48. SOUTHWEST PACIFIC CENOZOIC PALEOCEANOGRAPHY[1]

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ABSTRACT

This is a synthesis of major middle and late Cenozoic oceanographic and climatic events revealed in a diverse suite of studies by Leg 90 investigators and involving analyses of oxygen and carbon isotopes, sediment character, and accumulation rates and microfossils.

The benthic $\delta^{18}O$ record in Leg 90 sites exhibits a number of large changes that reflect the sequential development of polar glaciation and cooling of bottom waters beginning in the latest Eocene–earliest Oligocene. Major climatic cooling events in the Leg 90 sequences include the Terminal Eocene Event (37 Ma); middle Oligocene cooling events clustered close to 31 Ma; the Middle Miocene Event (16.5–13.5 Ma); further temporary cooling events during the late middle Miocene (12.5 to 11.5 Ma) and the earliest late Miocene (11–9 Ma); the Terminal Miocene Event (~6.2–5.0 Ma), the Middle Pliocene Cooling Event at 3.4 Ma; the Late Pliocene Event at 2.6–2.4 Ma; and amplification of glacial–interglacial oscillations during the Quaternary at 0.9 Ma (Jaramillo Paleomagnetic Subchron). The climax of Neogene warmth occurred during the early Miocene, especially between 19.5 and 16.5 Ma.

The sequences record the development during the Cenozoic of latitudinal and vertical thermal gradients in the southwest Pacific region. Major, permanent increases in the vertical temperature gradients occurred in association with the Middle Miocene Event (16.5–13.5 Ma), the Middle Pliocene Cooling Event (3.4 Ma) and the Late Pliocene Event (2.6–2.4 Ma).

Deep-sea benthic foraminiferal assemblages underwent important changes near the Eocene/Oligocene boundary and during the earliest Middle Miocene, the latest Miocene, and the late Pliocene and Quaternary. Late Neogene benthic foraminiferal changes are, in part, related to changes in the organic flux rates that accompanied changes in biogenic sedimentation rates and inferred surface-water productivity.

Changes in clay mineralogy, wind-blown terrigenous sediments, and opal phytoliths in the Lord Howe Rise Sites record a general expansion of Australian deserts. Important steps in aridification occurred during the Middle Miocene Event; the Terminal Miocene Event (~5 Ma), and the Middle Pliocene Cooling Event (~3.4 Ma).

INTRODUCTION

Cenozoic oceanographic and climatic evolution is largely a record of progressive cooling and glaciation of the polar regions and perhaps some warming in the tropics, resulting in an increase in the planet's latitudinal thermal gradient (Savin et al., 1975; Shackleton and Kennett, 1975b; Loutit, Kennett, et al., 1983). This global climatic evolution did not proceed uniformly but was marked, in part, by discrete and sudden coolings that appear to have resulted from changes in the geometry of the ocean basins and associated changes in ocean circulation. Although the tectonic changes served as triggering mechanisms, strong, positive climatic feedback mechanisms such as changes in albedo must have been actuated. Previous work by many investigators has led to the development of general scenarios of Cenozoic climatic evolution (for example, Kennett, 1982; Haq, 1984) that must be tested by this and future drilling expeditions. Such scenarios can be expected to change, especially as a result of future high-latitude drilling. One of the most prominent changes took place near the Eocene/Oligocene boundary (38 Ma), when cold, deep water began to form in the ice-covered sea surrounding Antarctica. Subsequent coolings occurred during the middle Miocene (~15 Ma), when it is likely that much of the East Antarctic ice sheet accumulated; the latest Miocene (~6–5 Ma), when a substantial West Antarctic ice sheet may have accumulated; and during the late Pliocene to Quaternary (2.4 Ma to the present), when large ice sheets formed on the Northern Hemisphere and further ice accumulated over Antarctica.

The cooling of high southern latitudes resulted from the development of the Circum-Antarctic Current and related thermal isolation of Antarctica (Kennett, 1977; Kvasov and Verbitsky, 1981). The steepening of the oceanic latitudinal thermal gradient was thus closely linked to development of the Circum-Antarctic Current system.

The primary objective of DSDP Leg 90 was to study Cenozoic oceanographic and climatic evolution of the southwest Pacific (Table 1). This contribution synthesizes the main paleoceanographic results from many of the Leg 90 investigations, outlining the major events in the order in which they occurred through geologic time (Table 2); thus it provides a paleoceanographic history of the southwest Pacific based upon Leg 90 discoveries.

Leg 90 of the Deep Sea Drilling Project obtained a traverse of eight high-quality sections of middle to late Cenozoic age (from Sites 587–594) between equatorial and northern subantarctic water masses (Fig. 1; Table 1). For logistical reasons, Leg 89 cored an additional Site 586 at the equator (Ontong-Java Plateau), forming

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Table 1. Summary of Leg 90 drilling.

Hole	Latitude (S)	Longitude (E)	Water depth (m)	Penetration (m)	No. of cores	Meters cored	Meters recovered	Percentage recovered
586[a]	00°29.84′	158°29.89′	2207	44.4	5	44.4	38.98	87.8
586A[a]	00°29.84′	158°29.89′	2207	305.2	31	260.9	257.03	98.5
586B[a]	00°29.84′	158°29.89′	2207	240.3	25	240.3	234.93	97.8
586C[a]	00°29.84′	158°29.89′	2207	623.1	1	9.6	2.18	22.7
587	21°11.87′	161°19.99′	1101	147.0	17	147.0	88.81	60.4
588	26°06.70′	161°13.6′	1533	245.7	26	236.0	220.76	93.5
588A	26°06.70′	161°13.6′	1533	344.4	18	108.4	84.27	77.7
588B	26°06.70′	161°13.6′	1533	277.4	31	277.4	255.87	92.2
588C	26°06.70′	161°13.6′	1533	488.1	19	182.4	134.61	73.8
589	30°42.72′	163°38.39′	1391	36.1	4	36.1	35.08	97.2
590	31°10.02′	163°21.51′	1299	26.2	3	26.2	26.36	100.0
590A	31°10.02′	163°21.51′	1299	280.8	27	254.6	224.17	88.0
590B	31°10.02′	163°21.51′	1299	499.1	53	499.1	465.26	93.2
591	31°35.06′	164°26.92′	2131	283.1	31	283.1	278.21	98.3
591A	31°35.06′	164°26.92′	2131	284.6	30	284.6	233.15	81.9
591B	31°35.06′	164°26.92′	2131	500.4	24	229.8	130.86	56.9
592	36°28.40′	165°26.53′	1098	388.5	41	388.5	340.12	87.5
593	40°30.47′	167°40.47′	1068	571.5	60	571.5	468.21	81.9
593A	40°30.47′	167°40.47′	1068	496.8	27	257.3	227.71	88.5
594	45°31.41′	174°56.88′	1204	505.1	53	505.1	299.72	59.3
594A	45°31.41′	174°56.88′	1204	639.5	26	249.6	161.5	64.7
594B	45°31.41′	174°56.88′	1204	42.9	5	42.9	34.18	79.6

[a] For logistical reasons, Site 586 was cored on Leg 89.

the northern limit of the latitudinal traverse. Previous rotary drilling during DSDP Legs 21 and 29 (Burns, Andrews, et al., 1973; Kennett, Houtz et al., 1975) demonstrated that the southwest Pacific region is optimal for the study of thick, relatively uncomplicated and continuously deposited pelagic carbonate sequences of Neogene and Quaternary age between the equator and subantarctic. The sections are all located on shallow-water pedestals (between 1000 and 2000 m) that include Ontong-Java Plateau (Site 586) at the equator; Lord Howe Rise (Sites 587 through 592); the Challenger Plateau west of New Zealand (Site 593); and Chatham Rise east of New Zealand (Site 594). Sediment was collected from beneath every major surface water mass between the equator and subantarctic, permitting paleoceanographic records to be analyzed for each water mass. Recovered sections also form a vertical traverse at mid-latitudes from water depths of 1299 m (Site 590), 2131 m (Site 591), and 3196 m (Site 206, which was drilled during Leg 21).

Because these sedimentary sequences were obtained using the Hydraulic Piston Corer (HPC) and the Extended Core Barrel (XCB), they are relatively continuous and undisturbed and are of great value for studies of high-resolution stratigraphy and paleoceanography. HPC sequences in the soft carbonate ooze that blankets this shallow southwest Pacific region were longer than 200 m in each site. At Site 588, the HPC sequence is 315 m thick, the longest ever obtained. This sequence contains a continuous, largely uninterrupted record spanning the past 17 m.y. from the late early Miocene to the Quaternary.

Leg 90 recovered 3705 m of core, the longest for any drilling leg. Average core recovery for the entire leg was about 90% of the drilled section except for the Chatham Rise site (Site 594), where only 68% core recovery was achieved. Core quality is generally excellent with minimal core disturbance. The sites lie well above the modern southwest Pacific lysocline depth of 2500 to 3500 m (Berger, 1976).

Almost all sediment cored during Leg 90 is light-colored calcareous ooze or its more lithified equivalent, chalk. Foraminifers generally range from 5 to 15% with higher percentages during winnowed sedimentary intervals. Calcium carbonate content is greater than 90% in most sediments, which are mainly free of turbidites and received negligible amounts of terrigenous sediments. Siliceous biogenic material is usually absent and where present is found only in trace quantities. It usually consists only of radiolarians and sponge spicules. Diatoms are rare in these sediments. Bioturbation is ubiquitous in Leg 90 sediments and varies widely, both within and between sites (Nelson, this volume). Laminae are almost always volcanic ash or altered volcanic ash and provide a valuable measure for the amount of mechanical or biological disturbance. Most are relatively sharp, suggesting bioturbation or core disturbance had minimal influence.

Oceanographic Setting

The physical oceanography is not well known in the southwest Pacific region north of New Zealand but has been extensively studied in the area adjacent to New Zealand. Knox (1970) and Wyrki (1974) showed the position of the major surface water masses, their boundaries, and the directions of surface water flow in the region (Fig. 1). Site 588 lies within the warm-subtropical water mass, whereas Sites 590 and 591 lie close to the present-day position of the Subtropical Divergence (Tasman Front) that separates warm-subtropical temperate water masses (Denham and Crook, 1976; Stanton, 1979; 1981). The Subtropical Divergence represents the southern extent of the South Pacific subtropical gyre as the East Australian Current turns to the east, at about 30°S (Hamon, 1970), passing to the north of the barrier formed by New Zealand. The east Australian Current reaches maximum velocities of about 175 cm/s in the upper 100 m, and decreases to 10–20 cm/s at 1200 m water depth (Hamon, 1970). Upwelling at the Subtropical Divergence is caused by the divergence of the two surface-water masses and the interaction of the eastward-flowing gyral circulation with the Lord Howe Rise (Stanton, 1981). Upwelling in this region has created high biogenic sedimentation rates, which in the late Neogene ranged up to 131 m/m.y. in Site 591, the site closest to the Divergence.

Sites 588 and 590 are located in similar water depths, 1500 m and 1300 m, respectively, yet bottom-water temperatures at Site 590 are 0.5°C warmer (Site 588 = 3.75°C; Site 590 = 4.25°C; Rochford, 1960). The warmer bottom-water temperatures at Site 590 are due to the eastward passage of warm waters contained in the subtropical gyre and derived from the East Australian Current. Sites 592 and 593 are located well within the temperate (cool-subtropical) surface water mass and are under the influence of the eastward-flowing Tasman Current (Fig. 1). Site 593 is positioned within Antarctic Intermediate Water derived from cooling and sinking of surface waters at the Antarctic Convergence to the south. Temperatures at this depth range from 3 to 5°C (Ridgway, 1969). Site 594 is located in subantarctic waters to the south of the Subtropical Convergence which trends eastward across the Chatham Rise.

The sites on the Lord Howe Rise have moved about 5° to the north during the Neogene as a result of the movement of the Indo-Australian Plate (Sclater et al., in press). The northward movement of these sites into warmer waters during the Neogene should be reflected by planktonic assemblages indicative of increasingly warm surface water and by lower planktonic $\delta^{18}O$ values, unless the water masses themselves changed latitudinal positions.

Stratigraphic Continuity

Calcareous nannofossil biostratigraphy at all sites, planktonic foraminiferal biostratigraphy at Sites 586 through 593, and diatom and radiolarian biostratigraphy at Site 594 suggest that all but three of the Neogene to late Oligocene sections are completely continuous (Fig. 2). Site 590 contains a 1.5 m.y. hiatus in the latest early Miocene (18 to 16.5 Ma). Site 592 encountered the well-documented late Paleogene Tasman Sea regional unconformity (Kennett et al., 1975; Fig. 2). In this site, a 14.5 m.y. hiatus extends from the early Oligocene to the late early Miocene. We also penetrated the regional unconformity at Site 588 (= Site 208), which exhibits a hiatus of 19 m.y. from the middle Eocene to the late Oligocene. The regional unconformity is absent from Site 593 on Challenger Plateau, suggesting that bottom currents responsible for the erosional hiatus in the Tasman Sea did not extend far to the east. The section at Site 594 is interrupted by at least four unconformities, which include a 2 m.y. gap in the middle late Miocene, a 1 m.y. hiatus at the Miocene/Pliocene boundary, another between the early and late Pliocene, and another within the early Quaternary.

