Reports

Tertiary Climatic Change in the Marginal Northeastern Pacific Ocean

Abstract. *Analysis of distributional patterns of shallow-water molluscan faunas of the middle latitudes of the marginal northeastern Pacific Ocean discloses a sharp reversal during the Miocene of the progressive climatic deterioration. A low point in the Tertiary cooling trend during the Oligocene was followed by climatic warming that culminated during the middle Miocene, as illustrated by a series of zoogeographic profiles.*

Definitive studies of the Tertiary marine climate of the Pacific coast (*1*), based on investigations of larger marine invertebrates, revealed that tropical conditions occurred as far north as western Washington during the early Eocene. They further inferred a progressive cooling of the marine climate following the early Eocene until, during the Pliocene, temperatures approached those of modern times. A clue to the previously unrecognized climatic reversal during the middle Tertiary lies in the relative ease of correlation between the middle Miocene molluscan faunas of California and those of the Pacific Northwest; correlation between earlier or later Neogene faunas of both areas is much more difficult (*2*). The fauna of the Astoria Formation and coeval strata in coastal Oregon and Washington (*3, 4*), for example, may be readily correlated with middle Miocene faunas of southern California. These middle-latitude faunas are characterized by the persistent appearance of shallow-water mollusks of tropical or subtropical aspect far north of their most northern occurrence in both lower and upper Miocene strata. The relationship of the middle Miocene faunas in the Pacific Northwest to those in southern California is evidenced by the occurrence of similar genera, such as *Anadara* s.s., *Dosinia, Trochita, Catilon, Euclia, Antillophos*, and *Ficus*. These genera are now restricted to the Panamic or Surian molluscan provinces, the climates of which are generally considered tropical and subtropical.

By tracing the northernmost occurrences of certain warm-water genera during successive stages of the Tertiary, a distinct pattern emerges. Occurrences of these genera in low latitudes during the Oligocene are followed by higher-latitude occurrences during the Miocene, after which there is a more or less steady southward retreat, through time, to the present northernmost limits within tropical or subtropical latitudes of the west coast of Mexico. This pattern is well illustrated by the pelecypod *Dosinia* and the gastropod *Ficus* (Fig. 1). This qualitative analysis, however, is suited only for widespread and abundant taxa, and even these have incomplete geologic

