaido and early Coniacian palaeotemperatures for middle latitudes of the Northern Hemisphere (H, height; W, width).

				Diagenetic alterations						
Sample	Species	Group, locality	Location (H & W mm)	Diagenetic stage	Aragonite (%)	α-SiO_2 (%)	Colour	$\delta^{13}C$ (PDB) (‰)	$\delta^{18}O$ (PDB) (‰)	T°C
HB3435p-1	*Anagaudryceras limatum* (Yabe)	Lower Upper Yezo; Tanabe's loc. Hb3435; Haboro area, Nakafutamata Creek	Left lateral wall (H=22; W=15)	?	—	—	Cream	+1.77	0.00	15.4[a] (12.0)[b]
HB3435p-2	Same shell	Lower Upper Yezo; Tanabe's loc. Hb3435; Haboro area, Nakafutamata Creek	Right lateral wall (H=22; W=15)	?	—	—	Cream	0.77	+0.09	15.0 (11.6)
HB3435p-3	*Anagaudryceras limatum* (Yabe)	Lower Upper Yezo; Tanabe's loc. Hb3435; Haboro area, Nakafutamata Creek	(H=5.0; W=5.5)	3rd	62 ± 5	0	Cream and yellow	+0.07	− 1.16	20.4 (16.7)
HB3435p-4	*Anagaudryceras limatum* (Yabe)	Lower Upper Yezo; Tanabe's loc. Hb3435; Haboro area, Nakafutamata Creek	Ventral part (H=17)	3rd	67 ± 5	0	Cream and brown	− 0.13	− 0.67	18.3 (14.7)
HB3435p-5	Same shell	Lower Upper Yezo; Tanabe's loc. Hb3435; Haboro area, Nakafutamata Creek	Lateral wall (H=17)	2nd	83 ± 3	0	Cream	− 0.23	0.00	15.4 (12.0)
HB3535p-6	Same shell	Lower Upper Yezo; Tanabe's loc. Hb3435; Haboro area, Nakafutamata Creek	Dorsal wall (H=17)	3rd	65 ± 5	0	Cream	− 0.33	+0.09	15.0 (11.6)
HB3435p-7	Same shell	Lower Upper Yezo; Tanabe's loc. Hb3435; Haboro area, Nakafutamata Creek	Ventral part (H=19)	2nd	77 ± 3	0	Cream	+0.17	+0.19	14.5 (11.2)
HB3535p-8	Same shell	Lower Upper Yezo; Tanabe's loc. Hb3435; Haboro area, Nakafutamata Creek	Lateral wall (H=20)	2nd	72 ± 3	0	Cream	+0.27	− 0.48	17.5 (13.9)

[a]Grossman & Ku (1986); [b]Anderson & Arthur (1983).

& Lebedev, 1991) and Campanian (Krassilov, 1975, 1985; Vakhrameev, 1978) and minima in the Middle-Late Turonian (Herman & Lebedev, 1991) and Maastrichtian (Krassilov, 1985; Herman & Lebedev, 1991). Additionally, Wolfe & Upchurch (1987, 1989) concluded that temperatures declined sharply in the early Maastrichtian and rose again prior to the Cretaceous/Tertiary transition. They also inferred a brief low temperature excursion at the boundary. The trend of palaeobotanical events is not consistent with either the "Coniacian–Santonian temperature climax" of Lowenstam & Epstein (1954, p. 207) or the "thermal maximum" interpreted on the basis of an oxygen shift, which was discovered within the Coniacian–Santonian transition of the central Pacific (Coplen & Schlanger, 1973).

Our oxygen-isotope study of ammonoid, inoceramid bivalve and brachiopod shells from the shallow-water Hokkaido–south Sakhalin Basin has shown that two main trends can be recognized in Late Cretaceous temperature conditions in the south-northwestern circum-Pacific, corresponding to the subtropical humid phytoclimatic zone (Vakhrameev, 1978) (Figure 2):

(1) In general, palaeotemperatures are thought to begin a recurrent warming trend in the Turonian–Campanian, reaching temperature maxima in the early Late Santonian (19.6°C) and early Late Campanian and minima in the earliest Santonian

Table 4. Carbon and oxygen isotope analyses of aragonitic ammonoid shells (*Eupachydiscus* sp.) from the Lower Santonian of south Sakhalin and early Santonian palaeotemperatures for middle latitudes of the Northern Hemisphere (H, height).