SUMMARY OF SOUTHWEST PACIFIC PALEOCEANOGRAPHIC HISTORY

Late Eocene Warm Climates

During the last Eocene, oxygen isotope values of planktonic and benthic foraminifers of Site 277 in the subantarctic south of New Zealand (Fig. 1) were similar to those of Sites 592 and 593 in the Tasman Sea to the northwest of New Zealand. This similarity of inferred surface and intermediate-water temperatures suggests that the sites were influenced by the same surface and intermediate-water masses, and that no surface water front existed between the sites at this time (Murphy and Kennett, this volume). Temperate radiolarian assemblages of late Eocene age, which are similar to those of the tropics (Caulet, this volume), also indicate low surface water temperature gradients between the tropics and temperate areas. This conclusion is in agreement with the warm, equable climates predicted for the Eocene, with low pole-to-equator temperature gradients (Wolfe, 1971; Kennett, 1977; Frakes, 1979; Brass et al., 1982).

During the late Eocene, no Circum-Antarctic Current existed to interfere with the influence of the southward-flowing warm-subtropical arm of the South Pacific gyre (East Australian Current; Fig. 1). These warm-subtropical waters were transported close to Antarctica, warming this region and preventing the development of extensive seasonal sea ice (Kennett, 1977). The influence of this gyre resulted in similar temperatures through the southwest Pacific during the late Eocene, as recorded by the similar oxygen isotope values (Murphy and Kennett, this volume).

Terminal Eocene Event

The terminal Eocene event is well represented in Sites 592 and 593 (and subantarctic Site 277) and is marked by a rapid, distinct $\delta^{18}O$ enrichment of about 1‰ in both planktonic and benthic foraminifers. Sequential changes in various biotic elements in these sites mark the transition from the relatively warm conditions of the late Eocene to the distinctly cooler conditions of the Oligocene (Murphy and Kennett; Martini; both this volume). The oxygen isotope shift, isochronous throughout the oceans according to planktonic foraminiferal biostratigraphy, gave rise to maximum earliest Oligocene $\delta^{18}O$ values, which were followed by lower (lighter) values later in the Oligocene (Corliss and Keigwin, 1983). Oxygen isotope and faunal evidence indicates that the cold waters of the oceans (psychrosphere) were generated during the late Eocene to earliest Oligocene, when a glacial threshold was crossed in the Antarctic (Kennett and Shackleton, 1976; Benson et al., 1984).

No clear paleomagnetic age for the Eocene/Oligocene boundary was determined for the southwest Pacific sites, but the age of 36.5 to 37 Ma that has been suggested for the Eocene/Oligocene boundary (Berggren et al., in press) is close to that determined by the DSDP Leg 73 staff based upon Subchron C-13R (37.1–37.2 Ma), (LaBrecque, Hsü, et al., 1983). The extinction of *Globigerinatheka index*, marking the Eocene/Oligocene boundary occurs

Table 2. Major oceanographic and climatic events of the Cenozoic revealed in Leg 90 investigations.

Ma	Age	Oxygen isotope changes	Carbon isotope changes	Glacial and climatic interpretations	Surface water changes: Southwest Pacific	Bottom and intermediate water mass changes	Biotic changes	Australasian continental climatic changes	Other changes: Southwest Pacific	Other changes
1	Quaternary	Late Quaternary higher values and higher variability Early Quaternary lower values and lower variability		Major glacial/interglacial episodes ← Increase in polar ice volume. Expansion of Northern Hemisphere ice sheets				Warm/cold cycles in New Zealand vegetation and glaciation Dominantly arid climate over much of Australia	Increased winnowing of sediments Distinct cycles in sediments More distinct cycles in sediment	
2	late Pliocene	Increase of ← 0.4 ‰ (Late Pliocene Event)		Major Northern ← Hemisphere ice accumulation		← Increase in vertical temperature gradient	Further changes in benthic foraminifer assemblages			
3	middle Pliocene	Increase of ← 0.4‰ (middle Pliocene event)		← Cooling at high latitudes; warming at low latitudes. Some Antarctic ice-volume increase	← Warming of surface waters Increased upwelling	← Cooling of intermediate waters; increase in vertical temperature gradient	← Major turnover of benthic foraminifer assemblages		Major increase in biogenic sedimentation and mass accumulation rates; high biogenic productivity	← Antarctic glacial increase; cooling of AABW
4, 5	early Pliocene	Minimum Pliocene values		Global warmth Decreased ice volume			High diversity; highest Neogene nannoplankton diversity	Major increase in opal phytoliths (Lord Howe Rise)		Marine transgression
6, 7, 8, 9, 10, 11	late Miocene	Highly variable; enriched values 0.4 ‰ more enriched than modern equilibrium $\delta^{18}O$ values at each site Lower values Very high values (average 2.25 ‰)	← Distinct, rapid $\delta^{13}C$ decrease, up to −0.75 ‰ (late Miocene Carbon Isotope Shift)	Increase in Antarctic ice volume in West Antarctica. Global temperature decrease Relative warmth Greater ice volumes and/or cooler temperatures than modern ocean	Cooling ← Cooling; increased upwelling Intensification of upwelling at Subtropical Convergence		← Major turnover of benthic foraminifer assemblages	Increased Australian aridity/expansion of deserts. Increase in opal phytoliths. Cooler, drier New Zealand climates Low smectite/illite ratios in Australia, such as in Quaternary Increased aridity of Australia	← Increased biogenic sedimentation Greater organic flux to deep-sea sediments Biogenic sedimentation rates typical of carbonate platforms outside regions of high productivity	Isolation and dessication of Mediterranean Basin Glacioeustatic marine regression; increased Antarctic glaciation

Ma										
12		High values		Increased glaciation						
13										
14	middle Miocene	Planktonics and benthics covary	Decreased values	Major ice-volume increase in East Antarctic ice sheet				Increased aridity of northern Australia (decrease in smectite/illite ratio); first appearance of phytoliths (Lord Howe Rise)	Increased eolian sediments to Lord Howe Rise	
15		Major increase in values, ~1% (Middle Miocene Event)			Cooling at high latitudes	Cooling at high latitudes Major increase in vertical temperature gradient	Major turnover in deep-sea benthic foraminifer assemblages Decrease in planktonic/benthic ratios		Pale orange sediment subunit: Site 593 Temporary production of highly oxygenated intermediate water	
16										
17			Broad maximum of ~1‰ (early Neogene Carbon Isotope Excursion)	Climax of Neogene warmth	Maximum Neogene surface-water temperatures	Maximum Neogene Intermediate Water temperatures	High diversity			Marine transgression
18		Lowest values for Neogene								
19										
20	early Miocene									
21		Relatively high but decreasing values, although lower than late Miocene		Increasing warmth						
22							Increase in biotic evolution; most microfossil groups	First tropical climates in northern Australia		
23										

Table 2. (Continued).

Ma	Age	Oxygen isotope changes	Carbon isotope changes	Glacial and climatic interpretations	Surface water changes: Southwest Pacific	Bottom and intermediate water mass changes	Biotic changes	Australasian continental climatic changes	Other changes: Southwest Pacific	Other changes
					Little information for this age					
30–32	middle Oligocene	Highest values of Paleogene record Oscillating episodes (>0.5‰)		Coldest oceanic temperatures of Paleogene. Perhaps some accumulation of Antarctic ice	Strengthening of Circum-Antarctic Current					
33–34		← Increase in isotopic divergence of surface and intermediate waters between temperate and subantarctic areas		Subantarctic region cooled; temperate region warmed	Development and strengthening of latitudinal thermal. zonation in southwest Pacific subantarctic and temperate water masses. Warming at temperate latitudes; cooling at high latitudes	Vertical thermal gradients increased			↑ Northward drift of Australia toward tropics ↑	Deep opening of Tasmanian Seaway
35–36	early Oligocene						Low-diversity planktonic assemblages			
36–37		← Increase in isotopic divergence of surface and intermediate waters between temperate and subantarctic areas								
37–38		← Rapid increase of ~1‰ in planktonics and benthics at Sites 277, 592, and 593	← Temporary shift toward higher values	← Rapid cooling Major glacial increase of Antarctica First extensive sea ice	← Cooling. Initial decoupling of warm subtropical gyre from the Southern Ocean	← Major generation of cold bottom waters of oceans 2000 m drop in CCD	← Disappearance of numerous planktonics in middle- to high-latitude regions; reduction in diversity Distinct changes in benthic foraminifer faunas		← Reduction in siliceous biogenic sediment component	Shallow opening of Tasmanian Seaway
38–40	late Eocene	Very low values		Warm, equable climates Low pole-to-equator temperature gradient	No oceanographic front between temperate and subantarctic areas Warm subtropical gyre extended to high latitudes		Warm faunas and floras; high biotic diversity at high latitudes			

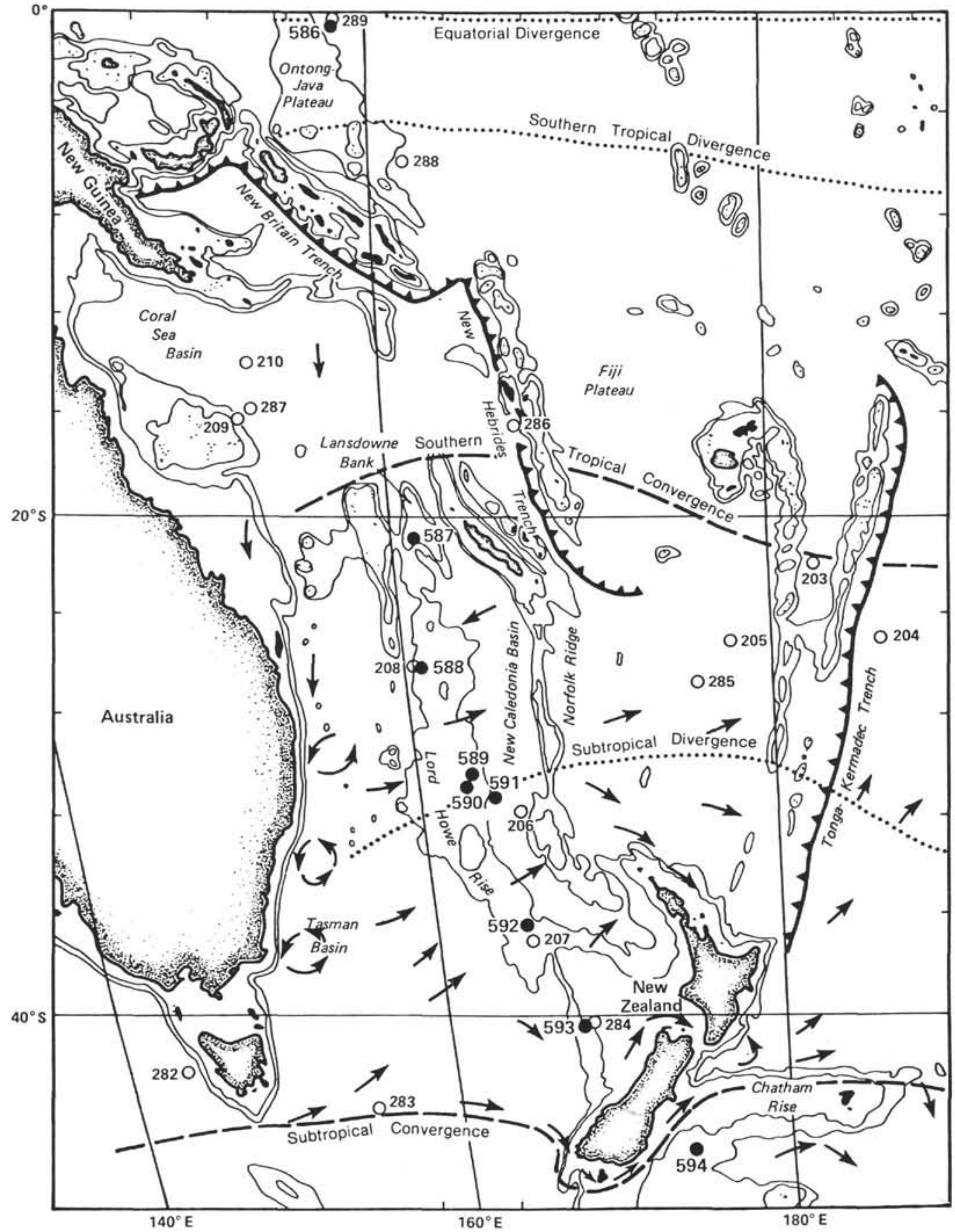

Figure 1. Location of DSDP Leg 90 drill sites (solid circles) and sites drilled on other DSDP legs (open circles) in the southwest Pacific in relation to approximate positions of major surface water mass boundaries and circulation. Shown also are 1000 m and 500 m isobaths.

about 0.4 m.y. after the extinction of *Discoaster saipanensis* and *D. barbadiensis* (Martini, this volume), although the disappearance of these discoasters may be slightly diachronous across latitudes in relation to the stratigraphic position of the Eocene/Oligocene boundary (Martini and Jenkins, this volume).

The benthic foraminiferal assemblages also exhibit significant changes at the Eocene/Oligocene boundary (Boersma, this volume). At Site 593, the globocassidulinids were replaced by a fauna consisting of hispidocostate uvigerinids, a relatively large number of anomalinids, and a large percentage of long-lived Tertiary cosmopolitan forms.

