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Magnitude of Middle Miocene warming in North Pacific high latitudes: stable isotope evidence from *Kaneharaia* (Bivalvia, Dosiniinae)

Anton Oleinik[1], Louie Marincovich, Jr[2], Konstantin B. Barinov[3], and Peter K. Swart[4]

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Abstract: The Middle Miocene Climatic Optimum (MMCO) at ~ 16 Ma was the warmest interval during the Neogene. The peak of the MMCO in the North Pacific is marked by the appearance of the bivalve genus *Kaneharaia* (Bivalvia, Dosiniinae) in the high-latitude regions of Kamchatka and Alaska (55 – 65°N). Specimens of *Kaneharaia* sp. were collected from two early middle Miocene high-latitude localities in the North Pacific – the Sea urchin Horizon of northwestern Kamchatka and the Narrow Cape Formation of Alaska. Middle Miocene *Kaneharaia* specimens were incrementally sampled for oxygen and carbon stable isotope records of seasonality. Results were compared with stable isotope profiles constructed for two Recent species of *Dosinia* from subtropical waters. Assuming a constant seawater $\delta^{18}O$ of -1.5‰ (Lear *et al.*, 2000), including latitudinal correction (Zachos *et al.*, 1994), oxygen isotope data yield mean annual temperatures of 19.3°C and 23.5°C and a mean annual range of temperatures of 19.8°C and 11.0°C for Alaska and Kamchatka, respectively. These temperature ranges are comparable to those of modern subtropical (40°N) mixed-layer waters, which implies significant warming episodes at high North Pacific latitudes during the peak of the MMCO.

The variations in isotopic composition and inferred temperature ranges, as well as patterns of stratigraphic occurrence, imply that warm surface waters of the MMCO were not persistently present in high North Pacific latitudes, as they were at low latitudes. Instead, relatively short-term incursions of warm surface waters from the subtropical western Pacific episodically introduced warm-water mollusks into this generally cooler region.

Keywords: Oxygen Isotopes, high-latitudes, Kamchatka, Alaska, *Kaneharaia*, Dosinia, Middle Miocene, Climatic Optimum.

1. Introduction

One of the most conspicuous climate changes of the Neogene Period was the early middle Miocene (14.5 to 17 Ma) global warming event known as the Middle Miocene Climatic Optimum (MMCO), when global warming peaked in the earliest Middle Miocene, at about 16 Ma. Marine and terrestrial temperatures were warmer than today and higher than at any time after the Eocene (Tanai and Huzioka, 1967; Kennett, 1982; Tsuchi and Ingle, 1992). The MMCO was confined mainly to Chrons C5C and C5B, primarily equivalent to the N.8 and part of the N.9 planktonic foraminiferal zones, with an age range of 14.8 to 16.4 Ma, and lasted for approximately 1.6 M.y.

The global nature of the MMCO is clearly suggested by sympathetic fluctuations of foraminiferal $\delta^{13}C$ and $\delta^{18}O$ values in the tropical eastern Pacific (Barrera *et al.*, 1985; Vincent and Berger, 1985), as well as by incursions of subtropical mollusks into the high-latitude North Pacific (Marincovich, 1990a, b). At the height of the Climatic Optimum (ca. 16 Ma), deep-water and high-latitude surface-water temperatures may have been as much as 6°C warmer than today (Shackleton and Kennett, 1975; Savin *et al.*, 1975), although high-latitude North Pacific inferences are largely speculation. The degree of warming, paleoseasonality, timing, latitudinal extent, and possible temperature fluctuations within the MMCO are reasonably well documented in low and middle latitudes, but are virtually unknown for northern high latitudes.

Surface-water warming in the high-latitudes North

[1]Department of Geosciences, Florida Atlantic University, Boca Raton, Florida, 33431, USA, aoleinik@fau.edu;
[2]Department of Invertebrate Zoology and Geology, California Academy of Sciences, Golden Gate Park, San Francisco, California, 94118, USA, louiem@calacademy.org
[3]Russian Academy of Sciences, Geological Institute, Moscow, Russia, 109017, barinov@geo.tv-sign.ru;
[4]Division of Marine Geology and Geophysics, Rosenstiel School of Marine and Atmospheric Sciences, University of Miami, Miami. Florida, 33149 USA, pswart@rsmas.miami.edu

Pacific is clearly implied by the northward incursion of warmer-water molluscan taxa as far north as northwestern Kamchatka and Alaska, up to 62°N. Modern analogs of subtropical mollusks that migrated northward in response to marine warming during the early middle Miocene now live no farther north than 43°N. These warm-faunal episodes occur primarily within the *Denticulosis lauta* diatom Zone (15.9 to 14.9 Ma), spanning approximately 1 M.y. (Barron and Gladenkov, 1995).

In this study we performed detailed sampling and analysis of carbon and oxygen stable isotopes of the bivalve genus *Kaneharaia* Makiyama, 1936 (Bivalvia, Dosiniinae) from early Middle Miocene beds in Alaska and Kamchatka in order to address the issue of seasonality during the peak of the MMCO in the high-latitude North Pacific. The fossil genus *Kaneharaia* Makiyama, 1936 is closely allied with the recent tropical-subtropical genus *Dosinia* Scopoli 1777 and was originally designated as a subgenus of *Dosinia* (Makiyama, 1936; Masuda, 1967). The most recent taxonomic review elevated *Kaneharaia* to a separate genus and treats Kodiak Island and Kamchatka species as the same one, without assigning any species name to it (Amano and Hikida, 1999). Systematic treatment of high latitude *Kaneharaia* is beyond the scope of the manuscript. Following Amano and Hikida (1999), the species from Kodiak Island and northeastern Kamchatka is treated herein as *Kaneharaia* sp.

