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Miocene Stable Isotope Record: A Detailed Deep Pacific Ocean Study and Its Paleoclimatic Implications

Abstract. *Deep Sea Drilling Project site 289 in the western equatorial Pacific has yielded an extremely detailed record of the carbon and oxygen isotopic changes in the Miocene deep ocean. The isotopic record reflects major changes in paleoclimate and paleoceanography, probably dominated by a major phase of Antarctic ice-cap growth. The transition from a relatively unglaciated world to one similar to today occurred between 16.5 × 10⁶ and 13 × 10⁶ years before the present, with the greatest change occurring between approximately 14.8 × 10⁶ and 14.0 × 10⁶ years before the present.*

We present here a detailed record of the stable isotopes of oxygen and carbon of Miocene benthic foraminifera from equatorial Pacific Deep Sea Drilling Project (DSDP) site 289. The record depicts Miocene climatic changes and permits speculation on the causes of the major changes in the earth's climate that occurred during the Miocene epoch, 5.5×10^6 to 22×10^6 years before the present (B.P.).

The results of this study are indicative of an early Miocene world characterized by relatively limited polar glaciation and by deep ocean waters significantly warmer than the near freezing waters of today. By late Miocene time, a large Antarctic ice cap existed and ocean temperatures approached today's values. The data presented document a rapid transition to an extensively glaciated world in early middle Miocene time.

DSDP site 289 on the Ontong-Java Plateau (00°29.92'S, 158°36.69'E) was chosen for this study because its thick, continuously cored Miocene section contains abundant, well-preserved foraminifera. It is located near the plateau crest and hence is free from sources of downslope contamination. Its water depth (2200 m) has probably been maintained by its high sedimentation rate, 36 to 71 m per 10^6 years (*1*).

Oxygen and carbon isotopic compositions of well-preserved foraminifera reflect the isotopic compositions of, respectively, the H_2O and HCO_3^- in seawater, as well as the water temperature during test growth (*2*). Disequilibrium (biological) isotopic effects may also affect the isotopic composition of the tests. Almost all the 200 samples that we analyzed were monospecific samples of the benthic foraminiferal genus *Cibicidoides*. Comparison of $\delta^{18}O$ and $\delta^{13}C$ values of different species of *Cibicidoides* from single sediment samples indicated no significant interspecific differences in isotopic compositions. Hence the $\delta^{18}O$ values of different *Cibicidoides* species used in this study may be directly compared. However, all *Cibicidoides* species studied appear to be depleted in ^{18}O relative to calcite in isotopic equilibrium with seawater by about 0.65 ± 0.15 per mil (*3*). The $\delta^{13}C$ values of the Miocene benthic foraminifera analyzed probably change primarily in response to changes in the $^{13}C/^{12}C$ ratio of seawater HCO_3^-. In the analyses, we used standard techniques (*2*); results are reported in δ notation relative to the Pee Dee belemnite standard (PDB).

The age determinations were based on planktic foraminiferal biostratigraphy (*1*, *4*), and we correlated the ages to the geochronologic-biostratigraphic framework (*5*) by assuming a constant sedimentation rate between biostratigraphic marker horizons.

Isotopic results are plotted in Fig. 1a, with additional detail shown in Fig. 1b. Oxygen isotopic data indicate a general but irregular decrease in ^{18}O from approximately +1.5 per mil 20×10^6 years B.P. (planktic foraminiferal zone N5) to an average of about +1.0 per mil and a minimum of +0.66 per mil 16.3×10^6 years B.P. The lowest $\delta^{18}O$ value, 0.66 per mil, corresponds to the inferred warmest bottom water or minimum polar ice, or both, found in this study. From 16.3×10^6 to 14.8×10^6 years B.P. $\delta^{18}O$ values increased gradually to approximately +1.5 per mil, and at that time the character of the record changed markedly. The oscillations between 14.8×10^6 and 14.2×10^6 years B.P. in cores 45 and 47 (Fig. 1b) are striking. The difference between $\delta^{18}O$ values of adjacent samples (at approximately 6000-year intervals) has an average value of 0.22 per mil and a maximum of 0.58 per mil. A change in the benthic foraminiferal fauna at site 289 occurs in the same time range (*6*).

The remainder of the middle Miocene section and the lower part of the upper Miocene section (planktic foraminiferal zones N12 through N17) are characterized by $\delta^{18}O$ values that are uniformly higher than those of the early Miocene. The $\delta^{18}O$ values vary between approximately 2.0 and 2.8 per mil. The latest Miocene record (5×10^6 to 7×10^6 years B.P.) shows only minor $\delta^{18}O$ variation about a mean value of approximately 2.4 per mil.