Site 592 contains a highly expanded 90 m section of late Eocene through early Oligocene sediment. The $\delta^{18}O$ record at Site 592 (Murphy and Kennett, this volume) exhibits relatively constant late Eocene values followed by a rapid decrease ($-0.4‰$) in the latest Eocene, and then a distinct increase ($\sim 1.0‰$) beginning at the base of Zone NP21, which is considered to represent the Eocene/Oligocene boundary according to calcareous nannoplankton biostratigraphy. This oxygen isotope shift con-

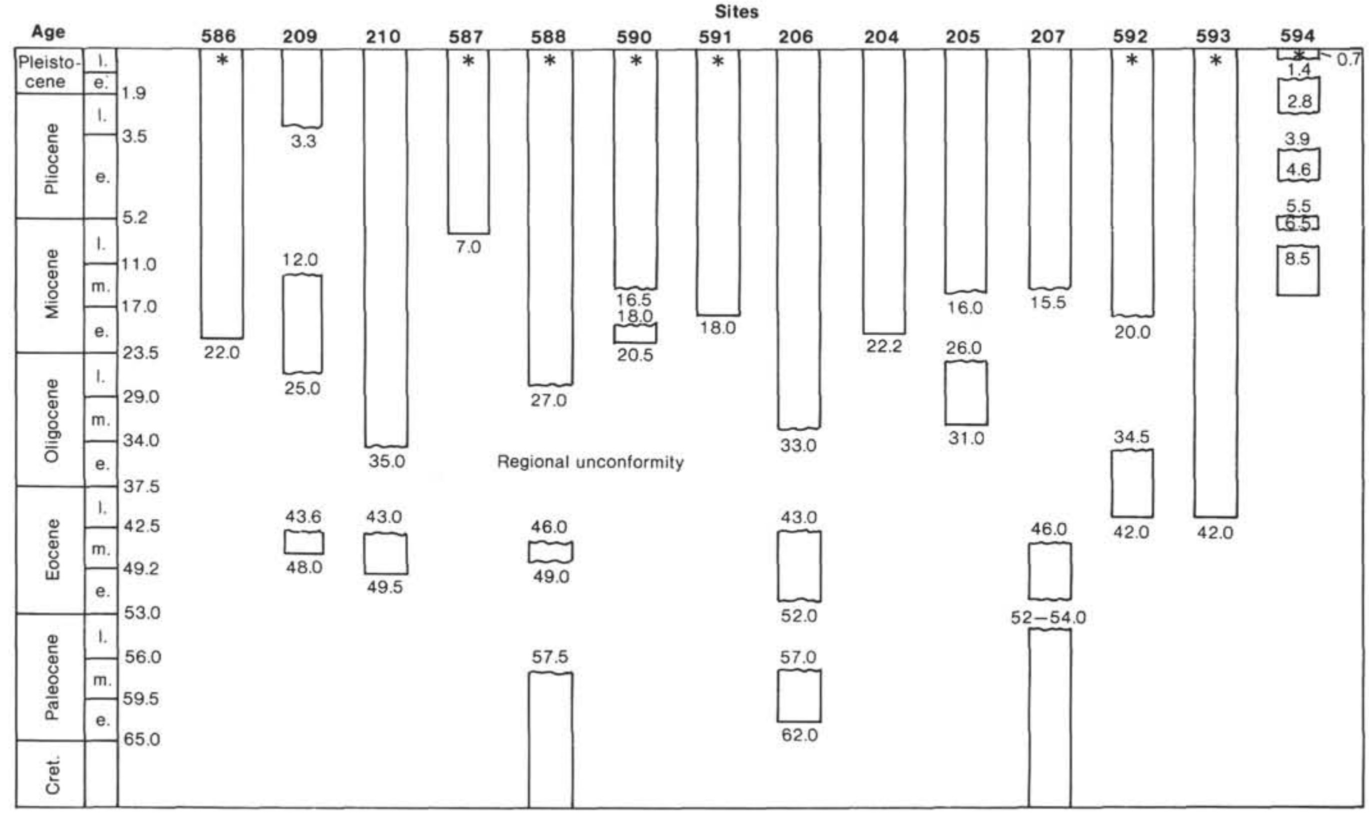

Figure 2. Age ranges represented in each of the Leg 90 drill sites (asterisk) and other sites in the southwest Pacific. Ages of contained unconformities shown in each case. Paleogene regional unconformity is clearly evident. Ages of stratigraphic boundaries were those used during Leg 90.

tinued until the latest part of Zone NP21. The Eocene/Oligocene boundary based upon planktonic foraminifers (last appearance of *G. index*) was placed near the beginning of this oxygen isotope shift. Oxygen isotope values decreased slightly ($\sim 0.2‰$) from the peak associated with the NP21/NP22 boundary and then steadily decreased with little variation during the remaining early Oligocene. Planktonic and benthic oxygen isotope variations are remarkably parallel.

Faunal and floral assemblages underwent distinct but not drastic changes at the Eocene/Oligocene boundary. Various planktonic faunal and floral assemblages exhibit reduced diversity across the boundary (Jenkins and Srinivasan, this volume; Martini, this volume) and cool-water forms increased in abundance to replace warmer-water late Eocene elements. The Eocene/Oligocene boundary is biostratigraphically linked with the last appearances (LAD) of *Globorotalia cerroazulensis–G. cocoaensis* group, *Hantkenina, Globigerinatheka*, and the rosette-shaped discoasters including *D. barbadiensis* and *D. saipanensis* (Berggren et al., in press).

A significant drop of up to 2000 m in the calcium carbonate compensation depth and related oceanwide lithofacies changes were associated with the Eocene/Oligocene boundary (Berger and Winterer, 1974). The late Eocene sedimentary sequences are largely represented by nannofossil chalk containing siliceous microfossils such as Radiolaria and sponge spicules, whereas the Oligocene is represented by surprisingly soft nannofossil ooze lacking biosiliceous material.

The terminal Eocene event may have had its origin in paleoceanographic changes that occurred in the high-latitude southwest Pacific sector of the Southern Ocean (Murphy and Kennett, this volume). Kennett et al. (1975) showed that the first high-latitude surface-water communication between the South Indian and South Pacific oceans occurred in the latest Eocene across the shallow, subsiding South Tasman Rise (Fig. 3). The opening of the Tasmanian Seaway at shallow depths was a major step in the development of the Circum-Antarctic Current, allowing relatively cool Indian Ocean waters to pass into the South Pacific. This led to cooling of waters in the South Pacific sector of the Southern Ocean and initial decoupling of the warm-subtropical gyre from the Southern Ocean (Kennett, 1977, 1978). It is inferred that, as a result, the first extensive sea ice appeared and cold, dense, oceanic psychrospheric bottom waters began to be produced in close association with the Eocene/Oligocene boundary in areas adjacent to the Antarctic continent (Shackleton and Kennett, 1975b; Kennett, 1978). The Eocene/Oligocene boundary event, as delineated by the $\delta^{18}O$ shift, is not isolated but rather marks the crossing of a threshold in the sequential deterioration seen in the Paleogene climatic record (Kennett, 1978; Corliss et al., 1984; Murphy and Kennett, this volume).

Oligocene Increase in the Thermal Gradient of Southwest Pacific Surface Waters

As discussed by Murphy and Kennett (this volume), changes in oxygen isotope values, measured in benthic

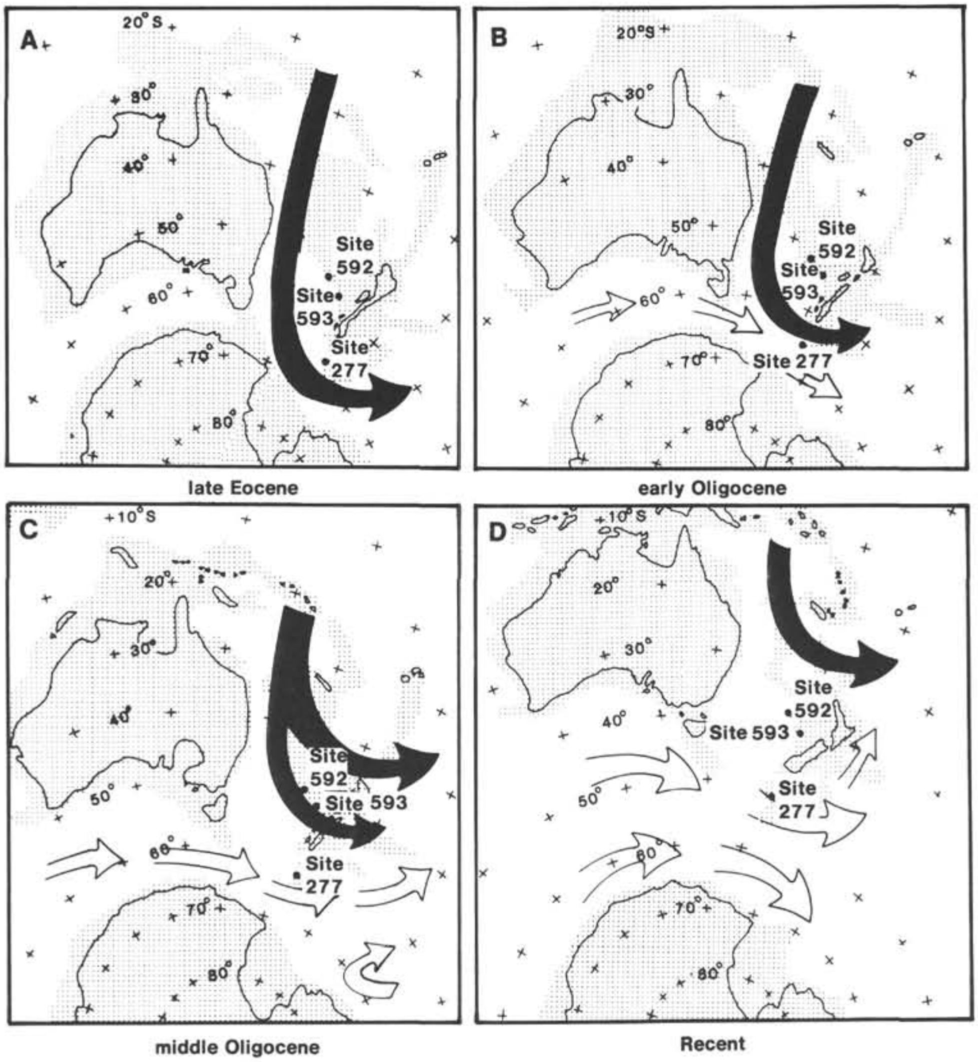

Figure 3. Changes in surface-water circulation during the Cenozoic proposed by Murphy and Kennett (this volume) to account for the decoupling of warm gyral surface currents from the Antarctic-subantarctic region. Dark arrows indicate warm currents; open arrows cold currents. Locations of Sites 592, 593 and 277 are indicated.

and planktonic foraminifers, document the Oligocene development and strengthening of latitudinal thermal zonation in southwest Pacific subantarctic and temperate water masses. The oxygen isotope trends are not considered to have been affected by diagenesis, for reasons discussed in Murphy and Kennett (this volume) and Nelson (this volume). Weak temperature gradients of the Eocene are transformed, during the Oligocene, to the steeper gradients of the Neogene, with more distinct, latitudinally distributed surface water mass belts. The thermal structure changed in the earliest Oligocene ($\sim$36.5–36 Ma) immediately after the oxygen isotope shift associated with the Eocene/Oligocene boundary, when Site 277 began to record consistently higher ("cooler") oxygen isotope values compared to Sites 592 and 593 to the north. Sites 592 and 593 exhibit a decrease in $\delta^{18}O$ values during the early to middle Oligocene (Fig. 4). The temperature difference between Site 277 and the more northern sites continued to increase, in surface waters, during the early to middle Oligocene (37.5–33 Ma), except for a temporary reversal of the gradient at $\sim$33 Ma. The oxygen isotope records of the benthic foraminifers also began to diverge in the earliest Oligocene. These trends also document the beginning of vertical thermal segregation as subantarctic waters cooled relative to those at temperate latitudes.

Isotopic temperature records from these sites diverged in two major steps at 36 Ma and 33 Ma, representing successive stages in the evolution of latitudinal thermal gradients between subantarctic and temperate regions in the Southern Hemisphere. Early to middle Oligocene values diverge slightly because temperatures continued to decrease at high latitudes but not at temperate latitudes. For the middle Oligocene, Oxygen isotope values between sites exhibit major, rapid divergence of both planktonic and benthic signals because the subantarctic region continued to cool and the temperate regions warmed.

This pattern of increasing isotopic offset between latitudinally distributed southwest Pacific sites is linked to the establishment and strengthening of the Circum-Antarctic Current, previously considered to have developed during the middle to late Oligocene (Kennett, 1977). As Australia and Antarctica continued to separate and the Southern Ocean expanded northward, the intensification of this current system progressively decoupled the warm subtropical gyres from the polar region and eventually led to increased Antarctic glaciation.

