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38. SCIENTIFIC RESULTS OF DRILLING THE NORTH PACIFIC TRANSECT[1]

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ABSTRACT

Ocean Drilling Program Leg 145 crossed the North Pacific Ocean from Japan to Canada in the summer of 1992, the first deep ocean drilling in the Subarctic Pacific since the 1971 cruises of Deep Sea Drilling Project Legs 18 and 19. All of the Cenozoic paleoceanographic objectives of the cruise were accomplished. We determined the history of silica deposition in the North Pacific and resolved the timing of the late Miocene "silica switch" when the locus of silica deposition changed from the North Atlantic to the North Pacific. A depth transect drilled on the flanks of Detroit Seamount in the far northwestern Pacific allowed the reconstruction of the calcite compensation depth for the North Pacific over the past 70 Ma.

The Meiji sediment tongue was shown to be a drift deposit, identical in nature to those better known from the North Atlantic. The Meiji Drift contains northern-source diatoms and minerals from the Bering Sea region and has been accumulating since the early Oligocene. This means that southward-flowing bottom water has been exiting the Bering Sea to the North Pacific basin for the past 35 million years. Presently, water exits the Bering Sea at the same rate, 10 to 20 Sv (1 Sv = 10^6 m^3/s), as North Atlantic Deep Water leaves the northwesternmost Atlantic.

Late Cenozoic cooling was determined to have been underway by the end of Miocene time when ice-rafted debris first occurs at the Leg 145 drill sites. A middle Pliocene warm interval interrupted the high-latitude cooling for about a million years. Large-scale Northern Hemisphere glaciation is shown to have begun rather abruptly at 2.6 Ma by a rapid increase in the delivery of terrigenous hemipelagic and ice-rafted debris sediment to the North Pacific. At this same time abyssal circulation begins to modify sediment depositional patterns in the northwestern Pacific deep basin. The sequence of ash layers recovered downwind from both the Kamchatka Peninsula (the world's most active Pliocene–Pleistocene volcanic field) and the Aleutian arc allows the geochemical evolution of these volcanic centers to be determined. An order of magnitude increase in the number and thickness of ash layers occurred at 2.6 Ma. High-resolution studies of the past 4.0 Ma show that biogenic sediment fluxes are generally higher during interglacial periods. This observation indicates that more rapidly circulating deep ocean waters during interglacial episodes is the dominant source of nutrients to the Subarctic Pacific rather than those supplied by regional runoff or dust input.

INTRODUCTION TO THE NORTH PACIFIC TRANSECT

Paleoceanographic Setting

Subarctic Pacific sediment contains a critical record of late Mesozoic and Cenozoic oceanographic and climatic changes. Existing Deep Sea Drilling Project (DSDP) sites are too few and recovered sediment cores are generally too disturbed by rotary drilling to permit detailed reconstructions. The region therefore represents a significant gap in our knowledge of the evolution of the earth's ocean and climate system. This area extends over 35 × 10^6 km^2 and includes two major boundary currents (the Oyashio and Alaskan currents) and an oceanic and atmospheric frontal zone (the Subarctic Front), which is believed to have migrated over several degrees of latitude on both short and long time scales. Passes through the Aleutian and Kuril arcs provide exchange sites for deep waters that exert a strong influence upon the properties of North Pacific Intermediate Water and possibly deeper waters. The area is a source of heat and moisture for the North American continent and is one of the most biologically productive areas of the world ocean.

At present, the North Pacific is the terminus of the deep ocean circulation route originating in the northern North Atlantic and the Southern Ocean, and the beginning of the return surface circulation. These old deep waters are nutrient-rich, oxygen-poor and highly corrosive to calcium carbonate. Recent evidence suggests that at various times in the Quaternary better calcite preservation occurred in both the deep northeast and northwest Pacific (Keigwin, 1987; Keigwin et al., 1992; Zahn et al., 1991; Hovan et al., 1991) It is not clear to what extent these and other changes reflect changes in deep-ocean circulation, as opposed to local changes in depositional conditions.

Work in other regions of the world has defined a series of events or rapid changes in ocean circulation and global climate during the Neogene. These include the middle and latest Miocene, believed to be times of expansion of Antarctic glaciers (Woodruff et al., 1981; Savin et al., 1981; Kennett, 1985), the late Pliocene growth of ice in the Northern Hemisphere (Shackleton et al., 1984; Rea and Schrader, 1985), and the more recent increase in the amplitudes of the ice-volume $\delta^{18}O$ signal during the middle Pleistocene (Ruddiman et al., 1989). These longer term changes appear to have superimposed upon them ongoing higher frequency variability cycles at roughly Milankovitch periods. The effect of these changes upon the North Pacific has been largely unknown, given the small number of sites available prior to Leg 145 and the general absence of calcareous sediment. Strategic location of Leg 145 drilling sites situated upon oceanic highs and in the deep basins within the North Pacific subpolar gyre were intended

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to permit generation of latitudinal, longitudinal, and depth transects to complete the global picture of climate and circulation throughout the Neogene.