Interpretation of paleotemperatures from the isotopic data requires knowledge of the $^{18}O/^{16}O$ ratio of seawater at the time the foraminifera grew. The isotopic record described above reflects a combination of temperature change and change in the volume and isotopic composition of continental ice. We have attempted to set limits on the Miocene bottom-water temperatures and isotopic compositions at site 289.

We assume that throughout Miocene time, as at present, bottom water formed as a result of the sinking of cold, dense surface water in Antarctic coastal regions, and hence that bottom-water temperatures were similar to coastal Antarctic surface temperatures. We assume, further, that, whenever the Antarctic ice cap reached the ocean along extensive portions of the Antarctic coast or abundant sea ice was generated, bottom waters with temperatures between 0° and 3°C would form.

Shackleton and Kennett (*7*) have estimated that melting of the modern Antarctic ice cap and mixing of the meltwater with the oceans would decrease the $^{18}O/^{16}O$ ratio of seawater by 0.92 per mil, giving a value for Pacific bottom waters of approximately −1.10 per mil relative to standard mean ocean water (SMOW) [−1.30 per mil relative to PDB (*8*)]. We argue that, prior to the increase in $\delta^{18}O$ values 14.8×10^6 years ago, δ_w was most likely much closer to −1.30 per mil than to the modern value of −0.38 per mil (see Fig. 2). If *Cibicidoides* is consistently depleted by 0.65 per mil relative to the equilibrium value (*3*) (a value used in the construction of Fig. 2), the *Cibicidoides* $\delta^{18}O$ values before 14.8×10^6 years B.P. would correspond to growth temperatures of 3.8° to 6.5°C in an ice-free world. For modern seawater (and hence a major Antarctic ice cap) the same *Cibicidoides* $\delta^{18}O$ values would correspond to temperatures of 6.5° to 9.5°C. However, the latter temperatures are far too warm to be consistent with