At ~33 Ma, in both surface and intermediate waters, the thermal gradient between Site 277 and the northern sites significantly and rapidly increased (Fig. 4). This is interpreted as reflecting a major reorganization of Southern Ocean circulation, as proposed earlier by Kennett et al. (1975) and by Kennett (1977, 1978), when deep circum-Antarctic circulation developed through the Tasmanian Seaway.

Despite the increase in temperature gradients between subantarctic and temperate regions during the Oligocene, biogeographic similarities in calcareous microfossils (Jenkins, 1975; Jenkins and Srinivasan, this volume) suggest that the Subtropical Convergence had not yet formed by the end of the Paleogene and that separate biogeographic provinces had not yet developed.

Oligocene Climate and Glacial Episodes

Murphy and Kennett (this volume) have shown that the highest $\delta^{18}O$ values in all of the Paleogene records for the southwest Pacific cluster in the middle Oligocene, marked by oscillating episodes of enrichments >0.5‰, occurring most prominently in the subantarctic record of Site 277. These values can be interpreted as recording either the coldest oceanic temperatures of the Paleogene, accumulations of Antarctic ice, or both. Several workers have argued that an Antarctic ice sheet existed at certain times during the Oligocene (Miller and Fairbanks, 1983; Keigwin and Keller, 1984; Miller and Thomas, in press; Shackleton et al., 1984). These conclusions were based upon isotopically derived bottom-water paleotemperatures cooler than those of the present oceans, although there is little sedimentary evidence to support the existence of large accumulations of Antarctic ice during the Paleogene (Kennett, Houtz et al., 1975; Hayes and Frakes, 1975).

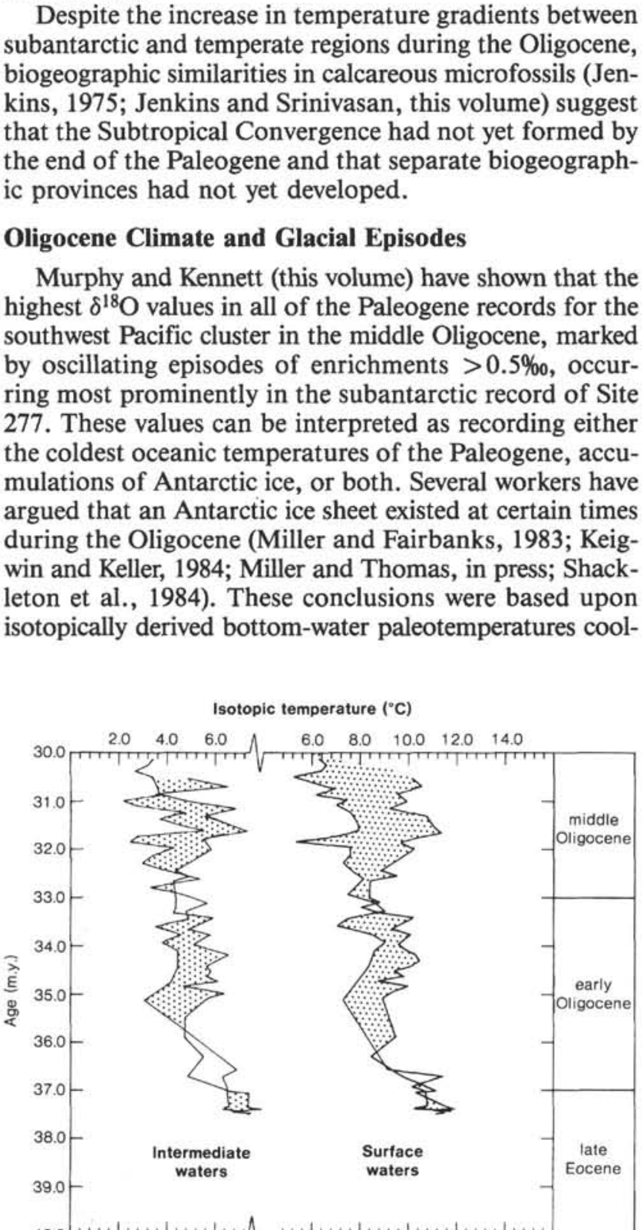

Figure 4. Isotopic temperature gradient from late Eocene to middle Oligocene between Sites 277 (more southern site) and 593 (from Murphy and Kennett, this volume). Reversals in gradient occur at ~37 to 35.5 Ma and ~33 Ma.

The data of Murphy and Kennett suggest that there may have been accumulations of Antarctic ice during the middle Oligocene, although Sites 277 and 593 do not seem to include the interval from 30 to 29 Ma in which other workers (Miller and Thomas, in press) have reported even higher $\delta^{18}O$ values. An enrichment of global δW values as a result of ice formation would appear as a synchronous enrichment in the surface and intermediate (and deep) oxygen isotope values at every site (Shackleton and Opdyke, 1973). Each site in the southwest Pacific exhibits strongly parallel planktonic and benthic oxygen isotope records until ~33 Ma, at which time they record the coolest isotopic temperatures (Murphy and Kennett, this volume). After this, the records from different sites diverge, and the cause is interpreted to be the combined effects of ice accumulation and the progressive decoupling of surface water temperatures resulting from circulation changes within the region. Furthermore, if the enriched Oligocene oxygen isotope values do indicate that ice had accumulated, this ice must have disappeared by the early Miocene, when depleted oxygen isotope values suggest very warm conditions (Kennett, this volume).

The climatic conditions of Australia also changed during the Oligocene in response to the combined effects of global climatic change and the northward movement of the Australian continent into lower latitudes. Stein and Robert (this volume) show that changes in clay mineralogy at Site 588 on the northern Lord Howe Rise monitor climatic changes occurring on Australia, the source region for the clays. During the latest Oligocene, dominant pedogenic smectite suggests dominantly warm climatic conditions with alternating periods of humidity and aridity in a low-relief area. Toward the end of the Oligocene, a gradual increase of the kaolinite/illite ratio is interpreted by Stein and Robert (this volume) to represent more tropical climates in northern Australia, leading to increased weathering and the formation of lateritic soils. The northward drift of Australia into the tropics created these changes.

Late Paleogene Regional Hiatus

It is quite well documented that the ocean basins of the southwest Pacific are marked by numerous unconformities that cut the Paleogene sequence, whereas the Neogene sequence is largely complete. The best-documented unconformity of the Paleogene removed much of the Oligocene and is commonly referred to as the Tasman Sea regional unconformity (Fig. 2; Burns, Andrews, et al., 1973; Kennett et al., 1972) or the Marshall paraconformity (Carter and Landis, 1972). Only three Leg 90 sites were drilled deep enough to potentially encounter the unconformity. At two of these (Sites 588 and 592) the unconformity was encountered whereas it is absent in the other (Site 593).

In Hole 588C, the hiatus separates sediments of middle Eocene age (Zone NP15/NP16) from those of late Oligocene age (Zone NP24, or *Chiloguembelina cuben-*

sis Zone) representing a time gap of 19 m.y. (Martini, this volume; Jenkins and Srinivasan, this volume).

The hiatus at Site 592 is of interest because it ranges in age from the early or middle Oligocene (NP22, or *Globigerina angiporoides* Zone) to the early Miocene (NN2, or *Globigerinoides trilobus* Zone), representing a time gap of about 15 m.y. Erosion at this site did not remove the Eocene/Oligocene boundary, unlike all of the other sites. At this location, erosion commenced after the time of the Eocene/Oligocene boundary.

The regional unconformity may have been formed by bottom-water masses that flowed northward through the Tasman Sea at times during the Paleogene. These water masses were activated by cooling that began at the beginning of the Oligocene (Kennett et al., 1972). The sequence at Site 592 is significant because it shows that at least in that area, bottom-water velocities were insufficient to erode sediment until the Oligocene, rather than at the Eocene/Oligocene boundary.

The absence of the unconformity in Site 593 on the Challenger Plateau indicates, as previously suggested by Kennett et al. (1975), that the bottom currents that cut the hiatus did not extend so far to the east.

Early Miocene Climatic Maximum

The earliest Miocene (older than 19.5 Ma) was marked by relatively high benthic $\delta^{18}O$ values, although the values were much lower than those of the late Miocene (Kennett, this volume; Fig. 5). This indicates warmer intermediate water and less continental ice during the earliest Miocene than during the late Miocene. A slow, general warming of intermediate water occurred between 23 and 19.5 Ma (Fig. 5), leading to the lowest $\delta^{18}O$ values for the entire Neogene between about 19.5 and 16.5 Ma (late early Miocene; late NN2 to middle NN5; Kennett, this volume). This interval represents the climax of Neogene warmth.

Warm early Miocene climates are also reflected in the pollen assemblages recovered at Site 594, to the east of South Island, New Zealand (Heusser, this volume). The pollen assemblages represent a mixture of subtropical (frost-intolerant) vegetation (trees similar to those now growing in New Guinea and New Caledonia) and temperate vegetation (trees now growing in lowland and montane parts of New Zealand). The early Miocene floras of New Zealand were thus transitional between warm-temperate to subtropical early Cenozoic vegetation and temperate vegetation of the late Cenozoic (Heusser, this volume).

Many benthic foraminiferal species first occur close to the Oligocene/Miocene boundary at Sites 588 and 593 (Boersma, this volume). This evolutionary radiation parallels that of other groups at the beginning of the Neogene, such as the planktonic foraminifers (Kennett and Srinivasan, 1983; Wei and Kennett, in press).

Early Neogene Carbon Isotope Excursion

One of the dominant features of the Neogene isotopic record (Fig. 6) is a broad $\delta^{13}C$ maximum of about 1‰ between about 19 and 14.5 Ma, from the late early to early middle Miocene, and best exhibited at Site 588, where it consists of broad peaks centered at 19 Ma, 16.5 Ma, and about 15 to 15.5 Ma (Kennett, this volume). The carbon isotope excursion corresponded to the maximum Neogene ocean temperatures as reflected in benthic and planktonic $\delta^{18}O$ values. This excursion has been recognized in other ocean basins and has been termed the "Monterey Carbon Isotopic Excursion" by Vincent et al. (in press) and Vincent and Berger (in press). The great similarity of the broad-scale Neogene $\delta^{13}C$ time-series records within and between ocean basins and with water depth clearly indicates that changes in ocean-wide average $\delta^{13}C$ of HCO_3^- in seawater dominated the records, rather than local effects.

In concurrence with other workers, Kennett (this volume) considers that this carbon isotope excursion resulted from an increase in the ratio of carbon leaving the oceans in the form of organic carbon as opposed to carbonate carbon. This increase was probably modulated by a marine transgression (Loutit, Pisias, et al., 1983; Vincent et al., in press; Woodruff and Savin, 1985). According to Vincent et al. (in press) and Vincent and Berger (in press), widespread transgression during this excursion occurred throughout the circum-Pacific region, creating major sinks for organic carbon. Organic and phosphate-rich deposits accumulated within the Monterey Formation of California and contemporaneous deposits throughout the Pacific margin. Vail and Hardenbol (1979) documented a period of coastal onlap that began at about 19 Ma, terminated about 14 Ma, and was contemporaneous with the interval containing the especially positive $\delta^{13}C$ values. The excursion thus occurred contemporaneously with a period of maximum coastal onlap (transgression) and maximum Neogene climatic warmth. Because the late early Miocene was the time of optimum climatic warming during the Neogene, tropical forests were probably widespread, and the continental organic biosphere would have been more extensive than at other times. The high continental biomass at this time would also have contributed to the positive $\delta^{13}C$ values.

The carbon isotope excursion terminated during the expansion of the Antarctic ice sheet and associated marine regression in the early middle Miocene (15.5–14.5 Ma); the decline from high values continued with little interruption until about 13 Ma. Associated global cooling probably led to greater aridity and reduced the terrestrial biomass, so that oceanic $\delta^{13}C$ values dropped during the middle Miocene.