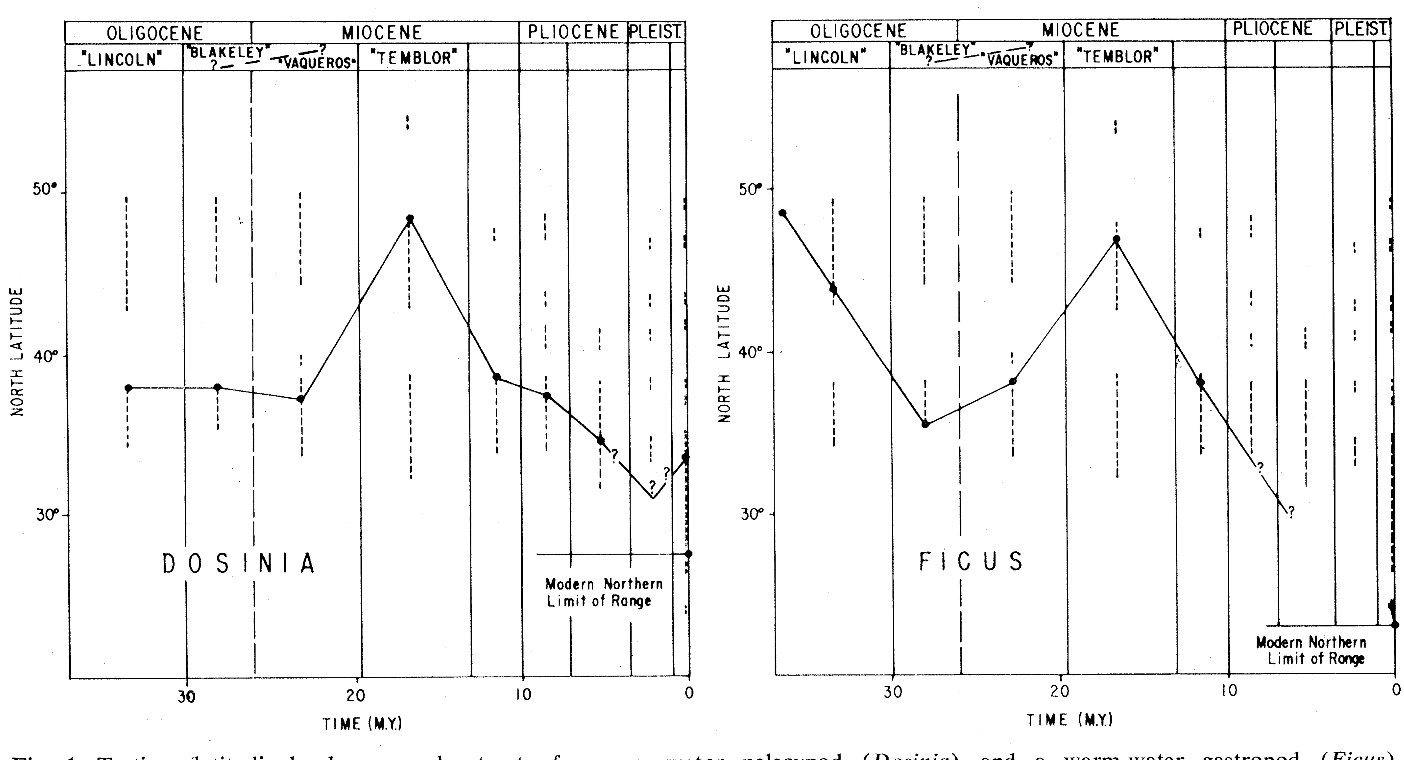
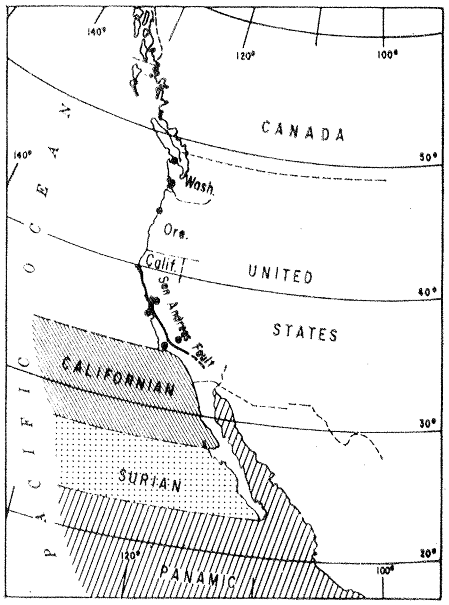


Fig. 1. Tertiary latitudinal advance and retreat of a warm-water pelecypod (*Dosinia*) and a warm-water gastropod (*Ficus*) along the west coast of North America. Scale (in million years) is based on available potassium-argon dates (*26, 27*). Latitudinal occurrences of fossiliferous shallow-water rocks of Pacific coast megafaunal "stages" are shown by broken vertical lines.



records because of inadequate collection and poor preservation of specimens, and the widely scattered occurrence of marine Tertiary embayments along the Pacific coast.

Because previous studies of Tertiary faunas of the Pacific coast failed to identify distributional trends associated with the Miocene climatic reversal, an objective analysis of all faunal data was needed in order to determine the climatic relationships of late Paleogene and Neogene faunas. Accordingly, I have devised a simple means of zoogeographic analysis of warm-water faunas of the middle latitudes. In each Tertiary fauna component living genera are classified according to the modern molluscan province in which their northernmost modern occurrence is recorded (*5*). From these data, the percentage of living genera restricted to warm-water molluscan provinces (Fig. 2)—Panamic (6°S to 23°N), Surian (23°N to 28°N), and Californian (28°N to 34.5°N)—can be calculated. These percentages can then be used to construct objective zoogeographic profiles for warm-water Tertiary faunas. Successive post-Eocene molluscan faunas of shallow-water aspect from the principal depositional basins along the Pacific coast (Fig. 2) have been analyzed in this manner.