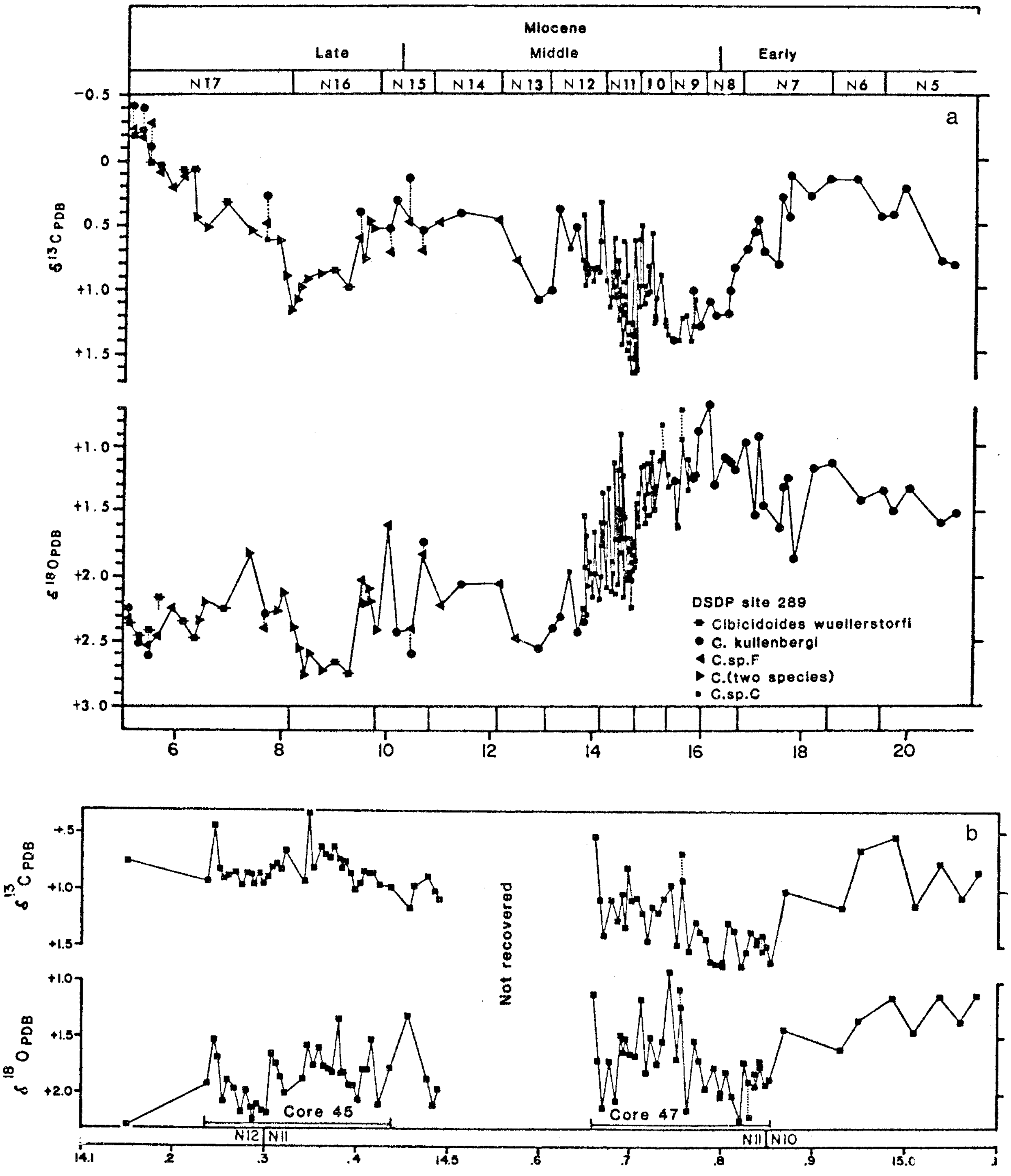

Fig. 1. Values of $\delta^{18}O$ and $\delta^{13}C$ for Miocene benthic foraminifera of the genus *Cibicidoides* from DSDP site 289: (a) record from ~6×10^6 to ~20×10^6 years B.P.; (b) more detailed record for the period 14.1×10^6 to 15.1×10^6 years B.P. By convention, incompletely recovered DSDP cores such as core 46 are shown as recovered from the upper portion of the cored interval.

the existence of a major ice cap on Antarctica. Even the former values of 3.8° to 6.5°C are inconsistent with extensive Antarctic sea-level glaciation. We therefore conclude that prior to 14.8 × 10^6 years B.P. the Antarctic ice cap was relatively small (*9*) and that the benthic oxygen isotope record for sediments before 14.8 × 10^6 years B.P. primarily reflected temperature changes.

We infer that by 13 × 10^6 years B.P. a large Antarctic ice cap had formed. This inference from the isotopic data is consistent with geologic evidence from the Antarctic continent and surrounding oceans (*10*). *Cibicidoides* $\delta^{18}O$ values of +2.5 per mil at 13 × 10^6 years B.P. suggest that δ_w lay fairly close to, but not at, modern values (Fig. 2). Our estimate of approximately −0.7 per mil for δ_w gives bottom temperatures (approximately 2.5°C) consistent with the existence of a large Antarctic ice cap but not with major amounts of sea ice formation. Warming and ice-cap shrinkage between 10 × 10^6 and 12 × 10^6 years B.P. was followed by conditions about 9 × 10^6 years B.P. which appear similar to today's. The measured $\delta^{18}O$ values for *C. wuellerstorfi* between 2.7 and 2.8 per mil are similar to those reported for Recent *C. wuellerstorfi* from the East Pacific Rise at depths of 3200 to 4600 m (2.7 to 2.9 per mil) (*11*). The latest Miocene saw some amelioration of the extreme Miocene glacial conditions of 9 × 10^6 years B.P. (Figs. 1 and 2).

The evolution of Miocene oceanic conditions as described above differs from that recently proposed by Matthews and Poore (*12*). They argued that the volume of continental ice was large throughout Oligocene and Miocene time and that the middle Miocene increase in benthic $\delta^{18}O$ reflected almost in its entirety a temperature drop.

Isotopic analyses of early and middle Miocene planktic foraminifera from site 289 are discussed by Shackleton (*13*). Planktic foraminiferal $\delta^{18}O$ decreased from −0.84 per mil in N5 to N7 (standard deviation = 0.20, N = 55) to −1.14 per mil in N9 (standard deviation = −0.14, N = 28), at approximately the time that benthic ^{18}O began to increase about 16.3 × 10^6 years B.P. Planktic $\delta^{18}O$ values then increased slightly, reaching values in N12 that are similar to those of N5. The interpretation of this planktic isotopic change depends on the value assumed for the isotopic composition of surface water at site 289. However, based on the interpretation summarized in Fig. 2, the increase in seawater $\delta^{18}O$ during foraminiferal zones N9 through N12 was sufficiently great to infer warming of equatorial sea surface temperatures in middle Miocene time. It would follow that middle Miocene Antarctic ice-cap growth was accompanied by an increase in the planetary temperature gradient (*14*). This redistribution of energy on the earth may have been related to changes in oceanic circulation accompanying widening of the Drake Passage and the resultant thermal isolation of Antarctica (*15*). However, detailed models of the effects of the Drake Passage on oceanic circulation await publication of current research on plate tectonic motions in that area. Alternatively, it has been proposed by Blanc *et al.* (*16*) and by Schnitker (*17*) that the rapid growth of the Antarctic ice cap in middle Miocene time was triggered by the onset of upwelling warm saline North Atlantic deep water at high southern latitudes. This became possible after the subsidence of the Iceland-Faeroe ridge.