Limited recovery from North Pacific and Bering Sea industry stratigraphic test wells suggests that regional sedimentation in the Eocene and early Oligocene was mainly calcareous. This was succeeded by a period of low sedimentation rates continuing until the middle Miocene, when siliceous sediment began to accumulate throughout the region (Keller and Barron, 1983). The timing and rate of decreased calcareous and increased siliceous accumulation is not well known. While plate migration may partially account for this trend, it does not explain the occurrence of in situ calcareous sedimentation in the Bering Sea or the rapidity and apparent synchroneity of the onset of siliceous sedimentation throughout the North Pacific. The evidence implies a change in regional circulation and productivity from a mid-Paleogene ocean that was warm, stratified, and with net downward transport (as the North Atlantic today), to a mid-Neogene ocean that was cool and well mixed with net upward transport (Woodruff and Savin, 1989). Such a change would also affect nutrient concentrations downstream, leading to lower silica production in the Atlantic and Indian oceans, and may signal a change in atmospheric circulation and climate. However, the number and location of North Pacific DSDP sites leave considerable doubt concerning the extent of the change because most of the sites lie near the continents and their records may reflect changes in the boundary currents, rather than in the open-ocean gyre. Leg 145 planned drilling sites within the subpolar gyre that were expected to permit an assessment of regional changes in the mass accumulation rate of silica during the Cenozoic and allow a clear definition of the middle to late Miocene silica switch (Keller and Barron, 1983).

The response of the North Pacific to major paleoclimatic events of the Pliocene, both the mid-Pliocene warm interval centered at about 3 Ma and the onset of major Northern Hemisphere glaciation at 2.6 Ma, is only poorly understood. The record of ice rafting has been reported from analyses of both piston cores (Conolly and Ewing, 1970; Kent et al., 1971) and DSDP cores (von Huene et al., 1973; 1976). Much of the DSDP information was summarized by Rea and Schrader (1985) who showed that, although older isolated pebbles occur, ice rafting effectively began all across the northern Pacific at 2.6 Ma (see also Krissek et al., 1985). The oceanic response to the onset of Northern Hemisphere glaciation has been documented from faunal and floral abundance patterns, but reliable estimates of changes in biological productivity have not been made. One goal of Leg 145 was to determine the fluxes of the biogenic components of the sediment and to interpret those data in terms of past biological productivity.

The North Pacific also provides special opportunities to investigate important oceanographic and climatic phenomena that are either better displayed there than elsewhere, or may be unique to this basin. One of these opportunities involves the record of atmospheric circulation preserved in the eolian component of North Pacific sediment. Atmospheric circulation and its link to sea-surface circulation and biological productivity is an important component of climatic change. Much of our understanding of this aspect of climate change has come from three North Pacific cores (Janecek and Rea, 1983; Rea et al., 1985; Janecek, 1985; Rea, 1994). These cores are generally of low biostratigraphic resolution and are all situated along about the same latitude, precluding any understanding of latitudinal variation in the global wind system. Leg 145 sites were chosen to increase the latitudinal span of eolian records which permits enhanced definition of changes in atmospheric circulation associated with the Cretaceous/Tertiary and Paleocene/Eocene boundaries (important for comparison to computer models of climate change). The Leg 145 sites also can be used to test the suggestion that enhanced Northern Hemisphere atmospheric circulation and concomitant biological productivity were directly responsible for the onset of massive silica sedimentation in the Miocene and to document changes in atmospheric circulation associated with the Pliocene onset of Northern Hemisphere glaciation.

A second special scientific opportunity offered by the North Pacific is to test the relation between spreading center formation (ridge jumps) and hydrothermal activity originally proposed by Owen and Rea (1985) and Lyle et al. (1987). Those authors showed that there is an order of magnitude increase in seafloor hydrothermal activity associated with the process of cracking a new spreading center through old ocean crust. Pelagic clay is a reliable recorder of ocean paleochemistry. Drilling on Leg 145 was planned to recover the geochemical signal associated with the plate boundary reorganization that occurred during the time of the Late Cretaceous magnetic quiet zone (Rea and Dixon, 1983; Mammerickx and Sharman, 1988). The rifting episode that resulted in the formation of the Chinook Trough in the central North Pacific is part of this event, and Site 885/886 (just south of the trough on somewhat older crust), was planned to recover a clear, proximal geochemical record of the hydrothermal activity associated with intraplate rifting.

The final special opportunity provided by North Pacific drilling arises from the presence, on the northeastern flank of the northern Emperor Seamounts, of the Meiji sediment tongue. Geologists have interpreted this deposit as being a drift deposit similar to those of the North Atlantic (Scholl et al., 1977; Mammerickx, 1985). If true, bottom water has been forming somewhere to the northwest of Detroit and Meiji seamount and moving rapidly to the southeast. Conversely, some physical oceanographers have stated that no bottom water forms or can form in the North Pacific (e.g., Knauss, 1978; Warren, 1983). Determining the nature and age of the Meiji sediment tongue, therefore, was an important target for the Leg 145 drilling.