Middle Miocene Event

The Middle Miocene Event, between about 16.5 and 13.5 Ma, represents a critical threshold in Cenozoic climatic evolution. At this time, the Leg 90 sites (588, 590, and 591) saw a major increase in $\delta^{18}O$ values (Fig. 5) interpreted by Kennett (this volume) and by numerous other workers (e.g., Savin et al., 1975; Shackleton and Kennett, 1975b) as representing a major, permanent accumulation of the East Antarctic ice sheet and cooling of bottom waters. This event lasted 3 m.y., and the average enrichment in ^{18}O was about 1.0‰. This ^{18}O enrichment event has been globally recognized in marine sedimentary sections by Savin et al. (1975); Shackleton and Ken-

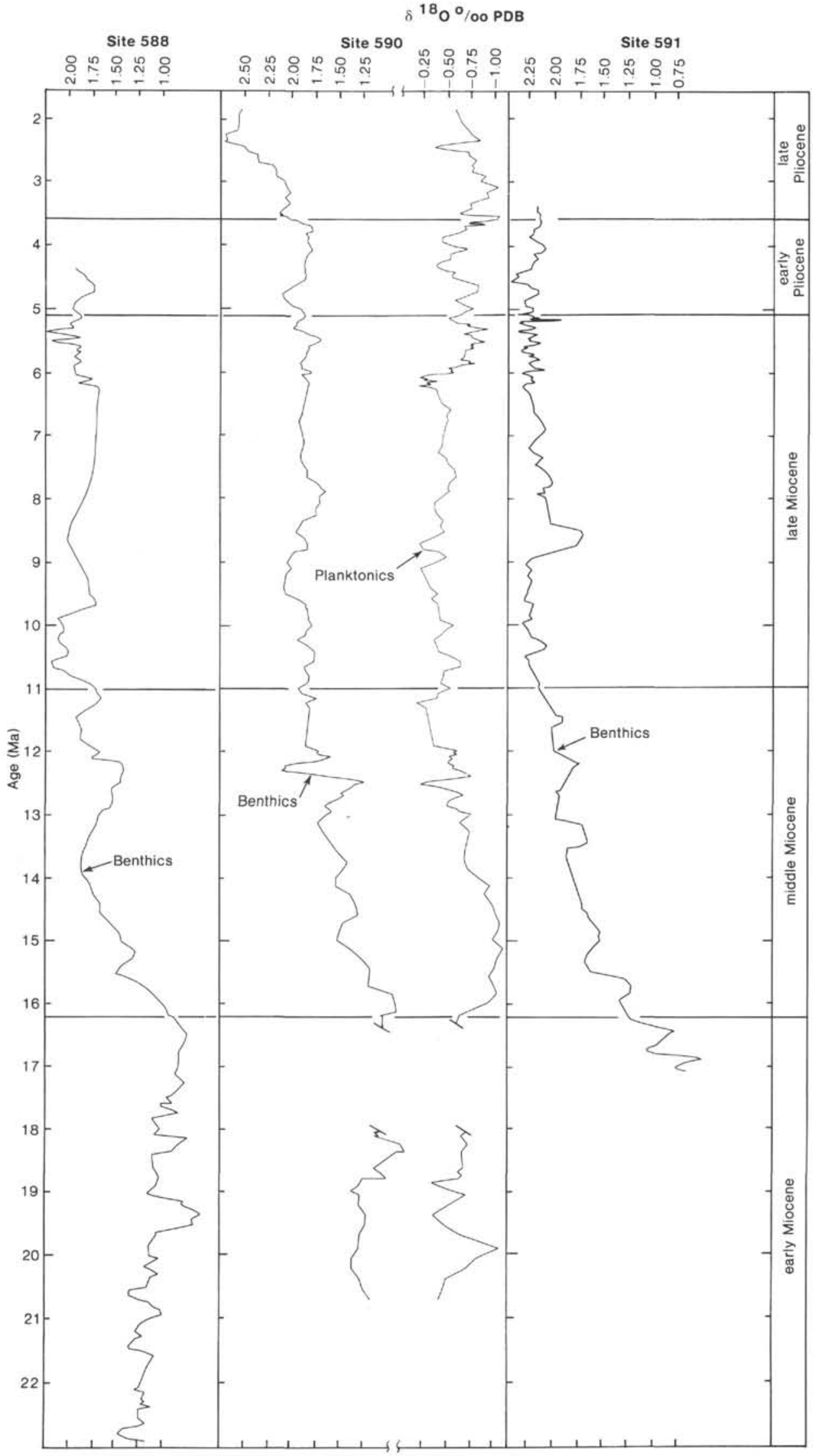

Figure 5. Smoothed $\delta^{18}O$ data (three-point running averages) for Sites 588, 590, and 591 plotted against age (from Kennett, this volume). For further details, see Kennett (this volume).

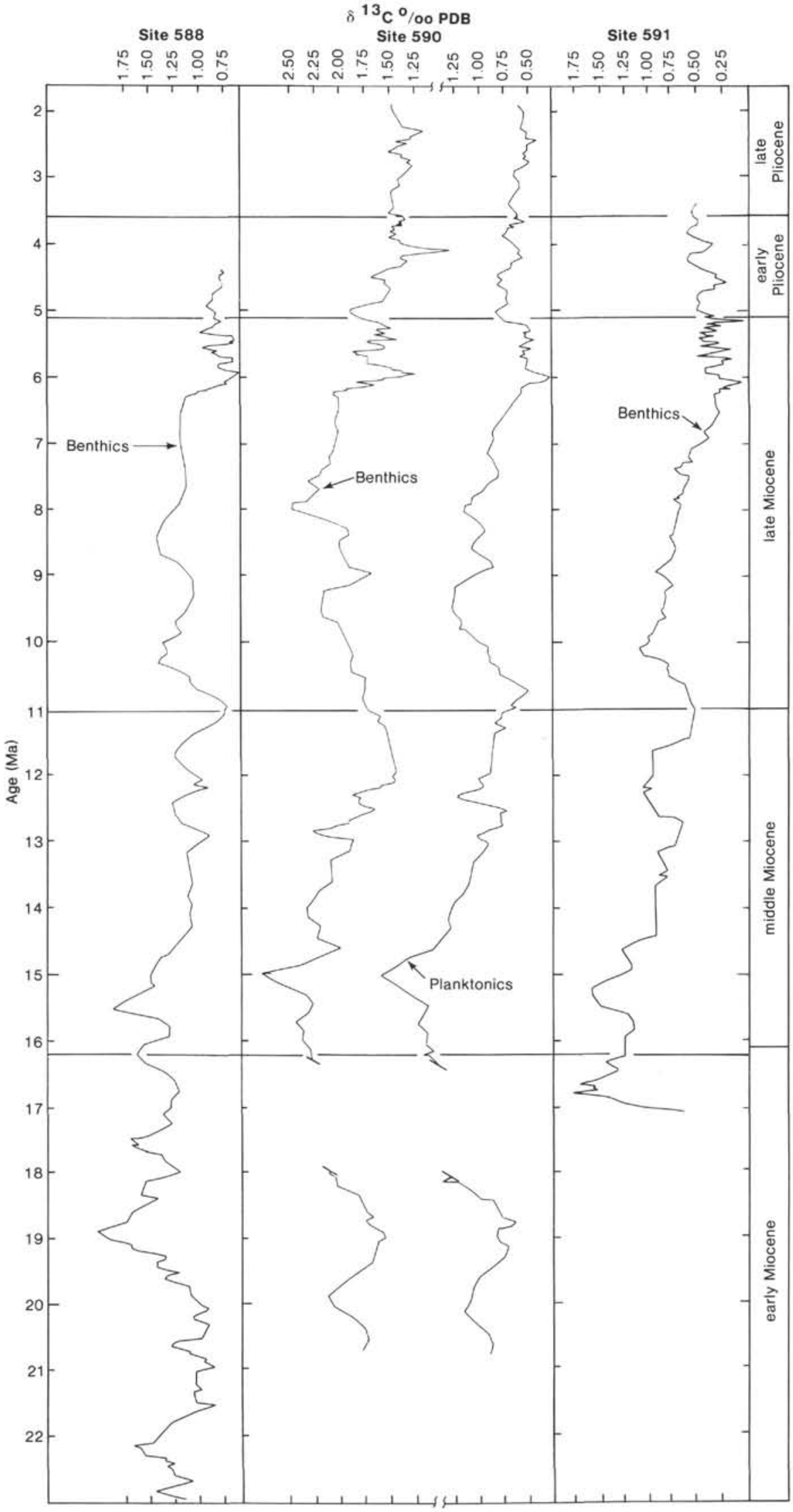

Figure 6. Smoothed $\delta^{13}C$ data (three-point running averages) for Sites 588, 590, and 591 plotted against age (from Kennett, this volume). For further details, see Kennett (this volume).

nett (1975b), Keigwin (1979), Margolis et al. (1975), Loutit (1981), Loutit, Kennett, et al. (1983), Vincent and Berger (in press), Vincent et al. (in press), Savin et al. (1981), Woodruff et al. (1981), Savin et al. (in press), and many other workers. The oxygen isotope shift was immediately preceded by the late early Miocene climatic optimum, from 19.5 to 16.5 Ma. Thus, sea-surface temperatures at high latitudes were relatively warm immediately preceding the buildup of the Antarctic ice sheet. Mercer and Sutter (1982) suggest that warm temperatures may be a necessary prerequisite for such ice accumulation.

Savin et al. (1975), Savin et al. (in press), and Loutit, Kennett, et al. (1983) have suggested that sea-surface temperatures in the tropical Pacific warmed during the middle Miocene. Tropical planktonic $\delta^{18}O$ values either decrease, show no change, or exhibit an increase that is smaller in magnitude than the shift observed in high-latitude sequences (Kennett, this volume). Warming of tropical surface waters during the middle Miocene may have resulted from the progressive thermal isolation of Antarctica and the contraction of the tropical-to-warm-subtropical gyres toward lower latitudes, as the polar and subpolar waters expanded toward the equator. Ocean circulation became less efficient at removing heat from the tropical regions. A major question remains, however: how much of the $\delta^{18}O$ shift during the early middle Miocene was due to an ice volume increase and how much was due to temperature decrease? Comparison of planktonic and benthic $\delta^{18}O$ records in Site 590 (Kennett, this volume) may assist in separating these effects, although interpretations are not unequivocal. At Site 590, the warming of surface waters during the early stage of the benthic $\delta^{18}O$ shift suggests that that part of the shift may have resulted largely from a decrease in temperature at high latitudes rather than an increase in ice accumulation. If little ice had then accumulated, glacioeustatic regression would not have occurred. $\delta^{13}C$ (benthic and planktonic) began to decrease, suggesting regression (assuming that $\delta^{13}C$ changes are related to sea level), at about 14.5 Ma, when the $\delta^{18}O$ shift occurred in both the benthic and planktonic records (Kennett, this volume). It is possible that this synchronous enrichment in both planktonic and benthic $\delta^{18}O$ represents the major ice-growth phase of East Antarctica. If this scenario is correct, then major ice accumulation and resulting regression occurred between 14.5 Ma ands 13 Ma.

In Site 593, 24 m of distinctive, pale orange nannofossil ooze is interbedded with normal, light gray to white nannofossil oozes of otherwise identical lithology. This pale orange sedimentary subunit was deposited between 15.5 and 15 Ma, contemporaneously with the early part of the middle Miocene oxygen isotope shift. It is interpreted as representing an increase in pore-water oxygen concentrations that were not subsequently reduced by postdepositional diagenesis. In the modern ocean, an orange oxidized layer is found in core-tops throughout the southwest Pacific (Nelson, this volume). We suggest that the relationship between the oxidizing event and the middle Miocene oxygen isotope shift is not coincidental. Since O_2 concentrations are controlled largely by temperature in the source area of bottom-water formation, the temperature drop between 15.5 and 15.0 Ma may have produced intermediate waters sufficiently oxygenated to prevent postdepositional reduction within the sediment. The origin of the oxidized sediment layer may, therefore, be related to temporary water mass changes connected with this major early middle Miocene development of Antarctic glaciation.

The middle Miocene development of the East Antarctic ice sheet was intimately associated with a number of other changes, including surface-water cooling—an inference based upon middle- to high-latitude Atlantic calcareous nannoplankton assemblages (Haq, 1980)—a marked steepening of the planetary temperature gradient (Savin et al., 1975), a major change in deep-sea benthic foraminiferal assemblages (Woodruff et al., 1981), an increase in hiatus abundance (van Andel et al., 1975), a shoaling of the CCD in the equatorial Pacific (Berger and Winterer, 1974), and an intensification in atmospheric circulation (Brewster, 1980). Several of these changes were also recognized in Leg 90 studies.

In Site 590, between 16 and 15 Ma, the average vertical $\delta^{18}O$ gradient ($\Delta\delta^{18}O$ benthics—planktonics) changed from about 1.75 during the early Miocene to about 2.25 during the middle and late Miocene (Kennett, this volume). This is equivalent to about a 2°C increase in the vertical temperature gradient between 1300 m and the ocean surface (assuming no salinity change occurred in surface waters). The average thermal gradient did not change significantly during the intervals before and after this event. Our results concur with those of Loutit, Kennett, et al. (1983), who suggested that much of the increase in thermal gradient during the Miocene (doubling of gradient from 6 to 12°C between the tropics and the subantarctic) took place in the middle Miocene.

An increase in upwelling, beginning in the middle Miocene (~14 Ma), in Sites 590 and 591 is indicated by a significant increase in biogenic opal (Stein and Robert, this volume), reflecting increased fertility of surface waters at the Subtropical Divergence.

A major change in deep-sea benthic foraminiferal assemblages also coincided with the Middle Miocene Event, according to the studies of Kurihara and Kennett (this volume) and Boersma (this volume). Boersma (this volume) found that the largest number of first appearances of the entire Tertiary were in Zone NN6 and, to a lesser extent, NN7 during the middle Miocene oxygen isotope shift. This interval, furthermore, heralded an increasing subdivision of bathyal benthic assemblages into bioprovinces with both depth and latitude. Differences became more pronounced between the assemblages of the lower and middle bathyal zones during this event. Kurihara and Kennett (this volume) found that *Globocassidulina subglobosa*, a dominant early Miocene element on the Lord Howe Rise sequences, became less dominant in the shallower sites (Sites 590 and 591), whereas *Epistominella exigua*, which was associated with the bottom waters of the New Caledonia Basin, migrated upslope and became dominant at these shallower depths. This suggests that the deeper water masses within the New Caledonia Basin became shallower, reaching water depths of about

1300 m during the early middle Miocene. These faunal changes occurred during the beginning of the $\delta^{18}O$ shift (NN5) at Sites 590 and 591, close to the early/middle Miocene boundary. The inferred change in vertical water mass structure that created the faunal changes was probably related to high-latitude surface-water cooling caused by increased Antarctic glaciation.