			Diagenetic alterations						
Sample	Formation, beds, locality	Location (H, in mm)	Diagenetic stage	Aragonite (%)	α-SiO_2 (%)	Colour	$\delta^{13}C$ (PDB) (‰)	$\delta^{18}O$ (PDB) (‰)	T°C
101-952-20	Bykov Fm lower *Eupachydiscus haumanni* beds (member 33, lower part, bed 11-6) (Zakharov *et al.*, 1981); Naiba	H<30	?	—	—	Cream	− 3.0	1.5	8.9[a] (6.3)[b]
101-952-18 (same shell)	Bykov Fm lower *Eupachydiscus haumanni* beds (member 33, lower part, bed 11-6) (Zakharov *et al.*, 1981); Naiba	H=42	1st	96 ± 4	0	Cream	− 2.5	+1.3	9.7 (7.0)
101-952-11 (same shell)	Bykov Fm lower *Eupachydiscus haumanni* beds (member 33, lower part, bed 11-6) (Zakharov *et al.*, 1981); Naiba	H=62	1st	99 ± 1	0	Cream	− 2.6	+2.0	6.7 (4.5)
101-952-9 (same shell)	Bykov Fm lower *Eupachydiscus haumanni* beds (member 33, lower part, bed 11-6) (Zakharov *et al.*, 1981); Naiba	H=70	1st	99 ± 1	0	Cream	− 2.5	+1.3	9.7 (7.0)
101-952-2 (same shell)	Bykov Fm lower *Eupachydiscus haumanni* beds (member 33, lower part, bed 11-6) (Zakharov *et al.*, 1981); Naiba	H=76	1st	99 ± 1	0	Cream	− 2.2	+1.7	8.0 (5.6)
101-952-1 (same shell)	Bykov Fm lower *Eupachydiscus haumanni* beds (member 33, lower part, bed 11-6) (Zakharov *et al.*, 1981); Naiba	H=80	1st	99 ± 1	0	Cream	− 2.3	+2.7	3.7 (3.0)
101-952-50	Bykov Fm lower *Anapachydiscus naumanni* beds (member 33, lower part bed 11-1) (Zakharov *et al.*, 1981); Naiba	H>45	2nd	89 ± 5	0	Cream	− 2.6	+1.6	8.4 (5.9)

[a]Grossman & Ku (1986); [b]Anderson & Arthur (1983).

(8°C) and perhaps in the latest Santonian–early Campanian (13.3°C).

(2) Through the course of the Maastrichtian, temperatures dropped sharply (7.1°C), with only slight warming in the early Late Maastrichtian (11.2°C).

A slight temperature increase appears to have occurred in the Late Turonian–Early Coniacian (from 15.8°–17–18°C). The higher temperatures for the early Late Santonian and Late Campanian were obtained from benthic fossils (aragonitic parts of the inoceramid bivalve shells and well-preserved calcitic shells of brachiopods). The lower temperature value for the Maastrichtian, which is more or less in agreement with data on Maastrichtian temperatures of the high-latitude shelf waters near Antarctica (Barrera *et al.*, 1987), was determined using both benthic (brachiopod) and semi-pelagic (ammonoid) fossils. These data appear to show the lower value for the surface-bottom temperature gradient of the shallow-water Hokkaido-south Sakhalin Basin in the Late Cretaceous (differences between surface-water and bottom-water temperatures are estimated to be not more than 1.0°–1.5°C).

New isotopic data on oxygen-isotopic palaeotemperatures for the Late Cretaceous of the Hokkaido-south Sakhalin Basin agree with both the isotopic data of Teiss & Naidin (1973) on the Russian Platform and those of Barrera *et al.* (1987) for the shallow continental shelves of Antarctica and most palaeobotanical reconstructions.

Temperatures of middle-latitude shallow waters in the Far East during the Maastrichtian were slightly higher (by 2–3°C) than those of high-latitude shelf waters near Antarctica (Barrera *et al.*, 1987; Stott & Kennett, 1990), slightly lower (by 3–4°C) than those of middle-latitude shallow waters on the Russian Platform (Teiss & Naidin, 1973), but considerably lower (by 5–9°C) than temperatures of surface water in the equatorial Pacific (Boersma & Shackleton, 1981).