Scientific Objectives

These long-standing questions and others were incorporated into the scientific objectives of Leg 145, the primary goal of which was to enhance our understanding of the paleoceanography and paleoclimatology of the North Pacific Ocean. Specifically, we hoped to be able to define the following:

1. The high-resolution Neogene record of the Subarctic region;
2. The nature and history of formation of North Pacific Deep Water;
3. The middle Miocene onset of silica deposition—the "silica switch" question;
4. The Late Cretaceous and Cenozoic record of atmospheric circulation;
5. The Late Cretaceous and Cenozoic record of ocean chemistry;
6. The record of Northern Hemisphere continental climate;
7. The paleoceanography of the late Mesozoic superocean;
8. The tephrochronology of the Kuril, Kamchatka, and Aleutian arcs;
9. The age and nature of basement in regions where it is poorly understood.

Leg 145—the North Pacific Transect

Leg 145 departed from Yokohama, Japan, harbor on 24 July 1992, and arrived two months later in Victoria, Canada. The return to the northernmost Pacific occurred 21 years after the previous visit to the region by a drilling ship, during Leg 18 and 19 of DSDP. Leg 145 drilled 25 holes at 7 drill sites (Fig. 1, Table 1) and recovered 4321 m of core. New, much more aggressive hydraulic piston-coring techniques, formulated because of the failure of the extended core barrel (XCB) bit to recover diatom ooze at our first drill site, 881, were directly responsible for the recovery of very long advanced piston corer (APC) cores at the ensuing locations. Hole 882A is still the longest

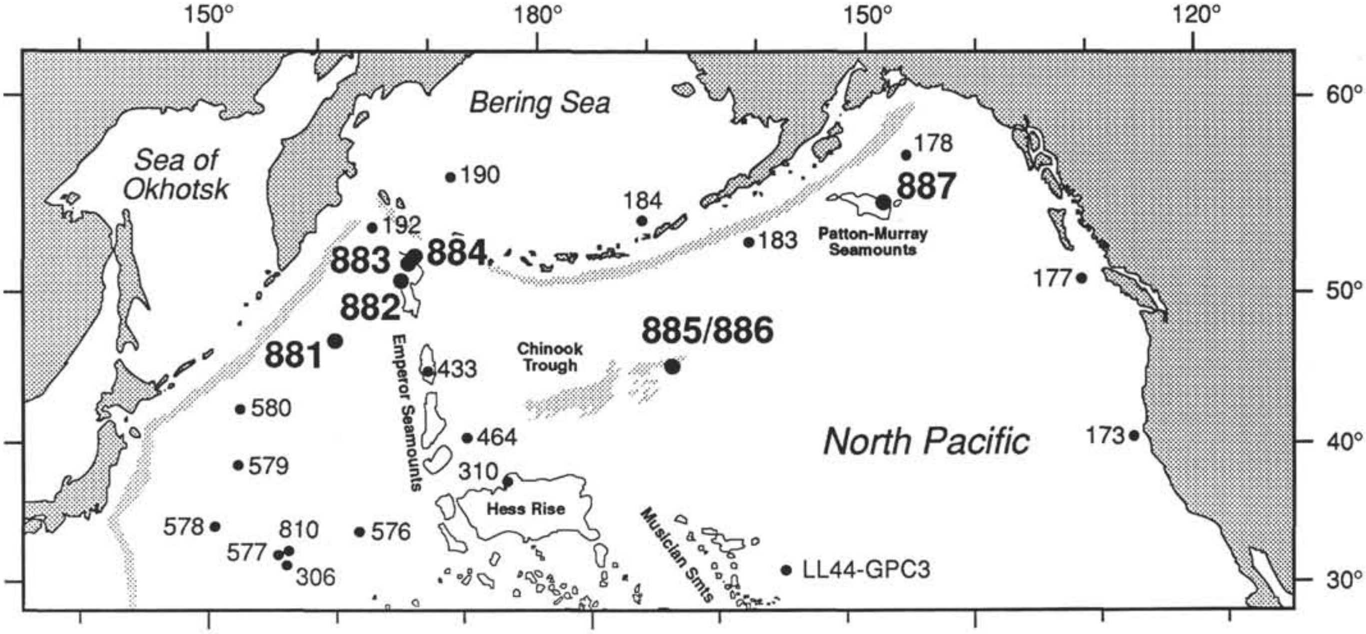

Figure 1. Index map of the North Pacific showing the location of Leg 145 drill sites and other ODP and DSDP sites mentioned in the text.

Table 1. Location of Leg 145 drill sites.

Site	Latitude	Longitude	Water depth (m)
881	47°06.1′N	161°29.5′E	5531
882	50°21.8′N	167°36.0′E	3244
883	51°11.9′N	167°46.1′E	2385
884	51°27.0′N	168°20.2′E	3826
885	44°41.3′N	168°16.0′W	5711
886	44°41.3′N	168°14.3′W	5713
887	54°21.9′N	148°26.8′W	3631

APC core recovered during the entire Ocean Drilling Program, resulting in 398 m of sediment drilled, 411 m recovered. The combination of multiple, long piston cores and clayey sediment at our mid- to high-latitude locations enabled the construction of continuous magnetic reversal stratigraphies down to the middle Miocene at nearly all drill sites. The existence of robust reversal stratigraphies at most sites allowed the regional biostratigraphy to be correlated directly with the geomagnetic polarity time scale, which in some cases represents the first ever such correlation (Barron et al., this volume).