2. Patterns in North Pacific MMCO Biogeography

Marine and terrestrial mega- and microfossil faunas and floras evidence the Pacific-wide effects of the MMCO (Tsuchi, 1990; Tsuchi & Ingle, 1992). In the low- and middle-latitude North Pacific, warm-climate biotas are present in formations such the Topanga and Temblor in California and the Kadonosawa and Suenomatsuyama in Japan, which contain abundant and diverse warm-water molluscan faunas that persisted for a million years or more (Noda & Watanabe, 1996; Ogasawara 1994; Itoigawa & Yamanoi, 1990; Addicott, 1969). Equivalent subtropical mollusks occupy relatively thin stratigraphic intervals in the Bear Lake Formation and Narrow Cape Formation of southwestern Alaska, and the Kavranskaya Series of northwestern Kamchatka (Fig. 1). These formations predominantly contain rich, unmistakably cool-water faunas, but warm-water mollusks that delineate the northern extent of the MMCO are present at a few stratigraphic intervals. It is generally thought that warm-water faunas on both sides of the high-latitude North Pacific are essentially derived from the tropical western Pacific. However, the presence of the gastropod *Ficus* in the Narrow Cape Formation of Kodiak Island implies that this may be a simplistic understanding of more complex biogeographic events, because *Ficus* is absent from post-Eocene faunas of the northwestern Pacific (Oleinik, 1998), but is present in Neogene faunas of western America (Moore, 1963; Addicott, 1976). Subtropical mollusks in Asia that migrated northward in response to marine warming during the Early Middle Miocene have been termed the Kadonosawa fauna in Japan (Chinzei, 1986; Ogasawara, 1994). Modern analogs of these taxa now live no farther north than 30°N in central Honshu, Japan. A subset of these taxa continued to migrate northward and is termed the Ilyinskaya fauna in western and eastern Kamchatka (Gladenkov *et al.*, 1987; Gladenkov & Shantser, 1990). A reduced number of species continued eastward across the northern margin of the Pacific to Alaska, where they appear in the Narrow Cape Formation on Kodiak Island (Marincovich, 1987, 1989; Marincovich & Moriya, 1992), the Bear Lake Formation on the Alaska Peninsula (Marincovich, 1978; 1981a,b; 1984 a, b; 1988a, b, c; Marincovich & Kase, 1986), and the Yakataga Formation in the northeastern Gulf of Alaska (Allison, 1978; Marincovich, 1990a). The easternmost North Pacific evidence for this migration of Asian taxa in response to the Climatic Optimum is the bivalve *Macoma optiva* in the Astoria Formation of Washington and Oregon (Moore, 1963; Addicott, 1976; Marincovich, 1983). Mollusks are found in abundance in the Narrow Cape Formation on Kodiak Island (57°N), the Bear Lake Formation on the Alaska Peninsula (56°N) and the Kavranskaya Series in northwestern Kamchatka (62°N). These formations contain rich, predominantly cool-water faunas, but warm-water mollusks that delineate the northern extent of the Climatic Optimum are present at a few stratigraphic intervals. This pattern of stratigraphic occurrences implies that warm surface waters of the MMCO were not persistently present in the high-latitude North Pacific, as they were at low latitudes. Instead, relatively short-term incursions of warm surface waters from the western Pacific periodically introduced warm-water mollusks and planktonic foraminifers into this cooler region (Kennett *et al.*, 1985; Marincovich, 1990a,b; Gladenkov, 1992). These periodic warm-water incursions provided an opportunity for warm-temperate and subtropical taxa to migrate along the southern margin of Beringia and dwell temporarily in high latitudes. Migration patterns were asymmetrical, primarily with Asian mollusks invading waters of the northeastern Pacific. Faunal studies based on North Pacific high-latitude occurrences of the bivalves *Anadara*, *Kaneharaia*, *Glycymeris*, *Macoma* and *Nuttallia*, and the gastropods *Fulgoraria (Musashia)*, *Gibbula*, *Nassarius*, *Turritella* and *Tyrannoberingius* in Kamchatka and Alaska is a major evidence of high-latitude warm-water incursions during the MMCO. These taxa have been recognized as primary evidence for the MMCO in Japan, Kamchatka and southwestern Alaska (Chinzei, 1986; Gladenkov *et al.*, 1987; Marincovich, 1983, 1988a,b,c; Marincovich &

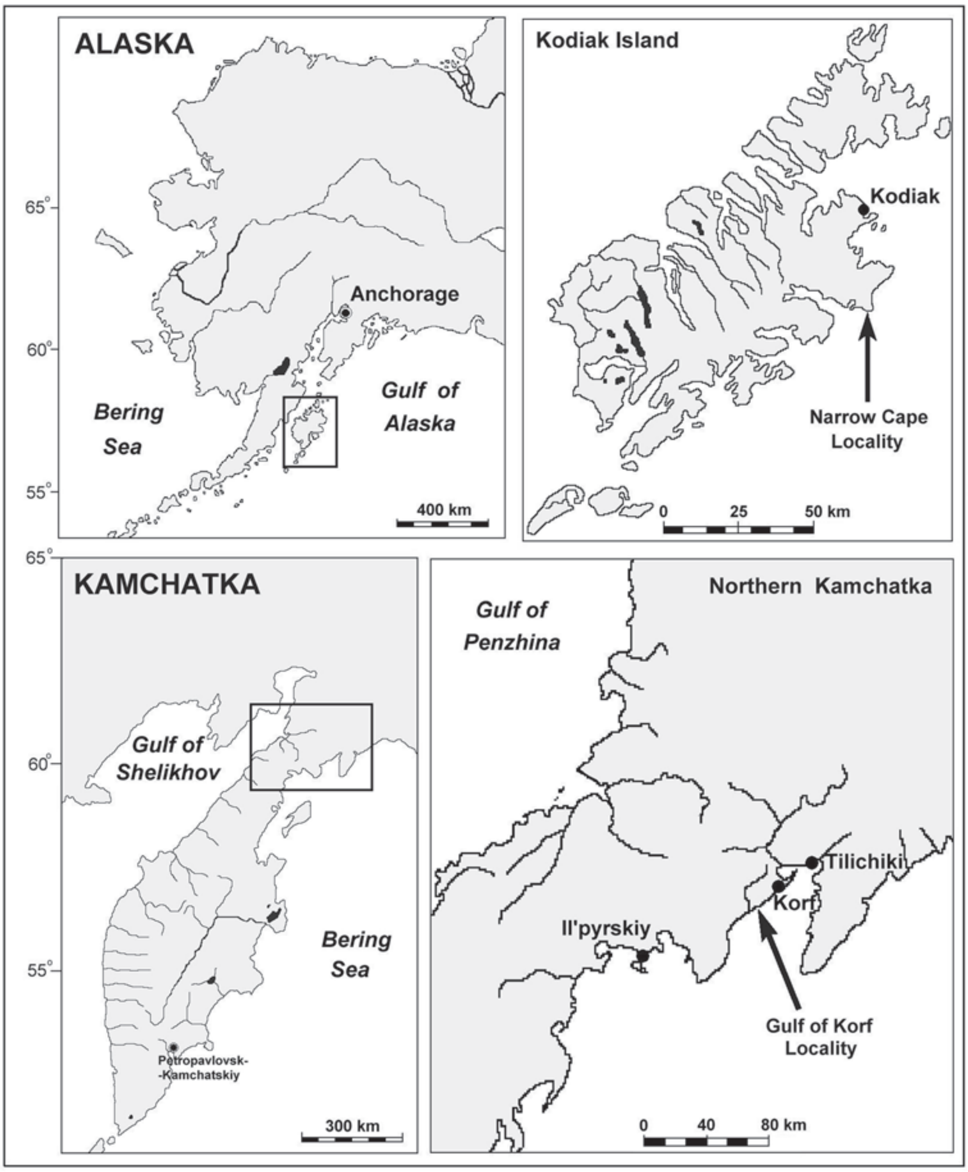

Fig. 1 Location map of Alaska and Kamchatka showing Narrow Cape and Gulf of Korf localities.

Moriya, 1992). The 1998 discovery of several of these taxa (*Anadara*, *Kaneharaia*, *Fulgoraria (Musashia)*, *Glycymeris*, *Macoma*, *Nuttallia and Tyrannoberingius*) in the lower middle Miocene Bear Lake Formation clearly suggest that these genera were common elements for all high-latitudes North Pacific MMCO molluscan faunas.