Fig. 2. Index map showing modern warm-water molluscan provinces and location of Tertiary sequences and faunas.

The most complete sequence of Tertiary molluscan faunas of shallow-water aspect occurs in the San Joaquin basin (latitude 35°N), a large interior basin roughly coincident with the southern third of the Great Valley of California. Warm-water genera now restricted to the Surian and Panamic molluscan provinces increase from a low point in the middle Oligocene to a peak in the middle Miocene, but decline sharply during the late Miocene (Fig. 3A).

The zoogeographic profile for the adjacent southern Coast Ranges west of the San Andreas fault (Fig. 3B) is remarkably similar to that of the San Joaquin basin. Cumulative percentages of tropical, subtropical, and warm-temperate genera show an even sharper decline in the late Tertiary from the middle Miocene peak.

Profiles constructed for the Santa Cruz basin (latitude 37°N) in the central part of the California Coast Ranges west of the San Andreas fault (Fig. 3C), although less well controlled, are similar to those from other California Tertiary basins. The principal difference between these profiles is the apparent replacement of tropical (Panamic) genera by subtropical (Surian) genera.

Zoogeographic profiles for western Oregon and Washington are similar to those for California, but the zoogeographic values (Fig. 3, D and E) are markedly lower than those from California basins. Unlike California basins,