Paleoceanographic results include documentation of the Neogene history of silica and carbonate deposition in the North Pacific. Silica fluxes begin to increase slowly at about 12 Ma, and rise sharply to a maximum occurring between about 6 and 3 Ma. The calcite compensation depth (CCD) in the northwestern Pacific has shoaled by about 1.5 km since the early Miocene, which was a time when the CCD deepened in the rest of the world. The modern CCD is about 2 km shallower on Detroit seamount than it is on Shatsky and Hess rises, only 12° latitude farther south. This is a classic example of CCD shoaling toward regions of high (silica) productivity. Other results include the observation that the middle and later Eocene was a time of significant downslope mass transport of sediment, broadening known the aerial extent of this regional process, that has been well documented from sites in the Central Pacific Basin. No reefal or neritic material was found in any of the downslope-transported sections, indicating that Detroit Seamount was never at sea level (Rea, Basov, Janecek, Palmer-Julson, et al., 1993).

Leg 145 drilling recovered basement basalt from Detroit Seamount at Sites 883 and 884, and from Patton-Murray seamount platform at Site 887. At Site 885/886 a lava flow of basaltic composition was encountered beneath about 10 m of nearly pure, almost black hydrothermal ooze. This rock, probably associated with the formation of a new spreading ridge just to the north at the Chinook Trough, has been dated at 80 m.y. old (Keller et al., this volume). Presumably this extrusive event and subsequent accumulation of hydrothermal materials mark the Late Cretaceous plate-boundary rearrangement, an important event in the evolution of the Pacific Basin (Rea and Dixon, 1983; Mammerickx and Sharman, 1988).

Confirmation of the Meiji sediment tongue as a drift deposit was the major new paleoceanographic discovery of Leg 145. That deposit contains a constant mineralogy (Arnold, this volume) of Siberian origin (Scholl et al., 1977), and diatoms of northern provenance (Barron and Gladenkov, this volume). The Meiji Drift which began forming in the early Oligocene is in all aspects similar to the North Atlantic drifts, except that the pelagic component is siliceous and not calcareous. The existence of this drift deposit is strong evidence for persistent northwest to southeast bottom water flow in this part of the North Pacific during the past 35 million years (m.y.).

SUMMARY OF RECOVERED SEDIMENT AND BASALT

Site 881

Site 881 was drilled in the deep northwestern Pacific in 5531 m of water (Fig. 1, Table 1). The 360 m of sediment penetrated were considered to be a single sedimentary unit with two subunits (Fig. 2). Unit IA, 0–164 m below seafloor (mbsf), is a clayey diatom ooze of late Pliocene and Quaternary age. Important minor components include ash layers and ice-rafted debris (IRD). This unit grades downward over a depth range of about 20 m into Unit IB, 164–364 mbsf, a diatom and radiolarian/diatom ooze of latest Miocene to late Pliocene age. Ash layers and IRD are present in Unit IB but in much lesser amounts than in the overlying unit. Nannofossils are absent or very rare, occurring in about 20% of the samples examined. Planktonic foraminifers occurred in one, and benthic foraminifers in three, of the 52 core-catcher samples. Very good age control is provided by the siliceous microfossils and magnetic reversal stratigraphy.