These changes in intermediate waters also markedly decreased planktonic/benthic ratios during the Middle Miocene Event (Kurihara and Kennett, this volume). Relatively higher numbers of benthic foraminifers after the early middle Miocene may have resulted from higher nutrient levels in deep-sea sediments caused by increased surface-water productivity which in turn resulted from increased upwelling at that time.

Middle Miocene paleoclimatic changes also had a marked impact upon the terrestrial climates of Australia (Stein and Robert, this volume). During the early middle Miocene, a distinct increase of illite at Site 588 is considered by Stein and Robert (this volume) to represent an increase in aridity in northern and central Australia. In contrast, high content of pedogenic smectite at Site 590, to the south, indicates that southern Australian continental climates were dominated by alternating humid and semiarid conditions. The expansion of aridity in northern Australia was almost certainly related to the expansion of the East Antarctic ice sheet in the middle Miocene. Increased availability of eolian sediments in Australia also increased the flux rates of terrigenous sediments to the Lord Howe Rise region (Stein and Robert, this volume). Increased aridity of Australia during the middle Miocene is also suggested by the first appearance of opal phytoliths in Lord Howe Rise sequences during Zone NN6 at 14.5 Ma (Locker and Martini, this volume). According to Locker and Martini (this volume) this record indicates the initial development of open grasslands in Australia. Westerly winds transported phytolith-bearing dust from the arid and semiarid regions of Australia more than 1000 km to the Lord Howe Rise region.

Late Miocene Paleoclimates

Following the Middle Miocene Event, during the remainder of the middle and late Miocene benthic $\delta^{18}O$ values underwent distinct fluctuations (Fig. 5), but the average value remained unchanged and the relatively enriched values reflect a period of prolonged, cool climates. The isotopic data show two distinct episodes of climatic cooling close to the middle/late Miocene boundary. The earliest of these events occurred between 12.5 and 11.5 Ma in the latest middle Miocene (Kennett, this volume).

The second cooling event, at the beginning of the late Miocene between 11 and 9 Ma, is marked by some of the highest $\delta^{18}O$ values of the entire Miocene. This was followed by relative warmth during the middle part of the late Miocene between about 9 and 6.5 Ma, as revealed by slightly lower $\delta^{18}O$ values. Relative warmth in the middle late Miocene (9–7 Ma) was also inferred by Haq (1980) from Atlantic calcareous nannoplankton biogeography.

During the early and middle late Miocene (10.5 to 6.5 Ma), sedimentation rates at Sites 586 (Ontong-Java Plateau) and 591 (Lord Howe Rise) were typical of carbonate platforms outside regions of high productivity (Gardner et al., this volume). The sedimentation rate on Lord Howe Rise was about 20 m/m.y., on the Ontong-Java Plateau about 25 m/m.y. The bulk-sediment mass accumulation rates of the two areas were about 2500 g/cm^2 per m.y. for Lord Howe Rise and about 3000 g/cm^2 per m.y. for Ontong-Java Plateau. These mass accumulation rates are typical for the southwestern Pacific at that time (Worsley and Davies, 1979). Changes in clay mineralogy and rates of accumulation of terrigenous sediments in Lord Howe Rise sequences (Stein and Robert, this volume) indicate that desertification of Australia continued to increase during the late Miocene. A sharp decrease in the smectite/illite (S/I) ratio during the middle to late Neogene in Lord Howe Rise sediments was interpreted by Stein and Robert (this volume) to represent increased transport of illite from Australia. The trends also indicate that the desert areas expanded southward (Fig. 7). By the middle late Miocene (~ 7.5 Ma), very low S/I ratios like those of the Quaternary occurred in all of the Lord Howe Rise sites (Sites 588, 590, 591) examined by Stein and Robert (this volume). During the late Miocene, the abundance of opal phytoliths on the Lord Howe Rise displayed a slight but noticeable increase compared with the middle Miocene (Locker and Martini, this volume), also reflecting increased aridity in Australia. Kemp (1978) made a similar finding for the Neogene, based upon palynological data. Distinct minima of the S/I ratios and increased accumulation rates of terrigenous sediments on the Lord Howe Rise suggest a maximum in aridity occurred between about 10 and 9 Ma in the early late Miocene, coinciding with the major cooling episode evidenced in the oxygen isotope record.

Terminal Miocene Event

During the latest Miocene, numerous oceanographic changes occurred within a relatively narrow time interval of only 1.3 m.y. Between about 6.3 and 5.0 Ma, evidence exists for conspicuous global cooling, worldwide regression, permanent depletion in carbon isotope values, intensification of oceanic circulation, possible development of the West Antarctic ice sheet, isolation/dessication of the Mediterranean Basin ("Messinian Salinity Crisis"), and several other oceanographic and climatic changes.

Studies of Leg 90 sequences also revealed an association of numerous oceanographic, climatic, and biotic changes during the latest Miocene. They are summarized in the following sections.

Carbon Isotope Shift

The latest Miocene at 6.2 Ma is marked by a distinct, rapid $\delta^{13}C$ shift of up to $-0.75‰$ in all of the southwest Pacific sites (Fig. 6), both in the benthic and planktonic records (Kennett, this volume; Elmstrom and Kennett, this volume). This depletion in ^{13}C was followed by markedly low values during much of the remainder of the late Neogene, which has led to the suggestion that the carbon isotope change was "permanent" (Keigwin, 1979). This well-known late Miocene carbon isotope shift is re-

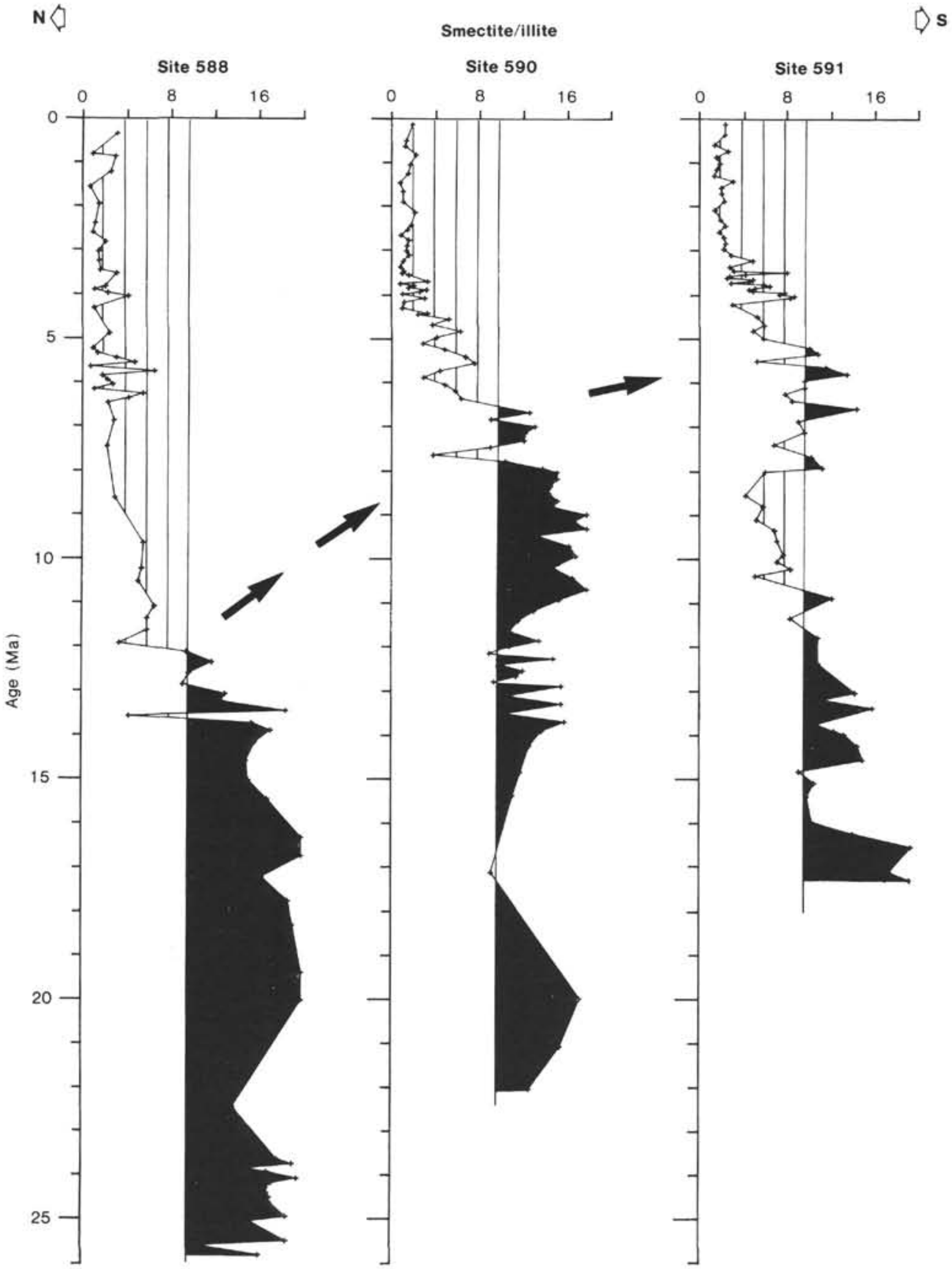

Figure 7. Smectite/illite ratios (S/I) of clay mineral assemblages in Sites 588, 590, and 591 from the Lord Howe Rise. Low S/I ratios reflect dominantly arid Australian continental climates. Note inferred expansion of continental aridity toward the south during the late Neogene (from Stein and Robert, this volume).

corded throughout the Indo-Pacific and South Atlantic and is considered to have been isochronous (Keigwin, 1979; Bender and Keigwin, 1979; Loutit and Kennett, 1979; Keigwin and Shackleton, 1980; Vincent et al., 1980; Haq et al., 1980; Hodell and Kennett, 1984). This shift, which seems to have occurred within a period of not much more than 100,000 yr. (Vincent et al., 1980), was assigned an age of ~6 Ma by Haq et al. (1980) and 6.2 Ma by Loutit and Kennett (1979), and is estimated at 6.4 Ma by Barron et al., (in press). The magnitude of the shift throughout the Indo-Pacific region is generally reported to be about −1‰ (Haq et al., 1980); in the South Atlantic a shift of 0.7‰ has been reported by Hodell and Kennett, 1984; in the North Atlantic a shift of 1.0‰ has now been identified by Keigwin et al., in press.

At Site 590, the shift occurs in close association with a number of biostratigraphic events that have been previously recognized to occur near the time of the carbon shift (Elmstrom and Kennett, this volume). These events include the first evolutionary appearance of *Globorotalia conomiozea* (Loutit and Kennett, 1979; Loutit, 1981); the first appearance of *Amaurolithus primus* (Haq et al., 1980); and a distinct switch in the coiling direction of *Neogloboquadrina pachyderma.*

Numerous hypotheses have been proposed to explain the cause of the carbon isotope shift, including a change in the rate of organic carbon burial and a change in the rate of upwelling and ocean fertility (Bender and Keigwin, 1979). The carbon shift is believed by some to have been caused by an increase in the flux of organic matter from coastal lowlands and continental shelves exposed by regression (Loutit and Keigwin, 1982; Vincent et al., 1980; Loutit, Pisias, et al., 1983), reinforced by increased oceanic fertility (Vincent et al., 1980). Kennett (this volume) found this theory very compelling because of the close temporal association of the carbon shift with global regression (Kennett, 1967; Adams et al., 1977; Vail and Hardenbol, 1979), inferred to have resulted from glacioeustatic lowering of sea level (Kennett, 1967; Loutit and Kennett, 1979; Mercer and Sutter, 1982) in the latest Miocene. Estimates of the magnitude of the marine regression are similar, ranging from 40 to 80 m (Loutit and Kennett, 1979; Berggren and Haq, 1976; Cita and Ryan, 1979).

The drop in the CCD throughout the oceans has an origin similar to that of the carbon isotope shift, having resulted from an increase in the fractionation of carbonate and organic carbon entering the deep basins from the continental shelves during the latest Miocene regression (Berger, 1970; Ciesielski et al., 1982).

Increased Sedimentation Rates and Benthic Foraminiferal Faunal Turnover

Also associated with the carbon isotope shift was an increase in sedimentation rates in both the fine and coarse biogenic sediment fraction (Gardner et al., this volume). This increase, general throughout the southwest Pacific (Fig. 8), was caused by higher biogenic productivity that resulted, at least in part, from an increase in upwelling at the Subtropical Divergence and the Equatorial Divergence.

Coincident with the carbon isotope shift and increase in biogenic sedimentation rates was a major turnover of the benthic foraminiferal assemblages (Kurihara and Kennett; Boersma; both this volume) near the NN11a/NN11b boundary (6.3 Ma). At this time, new uvigerinid and/or miliolid faunal elements evolved at all sites, but less so at Site 593 where, instead, the less ornamented brizalinids replaced the reticulate species in importance (Boersma, this volume). The uvigerinids particularly included the more hispid, spinose, or costate forms, rather than the hispido-costate forms that appeared slightly later in the latest Miocene. The uvigerinids are present only during the latest Miocene and permanently reappear again in late Pliocene to Quaternary assemblages. They are known to have appeared in increased abundances in many areas of the world's oceans during the latest Miocene in association with the $\delta^{13}C$ shift (Keigwin, 1979), reflecting increases in organic carbon flux rates that accompanied increases in global accumulation rates. Boersma (this volume) suggests that a direct relation exists among benthic faunal composition, increased biogenic sediment supply, and inferred surface-water productivity. This conclusion is largely based upon the increased abundance of uvigerinids (including *Rectuvigerina*), which have been shown to be related to episodes of high productivity and increased sedimentation during the Paleogene and Quaternary in other regions.