Some years ago, Krassilov (1989) and Wolfe & Upchurch (1989) discussed whether the Santonian or Campanian was the warmer age. The palaeotemperature curve for the Late Cretaceous in the northwestern circum-Pacific shows that the Campanian was apparently cooler than the Santonian in the Far East, but if we agree with Toshimitsu (Toshimitsu, 1988; Toshimitsu *et al.*, 1995a, b; Toshimitsu & Kakawa, 1997) on the position of the Santonian/Campanian boundary in Hokkaido located at the base of the

Table 5. Carbon and oxygen isotope analyses of aragonitic ammonoid shells and aragonitic elements of inoceramid bivalves from the Upper Santonian and Lower Campanian of Hokkaido and middle Senonian palaeotemperature for middle latitudes of the Northern Hemisphere (H, height; W, width; L, length).

				Diagenetic alterations						
Sample	Species	Group, locality	Location (H, W & L in mm)	Diagenetic stage	Aragonite (%)	α-SiO_2 (%)	Colour	$\delta^{13}C$ (PDB) (‰)	$\delta^{18}O$ (PDB) (‰)	T°C
3015F	*Damesites* sp.	Middle U. Yezo (?U. Santonian); Tanabe's loc. S3015; Abeshinai River, Nakagawa	H=13	1st	99 ± 1	Trace	Reddish cream	− 1.13	+0.29	14.1[a] (10.8)[b]
S3013-3	*Inoceramus* sp.	Middle U. Yezo (?U. Santonian); Tanabe's loc. S3013; Abeshinai River, Nakagawa	L=20	1st	97 ± 3	0	Cream	+2.37	− 0.97	19.6 (15.9)
S3013-2	Same shell	Middle U. Yezo (?U. Santonian); Tanabe's loc. S3013; Abeshinai River, Nakagawa	L=40	1st	98 ± 2	0	Cream	+2.47	− 0.77	18.8 (15.1)
S3013-4	*Inoceramus* sp.	Middle U. Yezo (?U. Santonian); Tanabe's loc. S3013; Abeshinai River, Nakagawa	L=15	?	—	—	Cream	+1.87	− 0.77	18.8 (15.1)
3103-10-9	*Eupachydiscus* sp.	Upper U. Yezo (L. Campanian, Zakharov's coll.); Wakkawenbetsu River	W=75	?	—	—	Cream	− 5.43	+0.48	13.3 (10.1)
3208-14-8	*Inoceramus schmidti* Michael	Upper U. Yezo (L. Campanian, Zakharov's coll.); Ososhinai	L=45	1st	94 ± 3	0	Cream	+1.47	− 0.48	17.5 (13.9)

[a]Grossman & Ku (1986); [b]Anderson & Arthur (1983).

Inoceramus japonicus Zone, we must recognize that there were two temperature maxima during the long Campanian age: a maximum in the Early Campanian and again in the Late Campanian separated by a short Middle Campanian minimum (not recognized in palaeobotanical investigations).

Turonian temperatures obtained for the Koryak Upland (14.1–16.3°C) are closely similar to those of Hokkaido (12.0–16.7°C). Apparently this illustrates the very low meridional thermal gradient from Kamchatka to Japan in the Northern Hemisphere during the mid Cretaceous. It agrees with palaeobotanical evidence from Kamchatka (Herman, 1996), Alaska (Spicer *et al.*, 1996) and Asuwa, central Japan (Matsuo, 1962). According to Herman & Lebedev (1991), the Coniacian stage is characterized by a close resemblance between the northeast Russian flora and that of Sakhalin, which disappeared at the beginning of the Santonian when these regions appear to have been part of different phytogeographic realms.

6. The problem of palaeoproductivity

As suggested by Alcala-Herrera *et al.* (1992), some variations in marine $^{13}C/^{12}C$ ratios recorded in deep-water organogenic carbonate are related to variations in different environmental factors, such as the carbon budget, upwelling and primary productivity. It is difficult to separate the effects of each of these on deep-water conditions, but when worldwide carbon isotope shifts are observed in shallow-water carbonates, they are generally attributed to changes in primary productivity. The temperature factor does not directly control $\delta^{13}C$, but biological productivity as a whole depends significantly on some factors, which include the temperature.

Judging from a very negative value of $\delta^{13}C$ (− 5.9‰) obtained from a Turonian ammonite from the Koryak Upland, most oxygen depletion of marine waters at that time had spread to high latitudes of the Northern Hemisphere. Waters of high latitudes characterized by very low $\delta^{13}C$ values were apparently strongly related to the Hokkaido–south Sakhalin Basin during the early Santonian, the latest Santonian–early Campanian, and early Maastrichtian, although water circulation during the Late Cretaceous, as has been shown by deep-sea drilling investigations (Coplen & Schlanger, 1973; Douglas & Savin, 1975; Boersma & Shackleton, 1981) was sluggish because of the low surface to bottom thermal gradient in the oceans at the time.