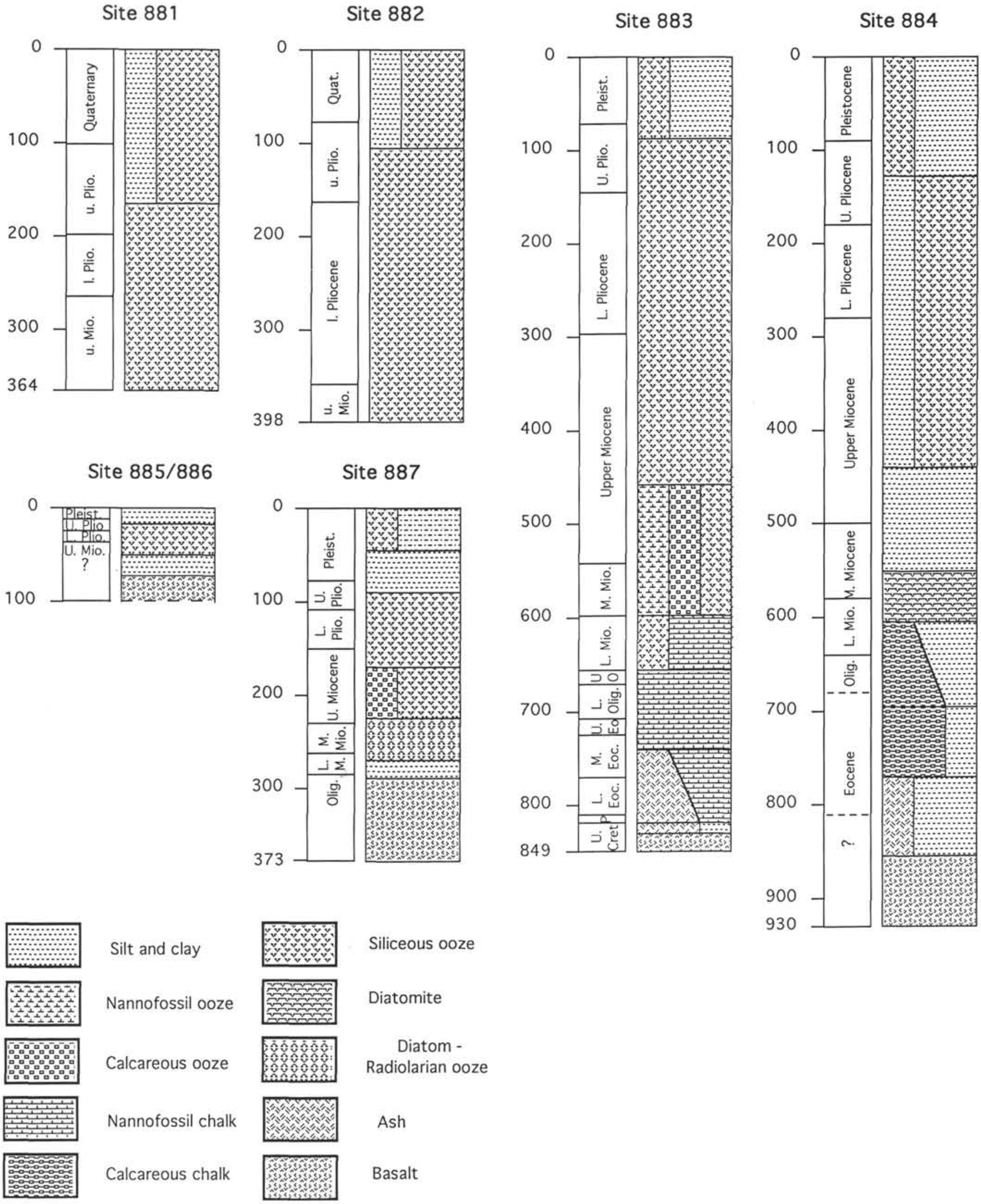

Figure 2. Stratigraphic columns of the Leg 145 drill sites.

Site 882

Site 882 was drilled on the flank of Detroit Seamount in 3244 meters of water (Figs. 1 and 3; Table 1). The 398 m of sediment drilled and recovered at Site 882 are all of a single lithologic unit that can be subdivided into two subunits (Fig. 2). Subunit IA, 0–110 mbsf, is a diatom ooze with ash, clay, and dropstones. Subunit IB is a diatom ooze with accessory nannofossils and sponge spicules; minor amounts of ash occur in the lower part of Subunit IB. Subunit IA is Quaternary to late Pliocene in age and Subunit IB is late Pliocene to late Miocene in age. Chronostratigraphic control is provided primarily by diatom zonation and in some intervals by radiolarians and nannofossils. Magnetic reversal stratigraphy at Site 882 is good in the more clay- and ash-rich Subunit IA. The late Pliocene and Quaternary deposits, Subunit IA, are characterized by higher concentrations of both volcanic ash and terrigenous material (clay and dropstones) than is Subunit IB. Dropstones, however, are far less abundant that they are 500 km to the south at Site 881.

Site 883

Site 883 was drilled on a level plateau near the summit of Detroit Seamount in 2385 m of water (Figs. 1 and 3; Table 1). The six holes drilled penetrated 830 m of sediment and 37.5 m into the basaltic basement below (Fig. 2). The sedimentary column can be divided into five major units. Sedimentary Unit I (0–86.9 mbsf), composed of clay with diatoms and quartz, is late Pliocene to Quaternary in age; the Matuyama/Gauss reversal boundary occurs at 84 mbsf. Accessory dropstones characterize this unit, and ash layers are common. Lithologic Unit II (86.9–458 mbsf) is a nearly pure diatom ooze of late Miocene to late Pliocene age and represents the interval of rapid siliceous sedimentation recorded at nearby drill sites. Calcium carbonate, present in minor amounts above 458 mbsf, becomes an important sedimentary component below that level. Lithologic Unit III is a middle to upper Miocene calcareous diatom ooze in its upper part (Subunit IIIA, 458–597 mbsf) and a lower Miocene diatom nannofossil chalk in its lower portion (Subunit IIIB, 597–655 mbsf). Lithologic Unit IV is an upper Eocene to upper Oligocene nannofossil chalk (Subunit IVA, 655–740 mbsf) grading down to Paleocene to Eocene clayey and ashy nannofossil chalk (Subunit IVB, 740–818 mbsf). Chert nodules of Oligocene to Eocene age occur in the chalk. An unconformity occurs where much of the upper Oligocene material is missing; other hiatuses occur in the Eocene and Paleocene parts of the section. The lowermost portion of this section, Subunit IVB (740–818 mbsf), displays evidence of downslope displacement of sediment. Laminated layers, thin turbidites, scour structures, current ripple marks, soft-sediment deformation structures, and debris flows with matrix-supported clasts of angular ashy chalk all suggest significant redeposition. Partly altered ash and completely altered ash, now seen as yellow palagonite and smectite, become important components of the sediment near the bottom of the section where they makes up Unit V (818–830 mbsf).

About 35 m of basalt was recovered below the sedimentary section in immediately adjacent Holes 883E and 883F. Basement rock is a series of moderately altered pillow basalt grading from moderately to highly plagioclase-olivine microphyric basalt to highly olivine-plagioclase microphyric basalt.