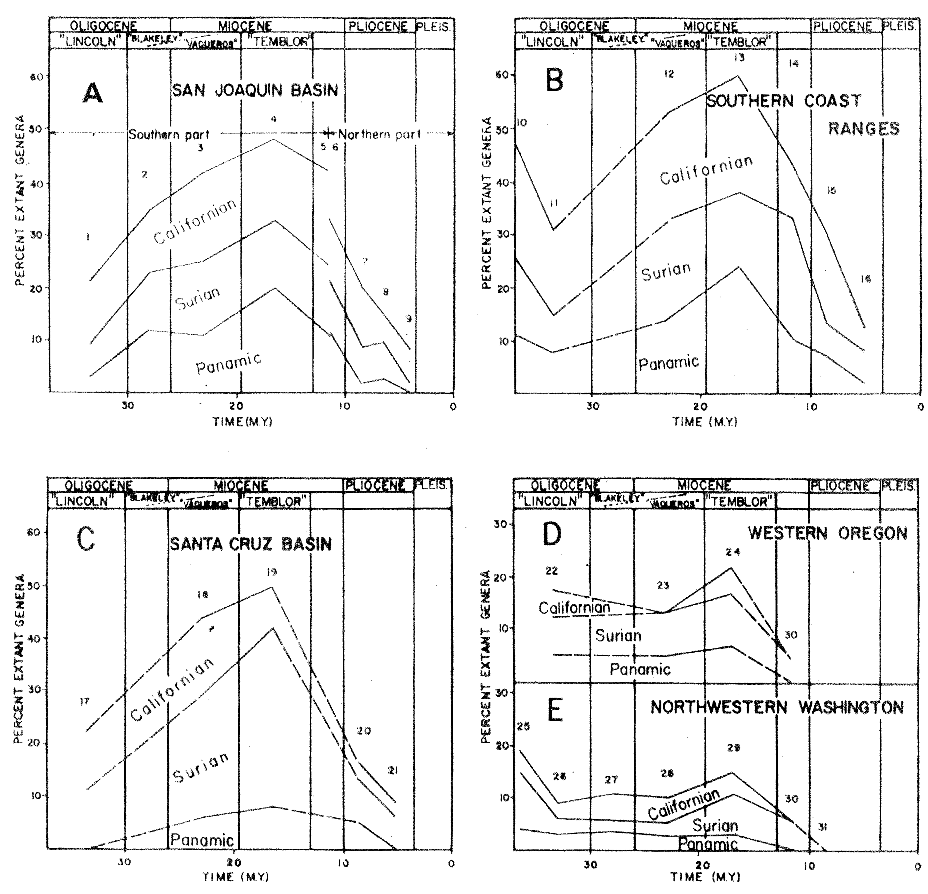


Fig. 3. Cumulative percentages of warm, shallow-water molluscan genera placed according to Pacific coast megafaunal sequence (*28*) for San Joaquin basin (A), southern Coast Ranges (B), Santa Cruz basin (C), western Oregon (D), and northwestern Washington (E). Time scale (in million years) is based on available potassium-argon dates (*26, 27*). 1, "Lincoln stage" (*29*); 2, so-called Phacoides sandstone (*20*); 3, 4, "Vaqueros" and "Temblor stages" (*20, 30, 31*); 5, 6, Santa Margarita Formation (*32, 33*); 7, Jacalitos Formation (*34*); 8, Etchegoin Formation, *Siphonalia* zone (*35*); 9, San Joaquin Formation, *Pecten-Trachycardium* zone (*35*); 10, Gaviota Formation, middle member (*36*); 11, Gaviota Formation, upper member (*36*); 12, Vaqueros Formation (*30, 37*); 13, Temblor Formation (*30, 38*); 14, Santa Margarita Formation (*39*); 15, Pancho Rico Formation (*40*); 16, Careaga sandstone (*41*); 17, San Juan Bautista Formation (*42*); 18, Vaqueros Formation (*20, 27, 30, 42, 43*); 19, "Temblor stage" (*27, 44*); 20, Purisima Formation, lower part (*45*); 21, Merced(?) Formation (*45*); 22, Eugene Formation (*46*); 23, Yaquina Formation (*20, 47*); 24, Astoria Formation (*48*); 25, Durham's (1944) Quimper sandstone (*6, 49*); 26, Durham's (1944) Lincoln Formation (*6*); 27, "Blakeley stage" (*6, 50*); 28, Sooke Formation (*51*); 29, Clallam Formation (*3, 6, 20, 52*); 30, so-called Montesano Formation (*53*); 31, Quillayute Formation (*54*).

there is little change in the combined Panamic-Surian curves from the middle Oligocene to the early Miocene, prior to the middle Miocene peak. The different configuration of this segment of the curves may result from the small number of warm-water genera represented in the northern faunas. Many Oligocene faunas of the Pacific Northwest, including such middle to outer sublittoral genera as *Aforia, Bathybembix, Irenosyrinx, Ancistrolepis*, and *Cuspidaria* (*6*), cannot be analyzed this way because they represent much deeper-water, and therefore cooler, environments.

A similar warming trend during the Miocene seems evident from the reported abundance and diversity of planktonic Foraminifera during successive Oligocene and Miocene stages of deposition in California. During the Oligocene and early Miocene [Refugian, Zemorrian, and lower part of the Saucesian benthonic foraminiferal stages of Kleinpell (*7*)], planktonic foraminifers are characterized by a low level of diversity of species and by relatively rare occurrence. In the middle Miocene, however, they become diverse and relatively abundant, permitting firm correlation with the tropical sequence of the Caribbean (*8*).

Late Miocene planktonic foraminifers are less diverse than earlier Miocene faunas and include the coolest-water planktonic faunas of the California Miocene (*8, 9*). A simple diversity curve based on these observations would have a peak generally coinciding with the peaks on the molluscan curves. Moreover, such a curve would seem to have similar significance in terms of climate in light of the reported relation between diversity and abundance of species and latitude (*10*). Bandy (*11*) initially held that there were no major northward expansions of tropical foraminifers in the North Pacific after the Eocene, but a later study revealed a slight northward expansion during the Miocene (*12*), presumably in the northwestern Pacific.