Further evidence for warm surface waters in the high-latitude North Pacific was the brief presence of the tropical Miocene planktonic foraminifers *Globorotalia siakensis* and *G. mayeri* coincident with early middle Miocene cold-water mollusks in the Yakataga Formation of south-central Alaska (Lagoe, 1983; Marincovich, 1990a). Both species have last-occurrence datums of 10.4 Ma (Bolli & Saunders, 1985; Berggren *et al.*, 1995) and normally dwelled in the equatorial Pacific during the early and middle Miocene (Fig. 2). In fact, *G. siakensis* and *G. mayeri* have been used to characterize a distinct biogeographic province that dominated the tropical eastern Pacific in both the early Miocene (22 Ma) and early middle Miocene (16 Ma) (Kennett *et al.*, 1985). During the latter episode, the occurrence of this shallow-dwelling species complex extended northward to about 20°N (southern Mexico). The presence of these two exclusively tropical planktonic foraminifers in the Yakataga Formation of southern Alaska is clear evidence for brief incursions of tropical water to 60°N and is a significant tie to paleoclimatic events at low latitudes (Fig. 2). This also implies that the MMCO peaks were episodic or cyclical in the North Pacific, as Barrera *et al.* (1985) inferred they were for the equatorial eastern Pacific. The associated cold-water Yakataga molluscan fauna is incompletely known but does contain the anomalously

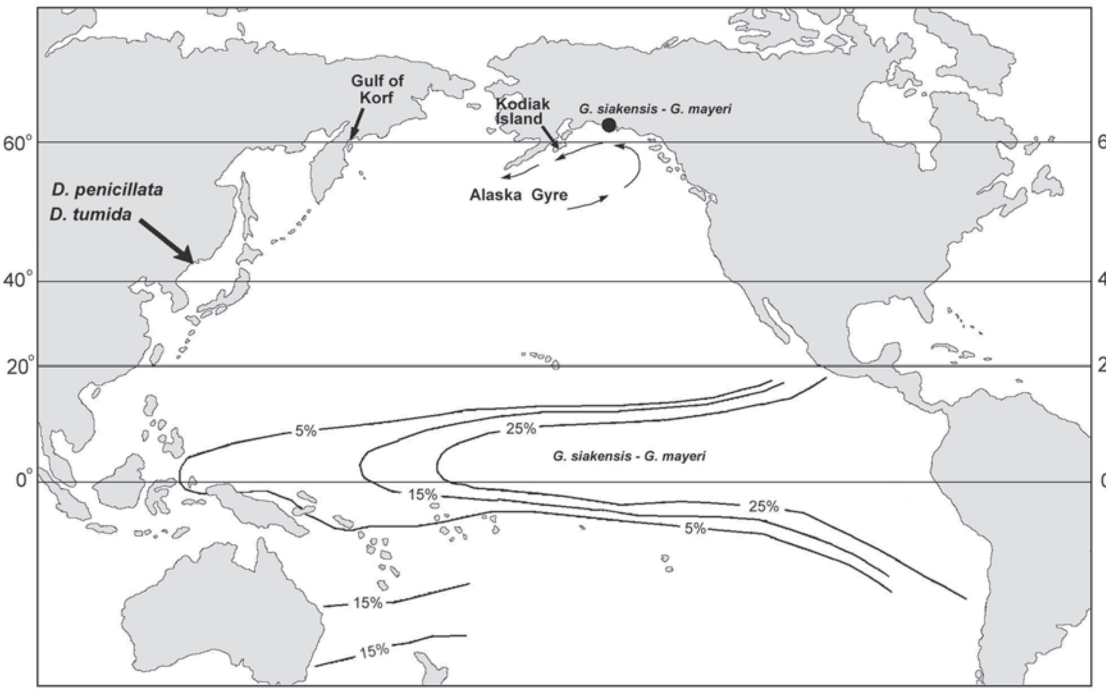

Fig. 2 Percent distribution of *Globorotalia siakensis – Globorotalia mayeri* complex of tropical planktonic foraminifers at ~ 16 Ma (Kennett *et al.*, 1985). Both species occur in glacial marine sediments of the Yakataga Formation in southern Alaska (black dot). Map also shows the northernmost occurrence of *Dosinia penicillata* and *Dosinia tumida* in the North Pacific today and location of Middle Miocene sections containing *Kaneharaia* sp.

warm-water bivalve *Dosinia* (University of California, Berkeley, fossil collections, *fide* L. Marincovich), one of the genera characteristic of other North Pacific MMCO faunas.

Shallow-water marine molluscan faunas in Alaska and Kamchatka are the northernmost empirical evidence of early middle Miocene global warming in the high-latitude North Pacific.

The peak of the MMCO in the North Pacific is marked by the appearance of the bivalve genus *Kaneharaia* in high latitude regions of Kamchatka and Alaska. The Recent counterpart of the *Kaneharaia* is the bivalve genus *Dosinia*, which is known to occur only in the tropical and subtropical waters of the world ocean. The northernmost occurrence of *Dosinia penicillata* (Reeve, 1850) and *Dosinia tumida* (Gray, 1838) in the North Pacific Ocean is at ~ 43°N at 2 - 7 m depth in the Gulf of Possjiet at temperatures from 18.4 to 23.5°C and salinities of 30‰ (Golikov and Scarlato, 1967; Scarlato, 1981; Kafanov and Lutaenko, 1997) (Fig. 2). However, Early Middle Miocene *Kaneharaia* at 62°N in northeastern Kamchatka are nineteen degrees of latitude (some 2000 km) (Fig. 2) to the North and imply profound warming during the MMCO. Subfamily Dosiniinae Deshayes, 1853, therefore, can be considered as reliable biotic indicators of subtropical water masses.

The use of faunal diversity to infer paleotemperatures is based on the well-established poleward decrease in the diversity of living marine organisms in response to latitudinal temperature gradients (Ekman, 1953; Thorson, 1957; Filatova, 1957; Fisher, 1964; Roy *et al.*, 1998). This relationship, enhanced by factor analytic transfer functions, has been successfully applied to planktonic microfossil assemblages (Molfino *et al.*, 1982; Barash and Blum, 1975; Cronin & Dowsett, 1990; Dowsett, 1991; Dowsett and Poore, 1990, 1991; Dowsett *et al.*, 1996). Microfossils are generally low in diversity or absent in shallow-water Tertiary faunas in the high-latitude North Pacific, where mollusks are the only abundant and diverse Cenozoic megafossils. Therefore, biogeographic and paleoclimatic analysis of molluscan faunas in onshore sections up to the present day remains the most important tool for paleoclimatic and biogeographic reconstructions.

Molluscan assemblages have been used with great success to infer North Pacific Cenozoic shallow-water paleotemperatures (Schenck and Keen, 1937; Schenck, 1945; Ida, 1956; Addicott, 1969, 1970; Amano, 1994; Kafanov & Volvenko, 1997). The most recent of these studies have been based on the temperature tolerances of modern analogs of particular genera, and on percentages of extra-limital warm-water genera classified based on their modern northernmost occurrences. Latitudinal diversity gradients have been used to evaluate Climatic

Optimum faunas of western Kamchatka by Gladenkov and Sinelnikova (1990), and preliminary paleotemperature estimates (6.36 to 9.05°C – annual, and 15.12 to 18.88°C – August) based on diversity gradients in limited collecting have also been done for the Gulf of Korf region in northeastern Kamchatka (Gladenkov *et al.*, 1987; Kiyashko *et al.*, 1988; Kafanov & Volvenko, 1997). These studies have shown the presence of coeval warm-water faunas in the Ilyinskaya and Kakertskaya Formations in western Kamchatka and the Sea-urchin (Ezhovyi) Horizon in the Gulf of Korf region, northeastern Kamchatka.