Site 884

Site 884 was drilled on the lower, northeastern flank of Detroit Seamount in 3826 m of water (Figs. 1 and 3; Table 1). Drilling penetrated 854 m of Cenozoic sediment and 87 m of the underlying basalt (Fig. 2). The sediment column can be divided into two main lithologic units, each with subunits. Lithologic Subunit IA, 0–128 mbsf, is a Quaternary to upper Pliocene clay with diatoms. Vitric ash layers, some over 1 m in thickness, and rare dropstones occur in this unit. Subunit IB, 128–440 mbsf, is an upper Pliocene to upper Miocene clayey diatom ooze. Lithologic Subunit IC, 440–550 mbsf, is an upper Miocene to middle Miocene claystone with accessory diatoms and some chalk. Subunit ID, 550–604 mbsf, is a middle Miocene to lower Miocene diatomite with clay. Unit II is differentiated from the overlying materials by the presence of reworked materials. Subunit IIA, 604–700 mbsf, is a lower Miocene to lower Oligocene claystone with minor chalk. This subunit shows evidence of downslope reworked material. Subunit IIB, 700–771 mbsf, is an upper Eocene claystone conglomerate. Diatoms are no longer present in this part of the section, which is dominated by downslope redeposited sediment. Ash layers are present in the lower part of this subunit. Subunit IIC, 771–854 mbsf, is a middle Eocene to upper Paleocene(?) claystone with ash. Native copper occurs as bladed and twinned crystals and as streaks on slickenside surfaces in units as far upcore as Subunit IC (Dickens et al., this volume). Lithologic Unit III, 854–941 mbsf, is basalt that occurs as 13 units, 10 of which are massive flows. Much of the basalt has coarse phenocrysts; fresh olivine is found in the lower 50 m of the recovered section. Keller et al. (this volume) have dated these basalts at 81 Ma.

Site 885/886

Site 885/886 was drilled in 5713 m of water in a sediment pond about 60 km south of the southern margin of the Chinook Trough in the central North Pacific Ocean (Fig. 1, Table 1). Drilling at Sites 885 and 886 encountered 66 and 72 m, respectively, of sediment overlying basalt (Fig. 2). The sedimentary sequence can be divided into three units: clay with diatoms, diatom ooze, and clay. Unit I, 0–17 mbsf, is a Quaternary to upper Pliocene clay with diatoms and spicules. Unit II, 17–50 mbsf, is an upper Pliocene to upper Miocene diatom ooze with clay. Large manganese nodules, both brown and black in color, occur at mid depth in this unit, roughly 40 mbsf. Unit III, 50–66 mbsf, is clay. This unit is the deep chocolate color of the classic North Pacific "red" clays. Lithologic Unit IV, 66–66.5 mbsf, is basalt that has been baked to a yellow-brown color and is recovered only as pieces of rubble. Keller et al. (this volume) have dated the basalt from Site 885/886 at 80 Ma.

Site 887

Site 887 was drilled in 3631 m of water in the Gulf of Alaska on the platform level of the Patton-Murray Seamounts (Figs. 1 and 4; Table 1). Drilling at Site 887 penetrated 289 m of sediment and 84 m into the top of the underlying seamount platform basalt-sediment edifice (Fig. 2). The sedimentary sequence can be subdivided into three units. Unit I, 0–90 mbsf, is a Quaternary to upper Pliocene siliceous silty clay (Subunit IA, 0–45 mbsf) and clay (Subunit IB, 45–90 mbsf). Dropstones are numerous and ash layers common in Unit I. Unit II, 90–270 mbsf, is an upper Pliocene to middle Miocene siliceous ooze with rare carbonate. Unit II can be subdivided into three subunits. Lithologic Subunit IIA, 90–171 mbsf, is effectively a pure diatom ooze of Pliocene age. Subunit IIB, 171–236 mbsf, is an upper Miocene calcareous diatom ooze, and Subunit IIC, 236–270 mbsf, is a middle Miocene siliceous ooze. Lithologic Unit III, 270–289 mbsf, is a sparsely fossiliferous clay presumably of early Miocene age that overlies basalt. Hole 887A recovered several meters of basaltic pea gravel in a clay slurry at the base of Unit III. Unit IV, 289–373 mbsf, is basalt that, from drilling, appears to occur in flows or sills interbedded with at least two layers of sediment.

PALEOGENE PALEOCEANOGRAPHY

Late Paleocene to Early Oligocene Isotopic Record

The Paleogene section of the northwestern Pacific was continuously cored three times at Detroit Seamount, once with the XCB bit (Hole 883B) and once by standard rotary drilling (Hole 883E). At Hole 884B, the Paleogene section was cored using the XCB bit (Fig.