Epistominella exigua was also replaced during the late Miocene *Globigerina nepenthes* Zone at Site 590 by *E. rotunda* (Kurihara and Kennett, this volume). Synchronous with this faunal change, assemblages at Site 206 became temporarily dominated by *E. umbonifera.* This species is abundant in Cenozoic sections of deeper DSDP sites of the Pacific (Resig, 1976), and is associated with Antarctic Bottom Water in the Atlantic Ocean (Streeter, 1973; Schnitker, 1974) and in the Indian Ocean (Corliss, 1978). The temporary dominance of *E. umbonifera* at Site 206 may indicate the influence of deep water masses, probably Antarctic Bottom Water, during the latest Miocene. Bottom-water temperatures seemed to have cooled at the three sites during this time.

Climatic Cooling

At 6.2 Ma, a marked increase of planktonic $\delta^{18}O$ of about 0.5‰ occurred in the Lord Howe Rise sites, which coincides exactly with the late Miocene Epoch 6 carbon shift. This represents a significant and rapid cooling of surface waters from the latest Miocene to earliest Pliocene (6.2 to 4.5 Ma). In Site 588, the carbon shift also coincided with a shift toward higher benthic $\delta^{18}O$ values (Fig. 5; Kennett; Elmstrom and Kennett; both this volume). Similar high $\delta^{18}O$ values are reported by Shackleton and Kennett (1975a) from Site 284 and are interpreted to represent a major expansion of the Antarctic ice sheet. In Site 590, this enrichment in $\delta^{18}O$ coincided with a time of cool surface waters, suggested by high frequencies of *Neogloboquadrina pachyderma* and low frequencies of the warmer-water planktonic foraminifers (Elmstrom and Kennett, this volume).

The Terminal Miocene Event was marked by widespread cooling at high and middle latitudes (Ingle, 1967, 1973; Barron, 1973; Keller, 1979; Kennett, 1967; Kennett and Vella, 1975; Loutit and Kennett, 1979; Bandy et al., 1971; Cita and Ryan, 1979; Poore, 1981; Haq, 1980). In Argentina, Patagonian glaciers extended beyond the Andean Mountain front, apparently for the first time, between about 7 and 5.2 Ma (Mercer and Sutter, 1982). In Sites 588 and 590, a number of brief intervals of high $\delta^{18}O$ values between 5.4 and 4.9 Ma are interpreted to represent further increases in Antarctic ice volume, although the variability of the $\delta^{18}O$ record reflects instability in this ice (Hodell et al., in press). Much of this ice buildup may have been related to the expansion of the West Antarctic ice sheet (Ciesielski et al., 1982). This conclusion is based upon a variety of observations, including the northward expansion of ice-rafted debris in the Southern Ocean (Ciesielski et al., 1982); a northward migration of the Antarctic Convergence, inferred from a rapid equatorward displacement of the Antarctic siliceous biogenic belt (Tucholke et al., 1976; Kemp et al., 1975); a conspicuous increase in biogenic opal production (Kennett et al., 1975; Brewster, 1980); and a late Miocene age for the formation of the Ross

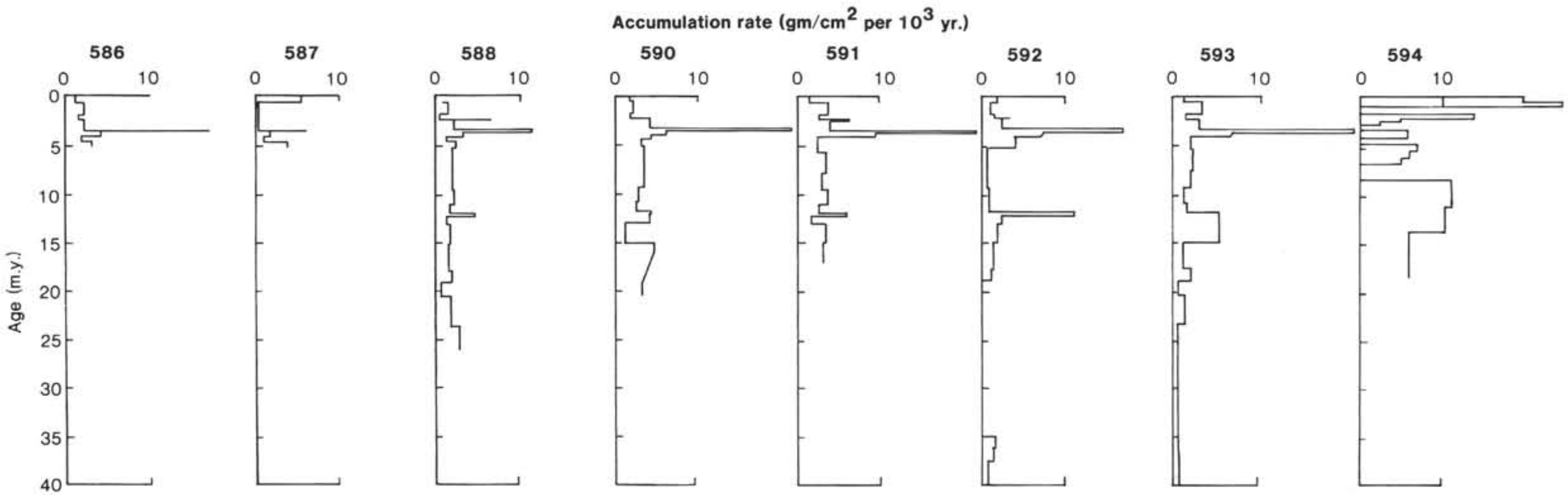

Figure 8. Mass accumulation rates of sediments at Leg 90 drill sites.

Sea disconformity, which is believed to be due to the expansion of a grounded Ross ice shelf (Hayes and Frakes, 1975).

Other climatic and oceanographic events closely associated with the Terminal Miocene Event include intensified oceanic circulation (Brewster, 1980; Savin et al., in press), high sediment accumulation rates (Davies et al., 1977), and marine regression (Kennett, 1967; Adams et al., 1977; Berggren and Haq, 1976). The latest sea-level fall was sufficient to isolate the Mediterranean and initiate the "Messinian Salinity Crisis" (Cita, 1982) between about 5.7 and 5.2 Ma. Previous work has indicated that this sea-level fall was largely glacioeustatic because of its rapidity and its association with surface-water cooling at middle and high latitudes (Kennett, 1967; Kennett and Watkins, 1974; Loutit and Kennett, 1979; Loutit, 1981) and with a period of relatively high $\delta^{18}O$ values (Shackleton and Kennett, 1975a; Kennett et al., 1979; Loutit and Kennett, 1979; Loutit and Keigwin, 1982; Ciesielski et al., 1982; McKenzie et al., 1984; Hodell et al., in press).

Continental Aridity

The latest Miocene to early Pliocene was also a time of increased cooling and aridity of the New Zealand and Australian land masses. Changes in pollens at Site 594 (Heusser, this volume) document a warm, moist climate in the earlier late Miocene, followed by cooler, drier conditions in the latest Miocene, when herbs and shrubs developed and temperate forests expanded. In Australia, the latest Miocene (close to 5 Ma) was marked by an episode of increased aridity, judging by increased accumulation rates of wind-blown, terrigenous sediments in the Lord Howe Rise region (Stein and Robert, this volume). At 5.1 Ma (close to the Miocene/Pliocene boundary), a sudden increase in opal phytolith abundance in Lord Howe Rise sequences reflected further aridification of Australia (Locker and Martini, this volume).

Early Pliocene Increased Biogenic Sedimentation

During the Pliocene (as shown by Site 590), average benthic $\delta^{13}C$ values were lower by about 0.25‰ and planktonic $\delta^{13}C$ by about 0.75‰ than during the Miocene preceding the carbon shift (Elmstrom and Kennett, this volume). An interval of relatively low values occurred during the early Pliocene between about 5 and 4 Ma. This interval corresponds with a period of relative global warmth (Kennett, 1967; Loutit and Kennett, 1979; Ingle, 1967; McKenzie et al., 1984), in which occurred the highest calcareous nannofossil diversity for the Neogene (Lohman, this volume), global marine transgressions (Kennett, 1967; Kennett and Watkins, 1974; Vail and Hardenbol, 1979), and relatively low $\delta^{18}O$ values in benthic foraminifers, as is shown at Site 590 and elsewhere (McKenzie et al., 1984; Hodell et al., in press). This depletion in ^{18}O values probably reflects a decrease in global ice volume and a marine transgression into the Mediterranean that restored pelagic sedimentation. This early Pliocene interval is also marked by relatively high $\delta^{13}C$ values, which Kennett (this volume) suggests may have resulted from marine transgression.

During the early Pliocene between 4 and 3 Ma, there was a remarkable, widespread increase in sedimentation rates (up to 131 m/m.y. at Site 591) and mass accumulation rates (MAR) in the Lord Howe Rise sequences (Fig. 8). At Site 591, the <63 um MAR increased from about 2100 to >8000 g/cm^2 per m.y. (Gardner et al., this volume). During this same interval, the >63 um MAR rose from less than 200 to about 800 g/cm^2 per m.y. Less dramatic, but significant increases in size-fraction MARs also occurred on Ontong-Java Plateau (Site 586) where the <63 um MAR increased from 2000 to 3000 g/cm^2 per m.y., and the >63 um MAR increased from 700 to 1100 g/cm^2 per m.y. (Gardner et al., this volume). The ratio of the coarse- to fine-fraction components underwent little change during this increase.

The large MARs are not due to dilution from noncarbonate components because noncarbonate material comprises only a minor amount of the sediment. Nor do they reflect variations in calcium carbonate dissolution, because the sites are located well above the lysocline and show little evidence of dissolution other than that caused by burial diagenesis. Redeposition from winnowed areas seems not to be a factor, because there is little evidence of reworking of microfossils. We do not believe that the high sedimentation rates are an artifact of an imprecise chronology, because the age boundaries would have to be substantially changed to offset the pattern of increased MAR rates. This early Pliocene episode of increased biogenic sedimentation on the Lord Howe Rise and Ontong-Java Plateau corresponds to a period of maximum sedimentation rates in the Columbia Basin (Prell, Gardner, et al., 1982), the Falkland Plateau (Ciesielski et al., 1982), the Walvis Ridge area (Moore et al., 1983; Shackleton et al., 1984), and maximum carbonate MAR averaged for the Pacific Ocean (Davies and Worsley, 1981).

The increases in sedimentation rates and bulk-sediment MARs on the Lord Howe Rise and Ontong Java Plateau were due to increased biogenic productivity of both calcareous nannoplankton and foraminifers (Gardner et al.; Elmstrom and Kennett; Nelson; all this volume). The increased productivity on the Lord Howe Rise probably was caused by increased upwelling at the Subtropical Divergence and that on the Ontong-Java Plateau by increased upwelling at the Equatorial Divergence. If planktonic foraminifers increased their productivity, then the planktonic/benthic foraminiferal ratio (P/B) should also have increased. However, the average P/B ratio of Site 591 in the early Pliocene, the time of highest calculated sedimentation rates, is only slightly higher than ratios in the Quaternary and the late Pliocene, and is comparable to late Miocene estimates (Kurihara and Kennett, this volume). To maintain constant ratios, the productivity of benthic foraminifers must have increased proportionally with planktonic productivity.

The early Pliocene between 4 and 3 Ma was also marked by maximum accumulation rates of wind-blown, non-carbonate terrigenous sediment in all sites of the Lord Howe Rise (Stein and Robert, this volume). This suggests an increase in wind strength and/or aridity at the time biogenic productivity increased in the southwest Pacific.

Both the stable isotope data and faunal analyses from Site 590 indicate that the character of surface waters changed during the time when biogenic sedimentation rates increased (Elmstrom and Kennett, this volume). Changes included a distinct increase in $\delta^{18}O$ of planktonic foraminifers; a decrease in the gradient between surface and intermediate water $\delta^{13}C$ and $\delta^{18}O$; a 1.0‰ depletion of the $\delta^{13}C$ of two species of planktonic foraminifers; mixing of warm and cool planktonic foraminiferal elements, which normally indicates seasonal upwelling (Thiede, 1983); and high variability in planktonic foraminiferal species frequencies and in planktonic oxygen isotope values, reflecting temperature fluctuations associated with variable rates of upwelling. These data suggest that surface-water productivity, induced by localized upwelling at the Subtropical and Tropical divergences, significantly increased during the early Pliocene.