3. Geologic Setting

The Narrow Cape Formation of the Kodiak Island (Fig. 1) unconformably overlies Paleogene accretionary complex deposits (Byrne and Fisher, 1987). The 570 meters of Narrow Cape clastics contain abundant inner-shelf (0-100 m) mollusks (Marincovich and Moriya, 1992). The strata contain a rich but largely unstudied molluscan fauna that is the best shallow-water expression of the Climatic Optimum in Alaska. This sequence contains mostly cool-water mollusks, but is interrupted by at least four horizons that exclusively contain subtropical mollusks (Marincovich and Moriya, 1992) that originated in the western Pacific and were introduced into the Narrow Cape fauna by relatively brief incursions of warm surface water. The introduction of warm-water mollusks stands out dramatically against the dominant cool-water molluscan fauna that developed as a response to tectonically-induced regional marine cooling in the Gulf of Alaska (Marincovich, 1990 a,b). The shallow-water paleotemperature fluctuations implied by these warm-water horizons are thought to be an expression of Climatic Optimum paleotemperature fluctuations. Warm-water taxa include the bivalves *Anadara devincta*, *Kaneharaia* sp., *Glycymeris* sp., *Macoma optiva* and *Nuttallia ochotica*, and the gastropods *Fulgoraria (Musashia) miensis*, and *Turritella sagai* (Marincovich, 1989; Marincovich and Moriya, 1992). The age of the Narrow Cape Formation is constrained by molluscs and benthic foraminifera. No planktonic microfossils were recovered from the section.

Middle Miocene rocks form the uppermost 30 meters of a 2,000-meter-thick, continuous stratigraphic section, starting from the early Oligocene, in northeastern Kamchatka. They crop out in the bluffs of the Bolshaya Medvejka River and in sea-cliffs along the coast of the Gulf of Korf to the North of Cape Okno (Fig. 1). The early middle Miocene interval of the climatic optimum in the Gulf of Korf section is represented by an informal unit, known as the "Ezhovyi (Sea-urchin) Horizon" (Khomenko, 1933; Dvali, 1955; Gladenkov *et al.*, 1987), which owes its name to abundant sand dollar echinoderm remains. The molluscan assemblage of the "Sea-urchin horizon" differs markedly from the underlying assemblages in having a large number of warm-water taxa. According to the latest survey, it contain 38 species of mollusks (Gladenkov *et al.*, 1987) with the common occurrence of warm-water genera, such as *Neverita*, *Nassarius*, *Cancellaria*, *Olivella*, *Sinum*, *Anadara*, *Kaneharaia*, *Pitar*, *Macoma*, and *Pseudocardium*. Several species, namely *Neverita jamesae*, *Nassarius arnoldi*, *Cancellaria oregonensis*, *Pseudocardium panzana*, *Lucinoma hannibali*, *Mytilus ochotensis*, *Securella ensifera chechalisensis*, also occur in the Middle Miocene climatic optimum deposits of the western North America and Japan. This assemblage is well correlated with the better-studied and well-dated Middle Miocene faunas of the lower part of the Kakertskaya Formation of western Kamchatka (Gladenkov *et al.*, 1987; Gladenkov and Sinelnikova, 1990). The occurrence of *Kaneharaia* sp. within the Korf Bay section is constrained to a single concretionary horizon close the base of the section.

4. Materials and Methods

Two high-latitude areas of the North Pacific – the Gulf of Korf in Kamchatka (~60.5°N and Narrow Cape on Kodiak Island (~57.5°N) (Figs. 1, 2) were chosen for sampling because they contain the northernmost well-preserved early middle Miocene *Kaneharaia* occurrences in the North Pacific. Three specimens of *Kaneharaia* sp. from the Sea-Urchin horizon at the Gulf of Korf in Kamchatka and one specimen from the Narrow Cape Formation at Kodiak Island, Alaska were chosen for stable carbon and oxygen isotopic analyses. Shells were collected from distinct but narrow stratigraphic horizons containing other warm-water mollusks. Three specimens from the Gulf of Korf section were collected from the same stratigraphic horizon only centimeters from each other. In addition, two recent species - *Dosinia dunkeri* (Philippi, 1844) from the Gulf of California, off Guaymas, Mexico (Fig. 3), and *Dosinia elegans* Conrad, 1844) from the Gulf of Mexico (Fig. 4) were sampled and analyzed for stable isotopes of oxygen and carbon for calibration and comparison with the North Pacific Miocene *Kaneharaia* specimens. Instrumentally measured sea-surface temperatures in the Gulf of California off Guayamas, Mexico (27°51'08.83"N, 110°55'28.24"W), where the specimen of *D. dunkeri* was collected in 15 m of water, range from ~ 18°C in the winter (February-March) to 28.7°C in the summer (August) (Levitus and Boyer, 1994). The salinity in the area is close to the average seawater value, ranging from 35.0 to 35.4‰. Seasonal variations in salinity were not considered for temperature calculations because of their insignificant (less than 0.1‰) effect on the $\delta^{18}O$ of the water. The $\delta^{18}O$ value of 0.38‰ was calculated based on an annual salinity of 35.2‰ for the upper 10 m (Schmidt, Bigg, Rohling, 1999; Levitus 1994) and used for temperature calcula-

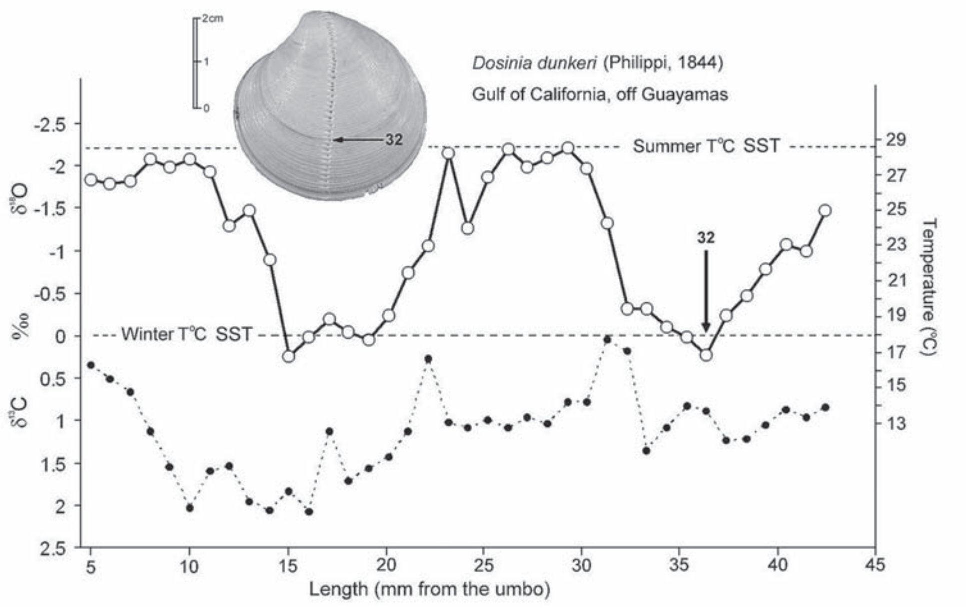

Fig. 3 Oxygen and carbon isotope profiles of modern *Dosinia dunkeri* from the Gulf of California. Temperature calibration from Epstein *et al.* (1953) using seawater $\delta^{18}O$ value of 0.38‰. Isotopic values plotted in reverse order (decrease upward).