The character of the middle Miocene isotopic record suggests that approximately 14.8 × 10^6 years B.P. the earth's climatic system became extremely unstable and for perhaps 1 × 10^6 years oscillated back and forth between glacial and interglacial modes. By about 14 × 10^6 years B.P. the glacial mode appeared to have been firmly established and has persisted ever since.

Two cores within the middle Miocene section at site 289 were closely sampled (25-cm intervals) (Fig. 1b). Each core is estimated to represent approximately 200,000 years (*18*). The variations seen in Fig. 1b appear to coincide with cyclical variations with periods on the order of 100,000 years, as are dominant in the Pleistocene isotopic record. Future use of the new DSDP hydraulic piston cores, which minimize core disturbance, should resolve any periodic signals present.

Carbon isotopic ratios fluctuate over a total range of approximately 2 per mil. The $\delta^{13}C$ values in benthic foraminiferal carbonate reflect changes in the $\delta^{13}C$ of marine HCO_3^- as well as insufficiently understood changes in disequilibrium (biological) isotopic fractionations during test secretion. Temperature effects on the equilibrium fractionation of carbon isotopes between HCO_3^- and $CaCO_3$ are small but are possibly significant (*19*). Some features of the carbon isotopic record appear to be correlative with other sites. These include the increase in $\delta^{13}C$ between 18 × 10^6 and 16 × 10^6

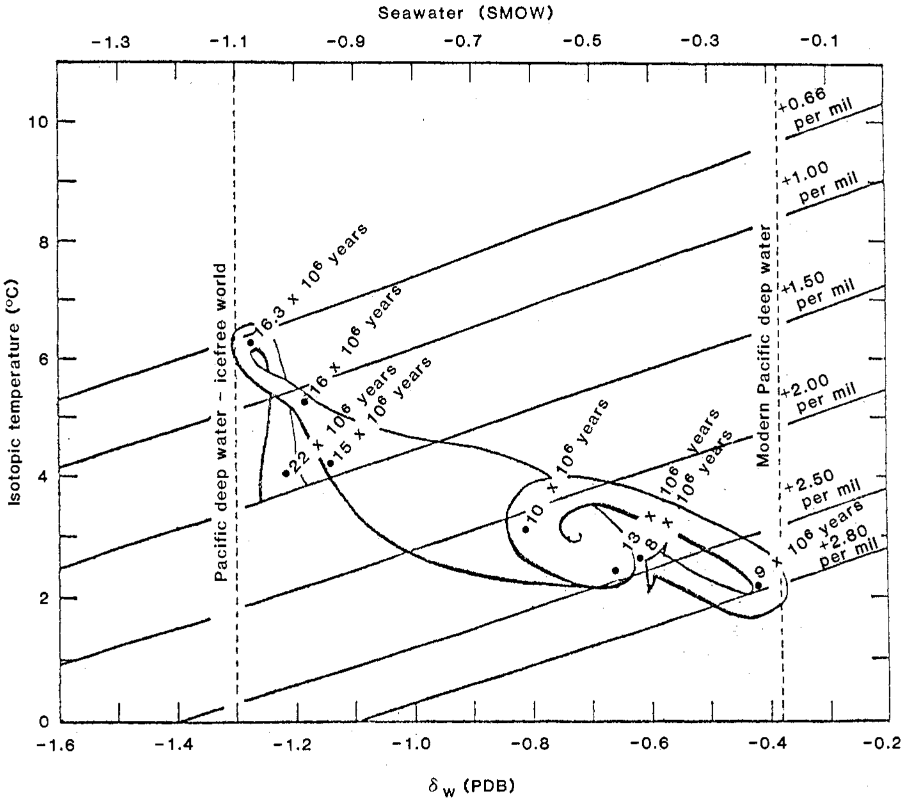

Fig. 2. Interpreted variation in bottom temperature and bottom-water isotopic composition at DSDP site 289. Curves labeled +0.66 per mil and so forth, show all possible values of temperature and δ_w for carbonates of the indicated isotopic composition. Curves are drawn for the genus *Cibicidoides*, assuming (i) that the paleotemperature equation of Epstein *et al.* (*2*) accurately describes oxygen isotopic equilibrium and (ii) that *Cibicidoides* are depleted in ^{18}O by 0.65 per mil relative to equilibrium values. The contorted arrow shows the approximate trend through time (from 22 × 10^6 to 8 × 10^6 years B.P.) of the temperature and isotopic composition of bottom water at site 289.

years B.P. and the subsequent decrease (*7*, *20*). The decrease in $\delta^{13}C$ in N17 has been discussed elsewhere (*21*).