An abrupt decline in the heavy-carbon isotope concentrations at the Cretaceous–Tertiary transition (Stott & Kennett, 1990; Alcala-Herrera *et al.*, 1992;

Table 6. Carbon and oxygen isotope analyses of well-preserved brachiopod shells from the Upper Campanian and Upper Maastrichtian of south Sakhalin and late Senonian palaeotemperatures for middle latitudes of the Northern Hemisphere (L, length).

Sample	Species	Formation, beds, locality	Location (L, in mm)	Diagenetic alterations				$\delta^{13}C$ (PDB) (‰)	$\delta^{18}O$ (PDB) (‰)	T°C
				Diagenetic stage	Luminescent test	Microstructure	Colour			
6-3	*Orbirhynchia* sp.	Krasnoyarka Fm, U. Campanian, upper *Canadoceras kossmati* beds (member 50, bed 6-3) (Zakharov *et al.*, 1984); Naiba	L=11.0	Initial	Positive	Well-preserved	Silvery-white	+0.9	−1.5	18.1[a]
141-952-65	*Orbirhynchia* sp.	Krasnoyarka Fm, lower U. Maastrichtian, middle *Pachydiscus–Pleurogrammatodon bykovensis* beds (member 62, bed 5-6) (Zakharov *et al.*, 1984); Naiba	Few small shells	Initial	Positive	Well-preserved	Silvery-white	−0.6	+0.7	9.3
KL111-1	Rhynchonellacea	Krasnoyarka Fm, lower U. Maastrichtian, middle *Pachydiscus–Pleurogrammatodon bykovensis* beds (member 63?, bed KL111) (Kalishevich's coll.); Naiba	L=11.5	Initial	Positive	Well-preserved	Silvery-white	+1.1	+0.3	10.8
KL111-2	Rhynchonellacea	Krasnoyarka Fm, lower U. Maastrichtian, middle *Pachydiscus–Pleurogrammatodon bykovensis* beds (member 63?, bed KL111) (Kalishevich's coll.); Naiba	L=12.0	Initial	Positive	Well-preserved	Silvery-white	+1.4	+0.3	10.8
KL111-3	Rhynchonellacea	Krasnoyarka Fm, lower U. Maastrichtian, middle *Pachydiscus–Pleurogrammatodon bykovensis* beds (member 63?, bed KL111) (Kalishevich's coll.); Naiba	L<12.0	Initial	Positive	Well-preserved	Silvery-white	+1.4	+0.2	11.2
KL10-6-1	Rhynchonellacea	Krasnoyarka Fm, ? middle U. Maastrichtian (bed KL10-6), (Kalishevich's coll.), Krasnoyarka, just below the mine	L=13.0	Initial	Positive	Well-preserved	Silvery-white	+0.6	+0.2	11.2
KL10-6-2	Rhynchonellacea	Krasnoyarka Fm, ? middle U. Maastrichtian (bed KL10-6), (Kalishevich's coll.), Krasnoyarka, just below the mine	L=14.0	Initial	Positive	Well-preserved	Silvery-white	+1.8	+0.5	10.0
KL10-6-3	Rhynchonellacea	Krasnoyarka Fm, ? middle U. Maastrichtian (bed KL10-6), (Kalishevich's coll.), Krasnoyarka, just below the mine	L=11.8	Initial	Positive	Well-preserved	Silvery-white	+1.4	+0.3	10.8
KL6	*Orbirhynchia* sp.	Krasnoyarka Fm, ?middle U. Maastrichtian (bed KL6) (Kalishevich's coll.), Sary River	L=11.0	Initial	Positive	Well-preserved	Silvery-white	0.0	+1.0	8.1

[a] Anderson & Arthur (1983).

Jenkyns *et al.*, 1995) reflecting a global reduction in primary biological productivity, might have been induced by an increasing oxygen deficiency in response to a dramatic decline in both continental and oceanic photosynthesis owing to a number of possible causes. These included the influence of a cold, arid climate,

Table 7. Carbon and oxygen isotope analyses of aragonitic ammonoid shells from the Lower and Upper Maastrichtian of south Sakhalin and early and late Maastrichtian palaeotemperatures for middle latitudes of the Northern Hemisphere (H, height).