Recent studies of post-middle Miocene planktonic foraminifers suggest paleoclimatic inferences which differ from the molluscan evidence. Periods of very cool surface-water temperatures during the late Miocene and the middle Pliocene alternating with periods of greatly expanded tropical isotherms have been inferred from reversals in the coiling direction of *Globigerina pachyderma* (*12*). However, the conclusion that sinistral coiling populations of this foraminifer in the late Miocene of California (upper Mohnian stage) are indicative of marine surface-water temperatures as cold as 5°C (*12*) conflicts with evidence of coeval warm-water molluscan faunas in which as many as one-third of the genera are now restricted to subtropical or warmer waters. The critical Foraminifera live at considerable depths in the water column (*13*) and are, therefore, normally not present in sublittoral or shelf sediments. Still, the apparent coexistence, during the late Miocene, of planktonic foraminiferal assemblages of such cool-water aspect with shallow-water mollusks of very warm-water aspect poses a perplexing problem. These relationships seem to require much stronger vertical temperature gradients than now exist offshore.

Paleoclimatic trends of mollusks of the northeastern Pacific generally agree with the sequence of Tertiary marine climates in the northwestern Pacific (*14*) and particularly with those in the southwestern Pacific (see *15, 16*). A marked rise in shallow-water temperatures in New Zealand began during the Oligocene and persisted through the middle Miocene (*16*). The climatic peak may have occurred in Australia during the early part of the Miocene (*15*), although Devereux (*16*) maintains that the new Zealand and Australian peaks, based on studies of oxygen isotopes, are congruent.

Terrestrial climatic curves for the middle latitudes of the northwestern Pacific Ocean (*17*) and the western United States (*18*), based on paleobotanical evidence, parallel the zoogeographic profiles based on mollusks from the northeastern Pacific. Tertiary floras from Alaska, and particularly those from the northwestern United States (*19*), provide a climatic interpretation similar to that provided by the molluscan trends of California.

Middle Miocene molluscan assemblages from the western part of the Gulf of Alaska (*20, 21*) and the Alaska Peninsula (*22*) reflect the trends seen elsewhere in the marginal North Pacific. An early Miocene fauna from near Kodiak Island, for example, includes no warm-water elements, whereas the middle Miocene fauna from Kodiak and the Alaska Peninsula includes such warm-water genera as *Dosinia, Crassostrea*, and *Neverita*, which presumably are related to western Pacific stocks. In the northeastern Gulf of Alaska, an entirely different climate prevailed. The middle Miocene fauna of the lower part of the Yakataga Formation (*20, 23*) includes no warm-water genera comparable to those from Kodiak Island and the Alaska Peninsula. This fauna is, in fact, of a cooler aspect than the early Miocene fauna of the underlying Poul Creek Formation. The suggested climatic deterioration may be the result of local cooling directly related to the onset of glaciation (*24, 25*) during deposition of the lower part of the Yakataga Formation. The cooling which occurred in the northeastern Gulf of Alaska during the middle Miocene may have served as a local barrier to the distribution around the Gulf of warm-water faunal elements found in the middle Miocene of the Alaska Peninsula, to the west, and of British Columbia and Washington, to the south.

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21 April 1969

Modified Spinel, Beta-Manganous Orthogermanate: Stability and Crystal Structure

Abstract. *A new high-pressure polymorph with a modified spinel structure, β-Mn_2GeO_4, is stable in a pressure range intermediate between the field of the polymorph with the olivine structure and that of another high-pressure polymorph. Oxygen atoms are located approximately in cubic close packing with manganese and germanium atoms in octahedral and tetrahedral interstices, respectively, as in the spinel structure; however, germanium atoms form Ge_2O_7 groups instead of isolated GeO_4 groups.*

High-pressure transformations in R_2MX_4 compounds (*1*) are important in the interpretation of the rapid increase of seismic velocity at a certain depth in the earth's mantle. The olivine-spinel transformation of R_2MX_4 compounds has been observed in Mg_2GeO_4, Fe_2SiO_4, Ni_2SiO_4, and Co_2SiO_4. Ringwood and Major (*2*) reported a noncubic high-pressure polymorph, a "distorted" or "modified" spinel, in transformations of $(Mg_{0.85}Fe_{0.15})_2SiO_4$ and Mg_2SiO_4. They considered that this high-pressure polymorph, β-Mg_2SiO_4, is produced from a true spinel when pressure is released. However, Ringwood's investigation (*3*) of the phase relations of the system Mg_2SiO_4-Fe_2SiO_4 at high pressures indicates that the β-phase is thermodynamically stable in its synthesis field. Akimoto and Sato (*4*) demonstrated that β-Co_2SiO_4, which is analogous to β-Mg_2SiO_4, is stable in a special field intermediate between the olivine and spinel fields.