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3. The depletion in ^{18}O of 0.65 ± 0.15 per mil for *Cibicidoides* relative to the equilibrium value is the average of relationships inferred from the following: modern *C. wuellerstorfi* from the East Pacific Rise [F. Woodruff, S. M. Savin, R. G. Douglas, *Mar. Micropaleontol.* **5**, 3 (1980)]; a comparison of Pleistocene *Uvigerina* and *C. wuellerstorfi* [N. J. Shackleton and N. D. Opdyke, *Quat. Res.* **3**, 39 (1973)]; and a comparison of Miocene *Uvigerma* and *C. wuellerstorfi* at site 289 (this study).
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Hibernation and Longevity in the Turkish Hamster *Mesocricetus brandti*

Abstract. *A positive correlation was found between the length of life of 288 Turkish hamsters and the amount of time spent in hibernation, suggesting that the process of aging is slowed during hibernation.*

Although the concept of suspended animation and resulting longer life has formed the basis for innumerable fictional stories, there is little scientific data to indicate that hibernation affects longevity in any mammal. Brace (*1*), using four woodchucks, concluded that either exposure to cold or hibernation prolongs the life-span of red blood cells, and Brock (*2*) demonstrated that elution, random destruction, and aging of red blood cells tagged with chromium-51 are greatly reduced in hibernating Syrian hamsters. The experiments of Hrůza *et al.* (*3*) with the tail tendons of dormice can be criticized because the hibernation periods were extremely short compared to the life-span of the species (more than 4 years) (*4*).

Tagging experiments in the field show that bats live much longer than other mammals of comparable size—21 to 30 years (*5*, *6*). Bats living in the temperate zone undergo periods of daily torpor during summer and long periods of uninterrupted hibernation during winter. Griffin (*5*) suggested that this might contribute to their longevity, but the concept has not been tested in the laboratory. Herreid (*7*) concluded from field studies that tropical and semitropical bats, which do not hibernate, live as long as the bats that hibernate.

The study of the relation between hibernation and aging requires a species which can be raised in the laboratory so that its age and history are known, and which hibernates for long periods when exposed to the cold. These requirements are met by the Turkish hamster, *Mesocricetus brandti*, which we first imported into the United States in 1965 (*8*). In contrast, North American ground squirrels breed in the laboratory only rarely and under special conditions, and the Syrian hamster, although easily raised in the laboratory, hibernates in an irregular manner. Our native microchiropteran bats are difficult to breed and maintain, and their long life-span challenges the middle-aged investigator to see the end of the experiment.

A total of 288 laboratory-bred Turkish hamsters was used in this experiment. Each animal was housed separately in a 24 by 17 by 17 cm cage with wood shavings and given unrestricted access to water and Purina Lab Chow. Oats and a slice of apple were provided weekly. Half of the hamsters were designated as controls and kept at 22° ± 3°C throughout their lives. The 144 experimental animals were kept at the same temperature until mid-November each year, then moved to a cold room (5° ± 2°C) until the end of April the following year. Daily illumination for all the animals paralleled the natural cycle at the latitude of Boston, Massachusetts. Each animal was numbered by tattoo. Except for 42 animals, matched pairs of littermates (one experimental and one control) of the same sex were used. The animals were adults—that is, fully grown (4 to 6 months) and capable of reproduction—when they were first moved to the cold room. Periods of hibernation were monitored by sprinkling oats on the exposed backs of the hibernating animals. Spontaneous arousal resulted in displacement of the oats, which were replaced when the animal resumed hibernation.

None of the controls ever hibernated, and hibernation among the animals exposed to cold varied considerably. For comparison, three categories were arbitrarily established among the cold-exposed group after the raw data were collected: poor hibernators, or animals that hibernated 0 to 11 percent of their lives ($N = 47$); moderate hibernators, or animals that hibernated 12 to 18 percent of their lives ($N = 48$); and good hibernators, or animals that hibernated 19 to