The increase in biogenic productivity is reflected mainly in the calcareous fossils, rather than in the siliceous forms more typical of areas of oceanic upwelling. Elmstrom and Kennett (this volume) suggest that this may be due to the nature of the upwelling regime. Most areas of siliceous biogenic productivity occur where cold, nutrient-rich intermediate waters are upwelled. In the southwest Pacific, the upwelling occurs over a shallow-water pedestal; thus, the upwelled waters are both shallow and warm, being associated with the East Australian Current. The upwelled water is thus warmer than in most oceanic upwelling regimes such as the Antarctic Convergence, the Equatorial Divergence, and the Eastern Boundary Current systems. It remains unclear why upwelling (and biogenic productivity) increased during the early Pliocene between about 4 and 3 Ma, a time of relative global climatic warmth and stability.

Middle to Late Pliocene Climatic Coolings

During the middle Pliocene at about 3.4 Ma, a 0.4‰ increase is recorded in the benthic $\delta^{18}O$ record of Site 590 (Fig. 5), documenting a net increase in average global ice volume and cooling of bottom waters (Elmstrom and Kennett; Kennett; both this volume). A similar oxygen isotope shift has been reported from the equatorial Pacific (Shackleton and Opdyke, 1977; Keigwin, 1979; Prell, 1984), the South Atlantic (Weissert et al., 1984), the North Atlantic (Shackleton and Cita, 1979), and the Mediterranean (Keigwin and Thunell, 1980). This shift almost certainly documents a cooling of intermediate waters (Prell, 1984), but possibly also some additional growth of Antarctic ice (Weissert et al., 1984). Increased glaciation ofAntarctica at about 3.5 Ma created a northward shift in the deposition of circum-Antarctic glacial marine sediments (Ciesielski and Weaver, 1974). A glacial increase at about 3.5 Ma is also consistent with the observation of cooling of the Southern Ocean at 3.6 Ma (Keany, 1978) and in temperate areas (Kennett and Vella, 1975; Kennett et al., 1979), and increased Patagonian glaciation (Mercer, 1976).

The planktonic $\delta^{18}O$ record during the Pliocene (as recorded in Site 590) is more variable than the benthic $\delta^{18}O$ record, and exhibits different trends. Between 3.6 and 2.2 Ma at Site 590, a positive shift of 0.4‰ in benthic $\delta^{18}O$ generally coincided with a negative shift of about 0.4‰ in planktonic $\delta^{18}O$ (Elmstrom and Kennett, this volume). This is interpreted by Kennett (this volume) to represent a surface-water warming of at least 2°C at these latitudes, in concurrence with the observation of Weissert et al. (1984) at similar latitudes (~30°S) in the South Atlantic. This warming occurred when high-latitude glaciers were growing.

During the late Pliocene between 2.6 and 2.4 Ma, $\delta^{18}O$ again increased ~0.4‰ (Elmstrom and Kennett, this volume). This isotopic shift heralded the beginning of major Northern Hemisphere ice accumulation (Backman, 1979; Prell, 1984; Shackleton et al., 1984). A decrease in the frequencies of warm-subtropical planktonic foraminifers and *Neogloboquadrina pachyderma* at this time may represent a decrease in the intensity of upwelling at the Subtropical Divergence (Elmstrom and Kennett, this volume).

Further distinct changes in the vertical temperature gradient occurred both during the middle Pliocene at 3.6 Ma, whereby the average thermal gradient increased by another 0.5‰ (~2°C), and during the late Pliocene at 2.4 Ma, with a further shift of 0.25 to 0.5‰ (~1–2°C) (Fig. 5; Kennett, this volume). Thus, the late Pliocene oxygen isotope trends are somewhat comparable to that which occurred during the early middle Miocene (16 to 14 Ma); that is, they indicate that surface waters warmed at these middle latitudes at times when large amounts of ice accumulated at high latitudes and that the vertical temperature gradient of the open ocean showed a major, permanent increase.

Mass accumulation rates during the late Pliocene are much reduced from early Pliocene values but are still higher than average Neogene rates. After about 3.5 to 3 Ma, the fine-sediment fraction decreased and values of the coarse fraction were persistently high, suggesting a significant episode of winnowing by bottom currents (Gardner et al.; Stein and Robert; both this volume). This persisted for the remainder of the Neogene and almost certainly reflects enhanced oceanic circulation associated with the further development of polar glaciation. Further major changes in benthic foraminiferal assemblages are associated with this change on the Lord Howe Rise, especially marked by an increase in uvigerinid abundance.

Australian continental climate from 3 Ma to the present was dominantly arid, based upon consistently low S/I ratios and high amounts of eolian terrigenous sediments on the Lord Howe Rise (Stein and Robert, this volume). Opal phytoliths increase drastically in late Pliocene sediments, peaking at 2.5 Ma (Locker and Martini, this volume) and indicating further expansion of Australian grassland areas and intensified transport of dust to the Lord Howe Rise area.

Quaternary Glacial–Interglacial Oscillations

Oxygen isotope studies of the Quaternary at Site 593 (Nelson et al., this volume) clearly exhibit two modes of Quaternary $\delta^{18}O$ variation (Prell, 1982): depleted values with generally low variability in the early Quaternary

(1.9–0.9 Ma), and enriched values with high variability during the late Quaternary (0.9–0 Ma). At Site 593, the major glacial–interglacial episodes are clearly recognizable. Correlation with magnetostratigraphy (Barton and Bloemendale, this volume) makes it possible to place the Stage 19/20 boundary at the Brunhes/Matuyama Chron boundary and the Stage 23/24 boundary at the end of the Jaramillo Subchron. The shift toward much more intense glacial–interglacial fluctuations near the beginning of the Jaramillo Subchron reflects a fundamental change in global ice budget and must be linked to an expansion of the Northern Hemisphere ice sheets, including perhaps the development of an Arctic Ocean ice sheet during glacial episodes (Williams et al., 1981). In Site 593, the Quaternary carbonate oozes display a cyclical variation in texture consisting of alternating zones of relatively enriched and impoverished sand-sized material, mainly foraminifers (Nelson et al., this volume). Carbonate dissolution is unimportant at these shallow water depths on the Challenger Plateau, and the coarser intervals are considered by Nelson et al. (this volume) to result from episodes of intensified winnowing by bottom currents, particularly during glaciation.

Sedimentary cycles during the Quaternary (and the remainder of the late Neogene) are also very conspicuous at Site 594. The section contains many fluctuations of hemipelagic and impure pelagic lithofacies that are evident from color changes in the core and calcium carbonate stratigraphy (Nelson et al., this volume). The hemipelagic sediments are typically greenish gray nannofossil-bearing clayey silts, rich in mica and quartz, and often diatom- or sponge-spicule-bearing. The $CaCO_3$ content in the hemipelagic sediments ranges from 0 to 25%. In content, the pelagic interbeds are mainly bluish gray foraminifer-bearing nannofossil oozes with reduced, but variable, amounts of terrigeneous material and only trace quantities of biosiliceous components. The $CaCO_3$ of these sediments ranges between 50 and 80%. Individual pelagic to hemipelagic cycles (at least 25 major hemipelagic sediment episodes during the last 6 m.y.) range from 0.5 to 10 m in thickness.

Oxygen isotope analyses of the last 0.7 m.y. (Nelson et al., this volume) confirm that the hemipelagic sediment intervals, marked by high $\delta^{18}O$ values, accumulated during glacial episodes when sea level was low, whereas the pelagic interbeds, marked by lower $\delta^{18}O$ values, were deposited during interglacial episodes when sea level was high. As with other Quaternary isotopic records (e.g., Shackleton, 1977), the $\delta^{13}C$ of Site 594 exhibits oscillations that are related to glacial-interglacial episodes; lower $\delta^{13}C$ values are associated with glacial intervals.

Fluctuating climatic modes were inferred by Heusser (this volume) from high-frequency changes in arboreal pollen in the upper 200 m of Site 594. High values in the podocarp/*Nothofagus* ratio are interpreted to represent warm climatic intervals (Heusser, this volume), and low values to represent cold climatic intervals (Mildenhall, 1976). Heusser (this volume) demonstrates that a close correlation exists between cool-temperate (glacial) pollen assemblages and hemipelagic oozes, low carbonate content, high $\delta^{18}O$, and low $\delta^{13}C$. Warm-temperate (interstadial and interglacial) pollen assemblages are associated with pelagic oozes, high carbonate content, low $\delta^{18}O$), and high $\delta^{13}C$ (Nelson et al., this volume). The history of alpine glaciations, cool vegetation, and associated erosion in South Island are contained within the hemipelagic oozes, which can be correlated with major fluctuations of Northern Hemisphere ice sheets, as evidenced by the marine oxygen isotope record.

The late Quaternary (0.7 Ma to present) of the Lord Howe Rise sites are marked by intensified winnowing, as is shown by substantial decreases in the mass accumulation rates of both the fine and coarse fractions (Gardner et al., this volume). This is due to intensified circulation of intermediate waters in the Lord Howe Rise region, but not on the Ontong-Java Plateau, where evidence for increased winnowing is lacking (Gardner et al., this volume).

SUMMARY

Leg 90 of the Deep Sea Drilling Project obtained a traverse of eight middle to late Cenozoic sections from relatively shallow water pedestals (1000 to 2000 m) in the southwest Pacific between tropical and northern subantarctic water masses. The sequences are largely calcareous ooze or chalk, relatively continuous and undisturbed, having been collected using the Hydraulic Piston Corer and the Extended Core Barrel. Sediment was collected during Leg 90 from beneath every major surface water mass between the equator and the subantarctic, permitting paleoceanographic records to be analyzed for each water mass. Paleoceanographic and paleoclimatic investigations of Leg 90 material have involved analyses of oxygen and carbon isotopes, sediment character and accumulation rates, and microfossils.

The benthic $\delta^{18}O$ record in Leg 90 sites exhibits a number of large changes that reflect the sequential development of polar glaciation and cooling of bottom waters beginning in the latest Eocene–earliest Oligocene. The late Eocene was marked by warm, equable climates with low surface-water temperature gradients between tropical and subantarctic regions. Major climatic cooling events in the Leg 90 sequences include the Terminal Eocene Event (37 Ma) which marks the transition from warm Eocene to cooler Oligocene conditions; middle Oligocene cooling events, clustered close to 31 Ma, and which may, in part, represent temporary accumulations of Antarctic ice; the Middle Miocene Event (16.5–13.5 Ma) representing a major, permanent accumulation of the East Antarctic ice sheet and cooling of bottom waters; further temporary cooling events during the late middle Miocene (12.5 to 11.5 Ma) and the earliest late Miocene (11–9 Ma); the Terminal Miocene Event (~6.2–5.0 Ma) marked by cooling, permanent depletion in carbon isotope values, intensification of oceanic circulation, increased biogenic sedimentation rates, and important biotic changes in the surface and deep oceans; the Middle Pliocene Cooling Event at 3.4 Ma, documenting an increase in average global ice volume and cooling of bottom waters; the Late Pliocene Event at 2.6–2.4 Ma, heralding the beginning of major Northern Hemisphere ice accumulation; and amplification of glacial-interglacial oscillations during the Quaternary at 0.9 Ma (Jaramillo Paleomagnetic Subchron).

The sequences record the development during the Cenozoic of latitudinal and vertical thermal gradients in the southwest Pacific region. During the Oligocene, latitudinal thermal gradients developed and strengthened between subantarctic and temperate water masses. A pattern of increasing offset between latitudinally distributed southwest Pacific sites is linked to the establishment and strengthening of the Circum-Antarctic Current during the Oligocene. Major, permanent increases in the vertical temperature gradients of the open ocean occurred in association with the Middle Miocene Event (16.5–13.5), the Middle Pliocene Cooling Event (3.4 Ma) and the Late Pliocene Event (2.6–2.4 Ma). The oxygen isotope records indicate that surface waters in middle latitudes warmed at these times of major ice accumulation or cooling at high latitudes.

The climax of Neogene warmth occurred during the early Miocene, especially between 19.5 and 16.5 Ma, as reflected in the oxygen isotope record and pollen assemblages from southern New Zealand. The middle late Miocene (9 to 6.5 Ma) and the early Pliocene ($\sim$5–4 Ma) were also times of relatively warm climatic conditions.

Deep-sea benthic foraminiferal assemblages underwent important changes near the Eocene/Oligocene boundary and during the earliest Middle Miocene, the latest Miocene, and the late Pliocene and Quaternary. The faunal changes associated with the Middle Miocene Event occurred during the early part of the $\delta^{18}O$ shift, which is interpreted to be largely a result of bottom-water cooling. The later part of the $\delta^{18}O$ shift probably largely reflects ice accumulation on East Antarctica. Late Neogene benthic foraminiferal changes are, in part, related to changes in the organic flux rates that accompanied changes in biogenic sedimentation rates and inferred surface-water productivity.

Changes in clay mineralogy, wind-blown terrigenous sediments, and opal phytoliths in the Lord Howe Rise sites record a general evolution of Australian continental climates during the middle and late Cenozoic. Tropical conditions developed during the late Oligocene in northern Australia as the continent migrated northward into the tropical region. During the Neogene, a series of changes led to continental aridity and expansion of grasslands. Important steps occurred during the Middle Miocene Event; the Terminal Miocene Event ($\sim$5 Ma), and the Middle Pliocene Event ($\sim$3 Ma). Increased continental aridity was linked to global climatic changes related to the sequential glacial development of the polar regions, especially Antarctica.

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