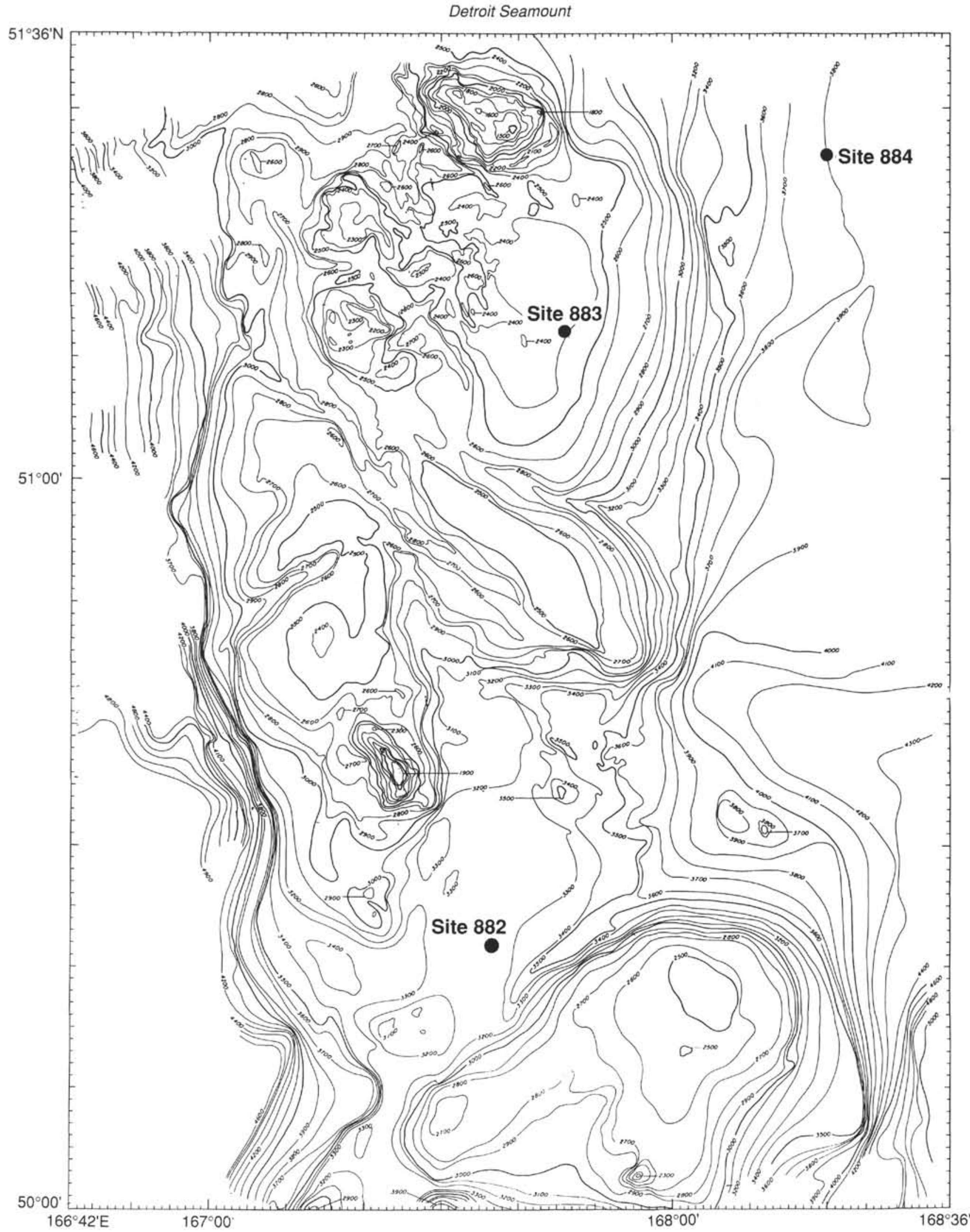

Figure 3. Bathymetric map of Detroit Seamount showing locations of Sites 882, 883, and 884. (Contouring by C. Brenner.)