				Diagenetic alterations						
Sample	Species	Formation, beds, locality	Location (H, in mm)	Diagenetic stage	Aragonite (%)	α-SO_2 (%)	Colour	$\delta^{13}C$ (PDB) (‰)	$\delta^{18}O$ (PDB) (‰)	T°C
103-952-31	*Pachydiscus* (*P.*) cf. *gollevillensis* d'Orbigny	Krasnoyarka Fm, L. Maastrichtian, lower *Zelandites japonicus* beds (member 60, bed 5-11) (Zakharov *et al.*, 1984); Naiba	Lateral wall (H>50	1st	99 ± 1	0	Cream	− 2.4	+1.8	7.6[a] (5.2)[b]
103-942-28	Same shell	Krasnoyarka Fm, L. Maastrichtian, lower *Zelandites japonicus* beds (member 60, bed 5-11) (Zakharov *et al.*, 1984); Naiba	Lateral wall (H=160)	1st	99 ± 1	0	Cream	− 1.1	+1.6	8.4 (5.9)
107-952-36	*Pachydiscus* (*P.*) cf. *gollevillensis* d'Orbigny	Krasnoyarka Fm, L. Maastrichtian, lower *Zelandites japonicus* beds (member 60, bed 5-11) (Zakharov *et al.*, 1984); Naiba	Lateral wall (H=70)	1st	99 ± 1	0	Cream	− 2.8	+1.9	7.1 (4.8)
108-952-39	*Pachydiscus* (*P.*) cf. *gollevillensis* d'Orbigny	Krasnoyarka Fm, L. Maastrichtian, lower *Zelandites japonicus* beds (member 60, bed 5-11) (Zakharov *et al.*, 1984); Naiba	Septa (H>120)	1st	99 ± 1	0	Cream	− 2.8	+1.9	7.1 (4.8)
110-952-45	*Pachydiscus* (*P.*) cf. *gollevillensis* d'Orbigny	Krasnoyarka Fm, L. Maastrichtian, lower *Zelandites japonicus* beds (member 60, bed 5-10) (Zakharov *et al.*, 1984); Naiba	Lateral wall (H=85)	1st	98 ± 2	0	Cream	− 2.0	+1.6	8.4 (5.9)
114-952-50	*Pachydiscus* (*Neodesmoceras*) *japonicum* Matsumoto	Krasnoyarka Fm, U. Maastrichtian, lower *Pachydiscus–Pleurogrammatodon bykovensis* beds (member 61, bed 5-9) (Zakharov *et al.*, 1984); Naiba	Lateral wall	1st	97 ± 3	0	Cream	− 2.0	+1.8	7.6 (5.2)
105-952-32	*Pachydiscus* (*P.*) sp.	Krasnoyarka Fm, L. Maastrichtian, lower *Zelandites japonicus* beds (member 61, bed 5-7) (Zakharov *et al.*, 1984); Naiba	Lateral wall (B>105)	1st	99 ± 1	—	Cream	− 2.5	+1.5	8.9 (6.3)
106-952-35	*Pachydiscus* (*P.*) sp.	Krasnoyarka Fm, lower U. Maastrichtian, lower (*Pachydiscus–Pleurogrammatodon bykovensis* beds (member 61, bed 5-7) (Zakharov *et al.*, 1984); Naiba	Lateral wall (B>106)	1st	98 ± 2	0	Cream	− 2.5	+1.4	9.3 (6.6)
106-952-42	*Pachydiscus* (*P.*) sp.	Krasnoyarka Fm, lower U. Maastrichtian, lower *Pachydiscus–Pleurogrammatodon bykovensis* beds (member 61, bed 5-7) (Zakharov *et al.*, 1984); Naiba	Lateral wall (B>80)	1st	98 ± 2	0	Cream	− 2.2	+1.8	7.6 (5.2)

[a] Grossman & Ku (1986); [b] Anderson & Arthur (1983).