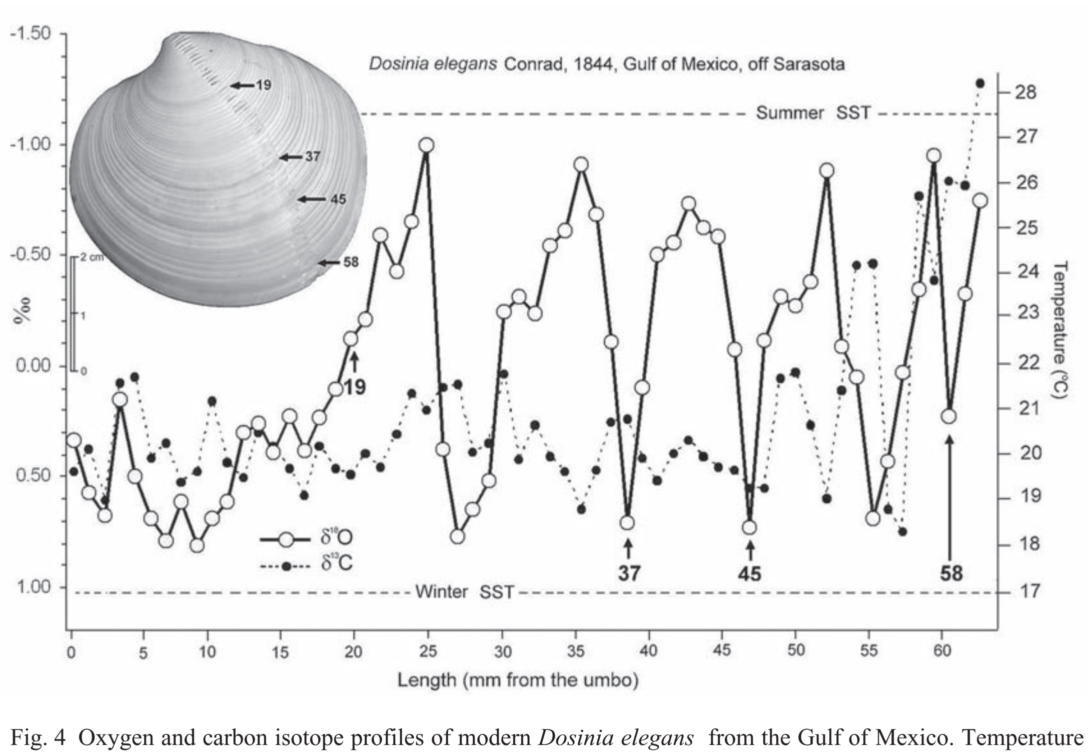

Fig. 4 Oxygen and carbon isotope profiles of modern *Dosinia elegans* from the Gulf of Mexico. Temperature calibration from Epstein *et al.* (1953) using seawater $\delta^{18}O$ value of 1.25‰. Isotopic values plotted in reverse order (decrease upward).

tions for *D. dunkeri*. In the Gulf of Mexico, Recent specimen of *D. elegans* was collected at 35 m by otter trawl off Sarasota, Florida (26°23’54.54”N, 82°57’50.69”W). Instrumental data for the area measure average $\delta^{18}O$ value of the water of 1.25‰ (Schmidt *et al.*,1999; Bigg and Rohling, 2000). Sea-surface temperatures range from ~ 17°C in the winter (February) to 27.5°C in the Summer (July – August). Salinity ranges from 35.4 to 36.4‰ with higher salinity during the winter, a result of evaporation and the absence of seasonal precipitation (Surge and

Lohmann, 2002).

The preservation of the fossil shells was assessed using x-ray diffractometry (XRD) and cathodoluminescent analyses. The XRD results indicate that the fossil *Kaneharaia* is calcitic, as are closely related Recent *Dosinia* shells, implying no significant diagenetic changes within the shells. These data show that fossil shells from Kamchatka and Alaska are suitable for isotope paleotemperature analyses.

The shells were gently polished to clean off any surface contamination, soaked in 30% hydrogen peroxide solution to remove organic material, rinsed and cleaned ultrasonically in distilled water to remove adhered calcium carbonate.

Specimens were milled using a 0.5 mm carbide bit to collect samples at 1 to 1.5 mm intervals from the outer shell surface along a transect of the maximum growth axis, across the growth bands from the umbo area to ventral margin. The samples were taken as 0.5-0.7 mm deep and 4 to 5 mm grooves along the same growth band to account for potential isotopic variability within growth bands. Powdered samples for the micromilled specimens did not exceed 50 μg. Powder samples were analyzed for stable oxygen and carbon using a Kiel II attached to a Finnigan Delta-plus mass spectrometer.

Oxygen and carbon isotopic results are reported relative to PDB (VPDB) (NBS-19) standard. The mean standard deviations for the cumulative of 300 samples milled from both recent and fossil specimens were 0.40‰ for $\delta^{18}O$ and 0.67‰ for $\delta^{13}C$. Analytical precision for all samples was better than ± 0.07‰ for $\delta^{18}O$ and ± 0.03‰ for $\delta^{13}C$.

Oxygen isotopic temperatures were calculated from the $\delta^{18}O$ values using the paleotemperature equation of Epstein *et al.* (1953), which was derived from both calcitic and aragonitic molluscan shells.

$$T\ °C = 16.5 - 4.3\ (\delta^{18}Oc - \delta^{18}O) + 0.14\ (\delta^{18}Oc - \delta^{18}Ow)^2$$

In this equation $\delta^{18}Oc$ is a carbonate sample value versus VPDB and $\delta^{18}Ow$ is the isotopic value of the ambient water (vs. SMOW). Our experience with *Dosinia* and *Kaneharaia* $\delta^{18}O$ data presented herein, clearly indicate that this equation allows more adequate paleotemperature estimates for calcitic shells. The oxygen isotopic composition of ambient water for Recent taxa was taken from global seawater $\delta^{18}O$ database (Schmidt *et al.*, 1999, Bigg and Rohling, 2000), based on the locality. Estimates of the $\delta^{18}O$ of the MMCO seawater in which biogenic carbonate precipitated is a function of the global ice volume variability and local salinity variations. In this study we used a value of -0.94‰ to account for the effect of ice volume during the MMCO. This value is derived from the global $\delta^{18}Ow$ curve for the Cenozoic (Lear *et al.*, 2000) by averaging the calculated $\delta^{18}Ow$ values between 17 and 14.5 Ma for the peak of the MMCO ice volume. For the effects of local salinity, we assume that the modern spatial gradients in salinity and $\delta^{18}Ow$ are applicable to the Miocene ocean. Constant baseline salinity values were assumed for the Middle Miocene without attempt to estimate effect of seasonal salinity changes.

Average annual mean $\delta^{18}Ow$ for the coastal waters off Kodiak Island and the Gulf of Korf (Schmidt *et al.*, 1999) is -0.56‰. Therefore, the cumulative local $\delta^{18}Ow$ value for the Kodiak Island and the northeastern Kamchatka during the time of MMCO, used for our paleotemperature calculations is inferred to be - 1.5‰ (vs. SMOW).