In our study of the phase relations of Mn_2GeO_4, β-Mn_2GeO_4 was obtained. Because the β-phase is important in the high-pressure transformations of R_2MX_4 compounds, the stability field and crystal structure of β-Mn_2GeO_4 have been investigated.

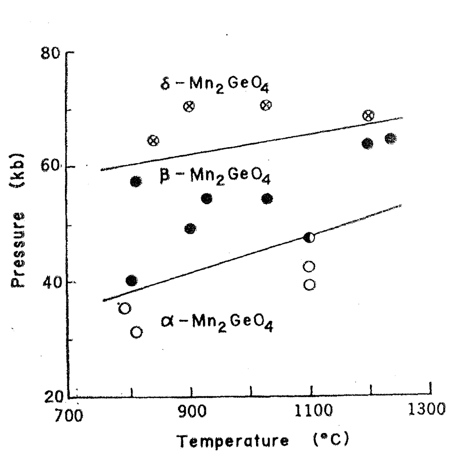

Fig. 1. Stability diagram for the high-pressure and high-temperature transformations of Mn_2GeO_4. Starting material is α-Mn_2GeO_4; ○, no change after runs; ● and ⊗, changes to β- and δ-Mn_2GeO_4, respectively, after runs.

Phase relations of Mn_2GeO_4 were studied from 790° to 1240°C in the pressure range 31 to 70 kb with the tetrahedral anvil type of high-pressure apparatus (*5*). The high-pressure polymorph β-Mn_2GeO_4 is stable in the pressure range intermediate between the fields of the olivine-type polymorph, α-Mn_2GeO_4, and another high-pressure polymorph, δ-Mn_2GeO_4 (Fig. 1) (*6*). In all experiments, α-Mn_2GeO_4 was used as the starting material. The cell dimensions, space groups, and densities of the three polymorphs are given in Table 1. A true spinel type, γ-phase, has not been observed in Mn_2GeO_4; the densest polymorph, δ-Mn_2GeO_4, has the Sr_2PbO_4-type structure in which Ge atoms are located in the octahedral interstices of oxygen atoms (*7*). The increases of density from α-Mn_2GeO_4 to β-Mn_2GeO_4 and from β-Mn_2GeO_4 to δ-Mn_2GeO_4 are 7.1 and 10.7 percent, respectively.

The structure of β-Mn_2GeO_4 has been determined from single crystals synthesized at 1240°C and 64 kb. The orthorhombic cell dimensions of β-Mn_2GeO_4 are comparable to those of β-Mg_2SiO_4 and β-Co_2SiO_4 (Table 2). The calculated density is 5.13 g cm^{-3} with eight formula units per cell. The diffraction pattern is *I--a*, which suggests the possible space groups *Imma*, *I2ma*, and *Im2a*. A nearly spherical crystal, 0.1 mm in diameter, was used for collecting the intensity data. Three-dimensional intensities for 521 symmetrically independent reflections were measured on an automatic four-circle diffractometer; molybdenum radiation was used out to a maximum diffraction angle of $2\theta = 60°$ by the $\omega - 2\theta$ scan method. The intensities were corrected for Lorentz and polarization factors. No absorption correction was made.

Because the unit cells of β-Mg_2SiO_4 and β-Co_2SiO_4 are obtained by the transformation matrix

$$\begin{bmatrix} \frac{1}{2} & \overline{\frac{1}{2}} & 0 \\ 1 & 1 & 0 \\ 0 & 0 & 1 \end{bmatrix}$$