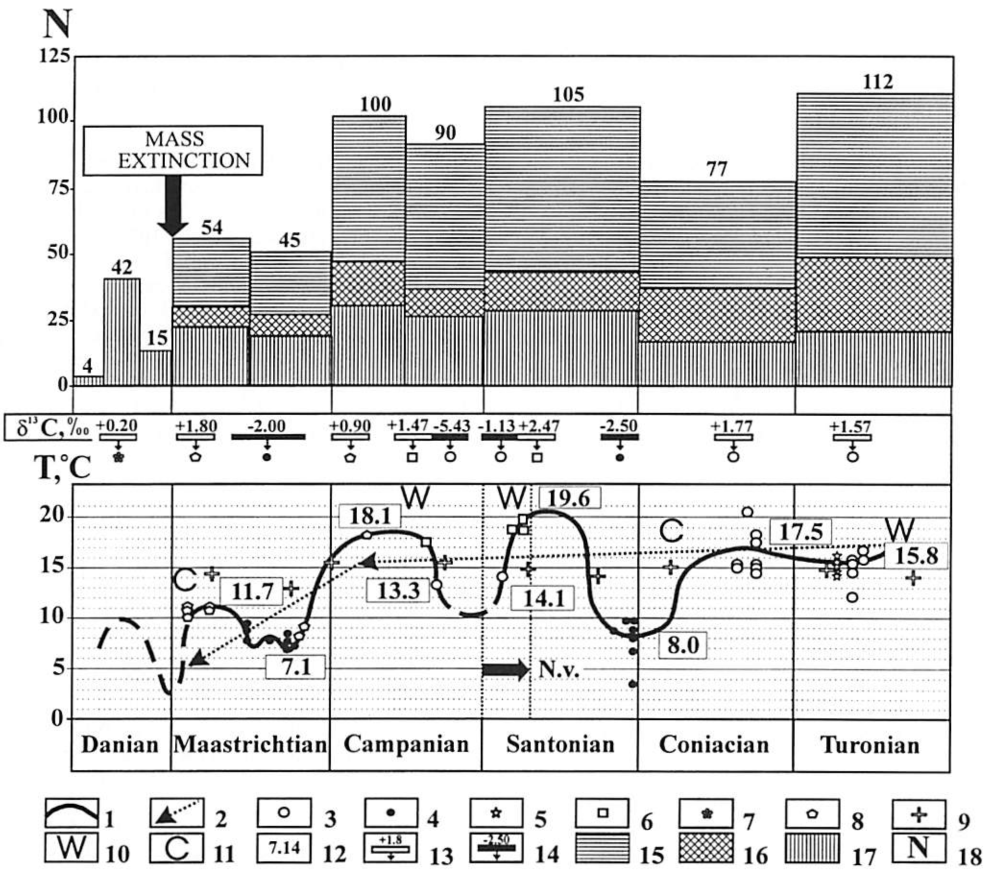

Figure 2. Palaeotetemperature curve for the Late Cretaceous of the northwestern circum-Pacific (Hokkaido, Sakhalin, Koryak Upland) based on isotopic data. 1, Isotopic palaeotemperature curve; 2, its general trends; 3, aragonitic shells of ammonoids from Hokkaido; 4, aragonitic shells of ammonoids from south Sakhalin; 5, aragonitic shell of an ammonoid from the Koryak Upland; 6, aragonitic shell elements of inoceramid bivalves from Hokkaido; 7, calcitic shell of a non-inoceramid bivalve from south Sakhalin; 8, well-preserved brachiopod shells from south Sakhalin; 9, calcitic rostra of belemnites from the Russian Platform (Naidin, 1973); 10, temperature maxima in palaeobotanical data (Krassilov, 1985; Goldberg, 1987; Wolfe & Upchurch, 1987; Herman & Lebedev, 1991; Herman, 1996); 11, temperature minima from palaeobotanical data (Krassilov, 1985; Wolfe & Upchurch, 1987); 12, oxygen-isotopic palaeotemperature in °C; 13, δ^{13}C positive values; 14, δ^{13}C negative values; 15, ammonoid species diversity (Sakhalin) (Zakharov *et al.*, 1984); 16, inoceramid bivalve species diversity (Sakhalin) (Zakharov *et al.*, 1984); 17, non-inoceramid bivalve species diversity (Sakhalin) (Zakharov *et al.*, 1984); 18, species abundance; N.v.=new version for the Santonian/Campanian boundary position in Hokkaido (Toshimitsu, 1988; Toshimitsu *et al.*, 1995a, b, 1998; Toshimitsu & Kikawa, 1997).

an important marine regression, some changes in oceanic circulation, volcanogenic activity and other factors that might have been linked to extraterrestrial causes. The declining Late Cretaceous mollusc fauna appears to have begun by at least the early Maastrichtian (Zakharov *et al.*, 1981, 1984, 1996) (Figure 2) and is not, therefore, related to the end-Cretaceous bolide impact suggested by Alvarez *et al.* (1980).

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