5. Results

5.1 Recent Dosinia

The oxygen isotopic record of the two Recent *Dosinia* species shows distinct records of seasonality. *Dosinia dunkeri* from the Gulf of California show oxygen isotopic records of 2 annual cycles of growth (Fig. 3). The oxygen isotope profile exhibits a cuspate pattern (Kobashi and Grossman, 2003) suggesting potential cold fronts during the winter and temporary shell growth shutdown (Wilkinson and Ivany, 2002; Goodwin *et al.*, 2003). Darker and thicker growth increments usually marking seasonal or periodic shutdowns in the shell growth are not common in *Dosinia*. The single dark growth band (sample # 32) correlates with heavy $\delta^{18}O$ values correlative with the winter season (Fig. 3). Based on the specimen sampled, the growth rate of *Dosinia dunkeri*, however, does not seem to change significantly with ontogeny and season. It is possible that growth is relatively uniform and rapid during the first two years, which is the age of this specimen. The $\delta^{18}O$ values for *Dosinia dunkeri* range from -2.22 to 0.24‰ with an average of -1.7 ± 0.07 ‰.

The oxygen isotopic profile of *Dosinia elegans* from the Gulf of Mexico clearly shows 5.5 cycles of growth. Compressed cuspate pattern of the profile indicate faster growth during the spring-summer seasons (light to heavy $\delta^{18}O$) and growth cessation during winter months (Fig. 4). This pattern is also indicative of decreased shell growth during ontogeny, with the fastest growth during the first year and slower growth for the remaining 4.5 years. Modern *Dosinia* species usually precipitate one-third to one-quarter of their adult shell during the first year of growth (Scarlato, 1981), which is consistent with the observed pattern for *Dosinia elegans*. Three out of four distinctive dark growth bands correlate with heavy $\delta^{18}O$ (winter) values (Samples 37, 45, and 58)(Fig. 4). One band does not show any particular correlation with $\delta^{18}O$ values (Sample19)(Fig. 4). The $\delta^{18}O$ values for *Dosinia elegans* range from -1.00 to 0.81‰ with an average of 0.45 ± 0.07 ‰.

Both specimens of *Dosinia* show similar pattern of

$\delta^{13}C$ with relatively heavy values during the first growth cycle becoming lighter as the shell growth progresses.

5.2 Middle Miocene *Kaheharaia*

The isotopic profiles from the early middle Miocene *Kaneharaia* sp. from high latitude regions of Kamchatka and Alaska show distinct intra-shell cyclicity in both $\delta^{18}O$ and $\delta^{13}C$. A strong positive correlation occurs between the $\delta^{18}O$ and $\delta^{13}C$ values in all 4 fossil shells (Figs. 5, 6). The $\delta^{13}C$ values of the *Kaneharaia* from the Narrow Cape Formation are relatively depleted, whereas $\delta^{13}C$ values of the *Kaneharaia* shells from the Gulf of Korf are relatively enriched throughout the shell transects. Oxygen isotopic values in all four shells are depleted. Growth bands are not distinctive in any of the four fossil specimens. The specimen from Alaska stands out because it shows only one and a half cycles consisting of two heavy and one extended light $\delta^{18}O$ excursion suggesting a total of only a year-and-a half growth. The $\delta^{18}O$ values of the Alaskan specimen range from -4.07 to -0.01‰ with an average of -2.08 ± 0.07‰ (Fig. 5). The broad shallow curve of light oxygen isotope values suggests continuous rapid growth throughout the warm season. Narrow peaks of heavier $\delta^{18}O$ values may indicate brief cessation of shell growth during the cold season. The cyclicity of the carbon isotope record follows the $\delta^{18}O$ pattern closely with an average value of -7.82 ± 0.03‰. The $\delta^{13}C$ amplitude is 50% or less of the $\delta^{18}O$ amplitude, suggesting that the carbon values are primarily derived from temperature-dependant metabolic effects (Grossman and Ku, 1986). The pattern of continuous growth throughout the year, recorded in the oxygen isotopic profile of Alaskan *Kaneharaia* is very similar to that of modern *Dosinia dunkeri*, particularly considering that the Alaskan Miocene specimen is smaller.

Three specimens of *Kaneharaia* from the Gulf of Korf section show good agreement in both oxygen and carbon isotopic values. Minimum $\delta^{18}O$ values in three Kamchatkan Miocene specimens are -4.17, -3.95, and -3.95‰, maximum values are -1.36, -1.79, and -1.73‰, with the averages being -3.21 ± 0.07‰, -2.93 ± 0.07‰, and -3.02 ± 0.07‰ for specimens # 1, # 2 and # 3 respectively (Fig. 6). The growth patterns appear to be a combination of a cuspate and asymmetrical saw tooth indicative of shallow-marine, near-shore environments with cold seasons and/or possible upwelling (Kobashi and Grossmann, 2003). The patterns of oxygen isotope profiles constructed for the Gulf of Korf *Kaneharaia* specimens do not indicate significant salinity fluctuations. The profiles represent 4.5 growth cycles for all specimens, irrespective of size. While two larger specimens (# 1 and # 2) are close in size, specimen # 3 is about a third of their size (Fig. 6). The well-developed growth lines and margin of the smallest specimen (#3) may be indicative of a dwarf, rather than a juvenile shell, which in not uncommon in large populations of mollusks. Sharp peaks of lighter $\delta^{18}O$ value for all three specimens indicate reduced or temporary cessation of growth during the cold seasons. Specimens # 1 and # 3 show rapid shell growth during the first two years and a distinct slow-down in shell material accumulation beginning with the third year, which is consistent with growth patterns of modern *Dosinia*. The oxygen isotopic profile of specimen # 2 shows an ontogenetic slow-down in shell growth during the fourth year.

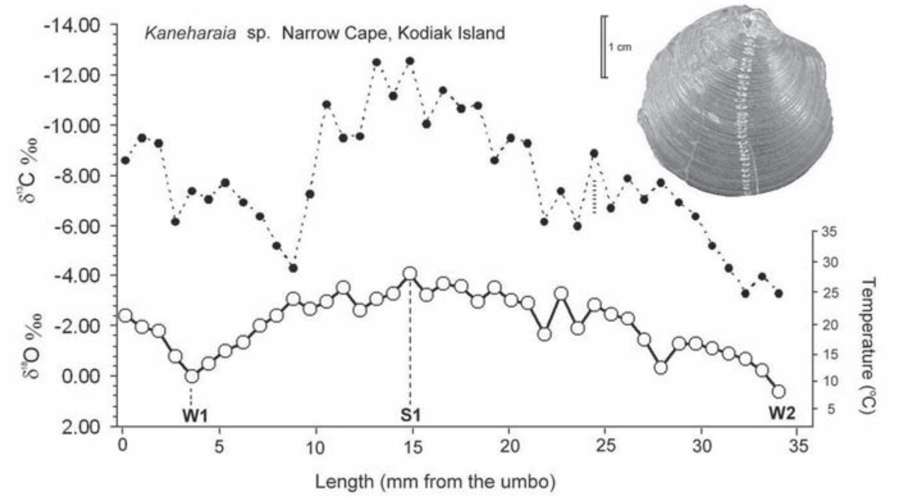

Fig. 5 Oxygen and carbon isotope profiles of the Middle Miocene *Kaneharaia* sp. from the Narrow Cape Formation, Kodiak Island, Alaska (~ 57.5°N). Summer (S) and winter (W) values are labeled. Temperature calibration from Epstein *et al.* (1953) using seawater $\delta^{18}O$ value of -1.5‰. Isotopic values plotted in reverse order (decrease upward).

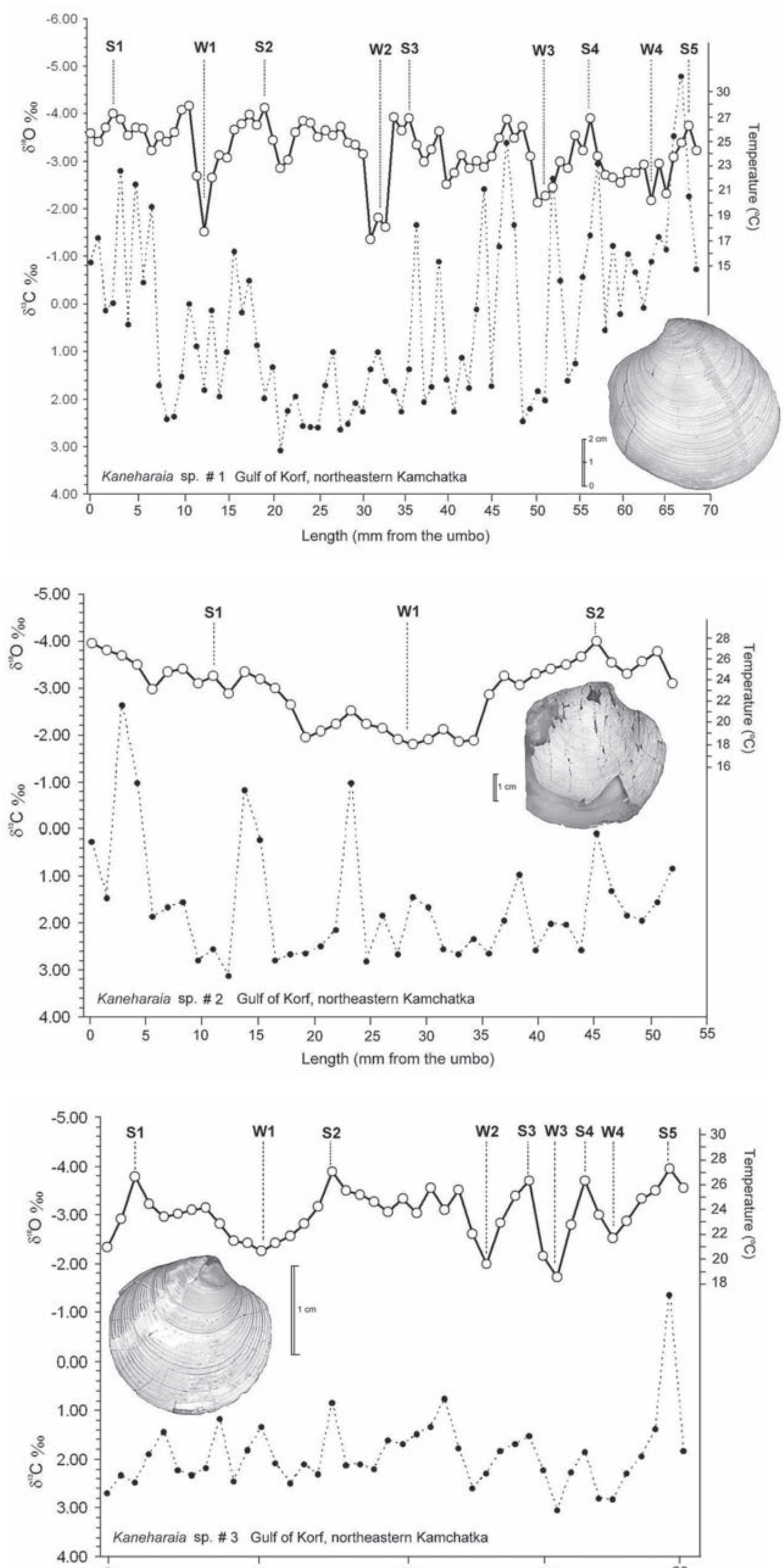

Fig. 6 Oxygen and carbon isotope profiles of three Middle Miocene *Kaneharaia* sp. specimens from the Sea-Urchin (Ezhovyi) Horizon, Gulf of Korf, northeastern Kamchatka (~60.5°N). Summer (S) and winter (W) values are labeled. Temperature calibration from Epstein *et al.*(1953) using seawater $\delta^{18}O$ value of -1.5‰. Isotopic values plotted in reverse order (decrease upward).

6. Discussion

Temperature calculations for modern *Dosinia dunkeri* and *Dosinia elegans* show good agreement with the instrumentally derived mean winter temperature (MWT) and mean summer (MST) temperatures. The fact that four isotopic values yielded slightly lower temperatures than the MWT at the surface in the central Baja California (Fig. 3) is probably an artifact of local unaccounted for temperature fluctuations at 15 m water depth off Guayamas, Mexico. Temperatures calculated from *Dosinia elegans* are well within the range of mean monthly temperatures (Fig. 4) for the surface waters.

Paleotemperatures derived from our isotope data imply substantial shallow-water warming in the high-latitude North Pacific during the peak of the MMCO. Use of the equation by Epstein *et al.* (1953) and a δ^{18} water value of - 1.5‰ for the Middle Miocene yields a MST of 28.4°C and MWT of 8.6°C with the calculated MAT of 19.3°C and MART of 19.8°C for the part of the Narrow Cape Formation on Kodiak Island (Fig. 7). Averaging data from three specimens of *Kaneharaia* from the Gulf of Korf yield average MST of 28.2°C and MWT of 17.2°C with an average MAT of 23.5°C and MART of 11.0°C (Fig. 7). MWT data should be treated with caution and may not reflect the lowest possible winter temperatures, but rather a temperature of growth cessation in the Middle Miocene high latitude *Kaneharaia*.

Compared to the modern northwestern Pacific, where shallow-sea temperatures are less affected by coastal upwelling than in the northeastern Pacific, the average temperatures of 21.55°C (*D. ausiensis*) would occur at least to 25 to 30° of latitude to the south of the Miocene fossil localities. The Kodiak *Kaneharaia* MAT and MART is comparable to that of modern subtropical mixed-layer waters, and closely resembles the temperature ranges obtained from *Dosinia dunkeri*. The Middle Miocene *Kaneharaia* from Kodiak Island has the largest seasonality (MART) of all Miocene high-latitude North Pacific specimens. The Gulf of Korf specimens from the Sea Urchin horizon indicate an even higher MAT with less seasonal range, compared to the Narrow Cape specimen. The MST values, however are very close for all four Miocene *Kaneharaia* specimens. The difference between MAT and MART may reflect the difference in ecological conditions. Deposits of the Narrow Cape formation, based on the molluscan and foraminiferal assemblage appear to have been deposited on an the open continental shelf (Marincovich and Moriya, 1990), whereas the Sea-Urchin horizon of the Gulf of Korf, seemed to accumulate in a shallow-water embayment (Gladenkov *et al.*, 1987). Differences in depth and circulation patterns between the open shelf of the Kodiak area and shallow embayment of the northeastern Kamchatka can potentially account for the MART differences between Alaskan and Kamchatkan *Kaheharaia* specimens. Our calculated MAT temeperatures are 1.7 to 7.9°C warmer than the inferred MAT obtained by Kiyashko *et al.* (1987) and Kiyashko (1992), based on bulk δ^{18}O samples from the early middle Miocene bivalves *Macoma, Mya* and *Serripes* from western Kamchatka. The western Kamchatka bivalves yielded average paleotemperatures ranging from 11.4 to 21.8°C. Our data also well exceed temperature estimates of 6.35 to 9.05°C MAT and 15.2 to 18.88°C MST, based on the diversity gradients and presence of warm-water mollusks, made by Kafanov and Volvenko (1997). The reason for the differences lies in the scale of sampling, location, and selection of target genera. Shells of *Macoma, Mya* and *Serripes*, which are cool-water taxa were sampled using bulk sampling method as opposed to a growth increments method used herein. Recent analogs of the Middle Miocene taxa were not sampled to check an accuracy of temperature estimates and account for vital effects. Temperature calculations based on faunal data (Kafanov and Volvenko, 1997) were based on bulk assemblages collected from wide stratigraphic range up to tens of meters thick and containing several fossiliferous layers. As we emphasized above, the bulk of the Climatic Optimum faunas in both Alaska and Kamchatka are made up of well-preserved shells of cool-water mollusks. It was further shown that the MMCO consisted of a number of warm and cool episodes, rather than a single warming peak (Oleinik et al, 2003, 2005, 2007). Isotopic sampling of these shells and faunal calculations based on the bulk composition will inevitably result in lower temperature estimates. *Kaneharaia* is not found in the western Kamchatka sections were isotopic studies of the Middle Miocene mollusks were made by Kiyashko *et al.*, (1987) and Kiyashko (1992). Both the restricted stratigraphic distribution of *Kaneharaia* and stable isotope data clearly suggest that the warm-water incursions at the peak of MMCO in the North Pacific brought substantial warming in the high latitudes, but were short-lived and only changed normal cool-water conditions to warm-temperate or subtropical only for brief periods of geologic time.

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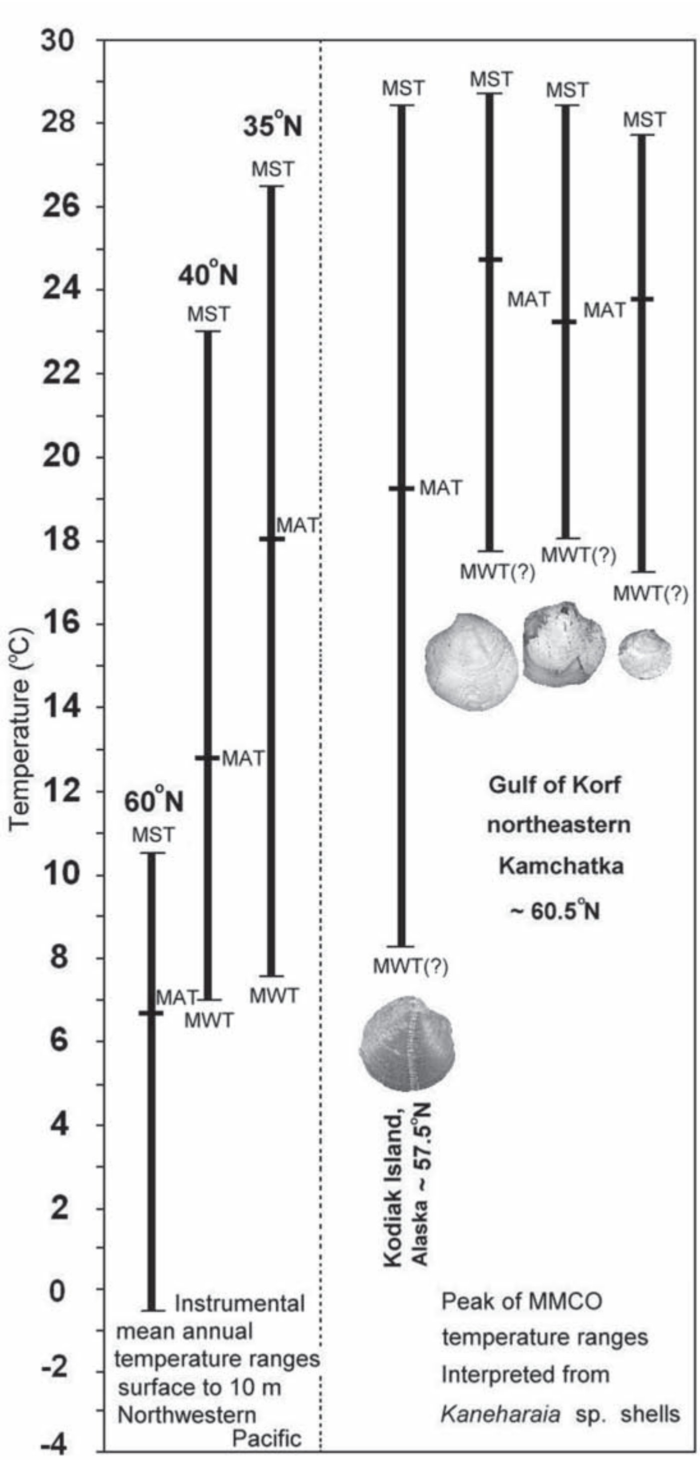

Fig. 7 Comparison of mean annual temperature ranges (January-August) temperatures measured instrumentally in the northwestern Pacific from surface to 10 m depth with temperature ranges interpreted based on the stable isotope data form Middle Miocene *Kaneharaia* sp. from Alaska and Kamchatka.

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北太平洋高緯度における中期中新世最温暖期の温暖化の度合：二枚貝 *Kaneharaia* の成長断面の安定同位体分析に基づいて

アントン　オレイニク・ロイ　マリンコヴィッチ　Jr.・コンスタンチン　バリノフ・ピーター　スワート

要　旨

16 Ma 頃の中期中新世最温暖期（MMCO）は，新第三紀では最も温暖な期間であった．北太平洋地域におけるこの最温暖期のピークは，アラスカとカムチャッカの化石 *Kaneharaia*（二枚貝綱カガミガイ科）に記録されている．*Kaneharaia* の化石標本は，北太平洋高緯度の初期中期中新世と認定した次の 2 ヶ所産地から採集した．それはカムチャッカ半島北西部のシーアーチン層準とアラスカのナローケープ層である．これらの産地から多くの *Kaneharai* 化石を採集し，最終的に成長に伴う炭素と酸素の安定同位体変動の分析可能な標本を得た．これらの化石の成長断面の分析値を，現在の亜熱帯域に生息する *Kaneharaia* 類似の 2 種の *Dosinia* の分析値と比較検討した。海洋の $\delta^{18}O$ の値を Zachos 等の用いた緯度補正を加味して-1.5 ‰と仮定すると，酸素同位体からのアラスカとカムチャッカの年平均水温は，それぞれ 19.3 ℃と 23.5 ℃，水温の年較差は 19.8 ℃と 11 ℃であることが示された．このような温度範囲は，現在の亜熱帯（北緯 40 度）の混合水塊に比較可能で，北太平洋地域での MMCO 期の，まさに最温暖期のピークを示したものと考えられる．

同位体組成の変化幅とそれから推定される水温変動幅は，その層序的な変化パターンとともに，MMCO 期の北太平洋高緯度域の温暖水塊が，現在の低緯度地域の温暖水塊のようには持続的に存在していたわけではないことを示している．そのかわり，表層の温暖水が西太平洋の亜熱帯地域から比較的短期間だけ流入し，一般的に冷温なこれらの地域に温暖性の貝類が入り込んだと判断される．