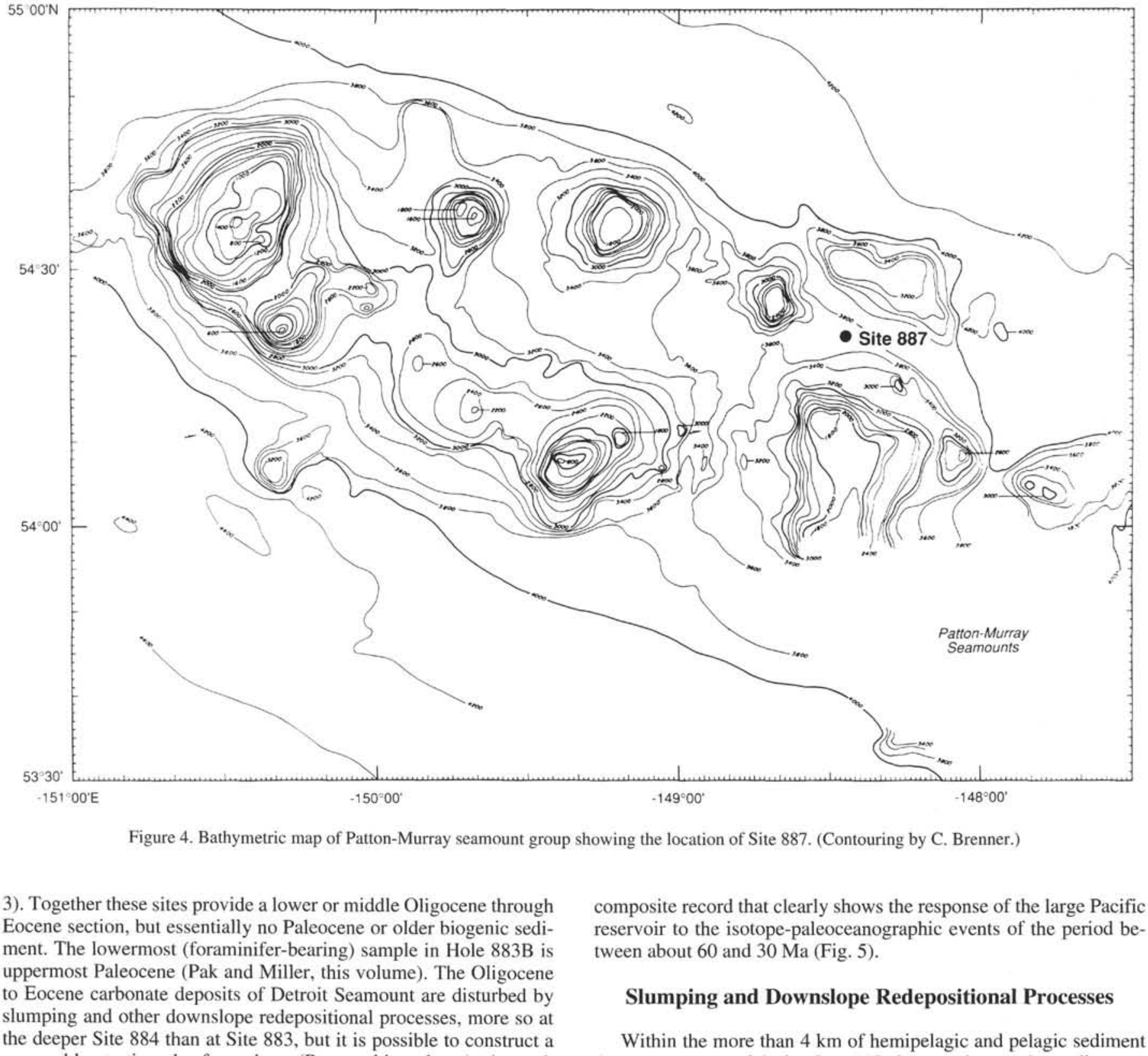

Figure 4. Bathymetric map of Patton-Murray seamount group showing the location of Site 887. (Contouring by C. Brenner.)

3). Together these sites provide a lower or middle Oligocene through Eocene section, but essentially no Paleocene or older biogenic sediment. The lowermost (foraminifer-bearing) sample in Hole 883B is uppermost Paleocene (Pak and Miller, this volume). The Oligocene to Eocene carbonate deposits of Detroit Seamount are disturbed by slumping and other downslope redepositional processes, more so at the deeper Site 884 than at Site 883, but it is possible to construct a reasonable stratigraphy from them (Basov, this volume). As such they provide the northernmost paleoceanographic record of mid-depth waters for the large Paleogene Pacific Ocean.

Pak and Miller (this volume) have analyzed benthic foraminifers *Nuttallides* and *Cibicidoides* from Sites 883 and 884 for oxygen and carbon isotopes (Fig. 5). The combined records from the two sites show characteristic paleoceanographic signatures, including (1) the large shift in oxygen and carbon isotopic values associated with the Paleocene/Eocene boundary; (2) the light $\delta^{18}O$ values (indicating warmth) associated with the early Eocene; (3) the cooling step that occurs at the early/middle Eocene boundary; and (4) the large positive shift in $\delta^{18}O$ values that occurs in the earliest Oligocene and denotes the onset of Antarctic glaciation (Pak and Miller, this volume). Planktonic foraminifer assemblage information also defines the early Eocene as being the warmest interval within the entire Paleogene section (Basov, this volume).

The most complete Paleogene isotope record from the North Pacific is from Site 577 on southern Shatsky Rise (Miller et al., 1987), about 2200 km to the southwest of Detroit Seamount. Pak and Miller (this volume) combine the three records to construct a North Pacific composite record that clearly shows the response of the large Pacific reservoir to the isotope-paleoceanographic events of the period between about 60 and 30 Ma (Fig. 5).

Slumping and Downslope Redepositional Processes

Within the more than 4 km of hemipelagic and pelagic sediment that were recovered during Leg 145, the most impressive sedimentary structures were those documenting sediment mass transport events in the vicinity of Detroit Seamount (Fig. 6). At Site 883, which is the shallowest site occupied on Detroit Seamount, redeposited sediment forms the lower to middle Eocene lithologic Subunit IVB, which lies in the depth interval 740–814 mbsf. At Site 884, the deepest site occupied near Detroit Seamount, redeposited sediment is more than twice as thick and forms the Eocene and Oligocene section of Lithologic Unit II, which lies at 604–771 mbsf. The oldest sediment recovered at Site 882, the intermediate depth site on Detroit Seamount, was late Miocene in age and showed no evidence of mass transport events.

At both Sites 883 and 884, evidence for mass movements is more abundant and the apparent volume of the mass movements are greater in the lower half of the reworked interval. At Site 883, the interval from 740 to 770 mbsf contains nannofossil chalk with discontinuous occurrences of centimeter-scale recumbent folds, scoured surfaces, and microfaults. The interval from 770 to 814 mbsf, in contrast, consists of carbonate turbidite beds and extensively deformed chalks with chalk and claystone intraclasts. Less than 10% of this interval

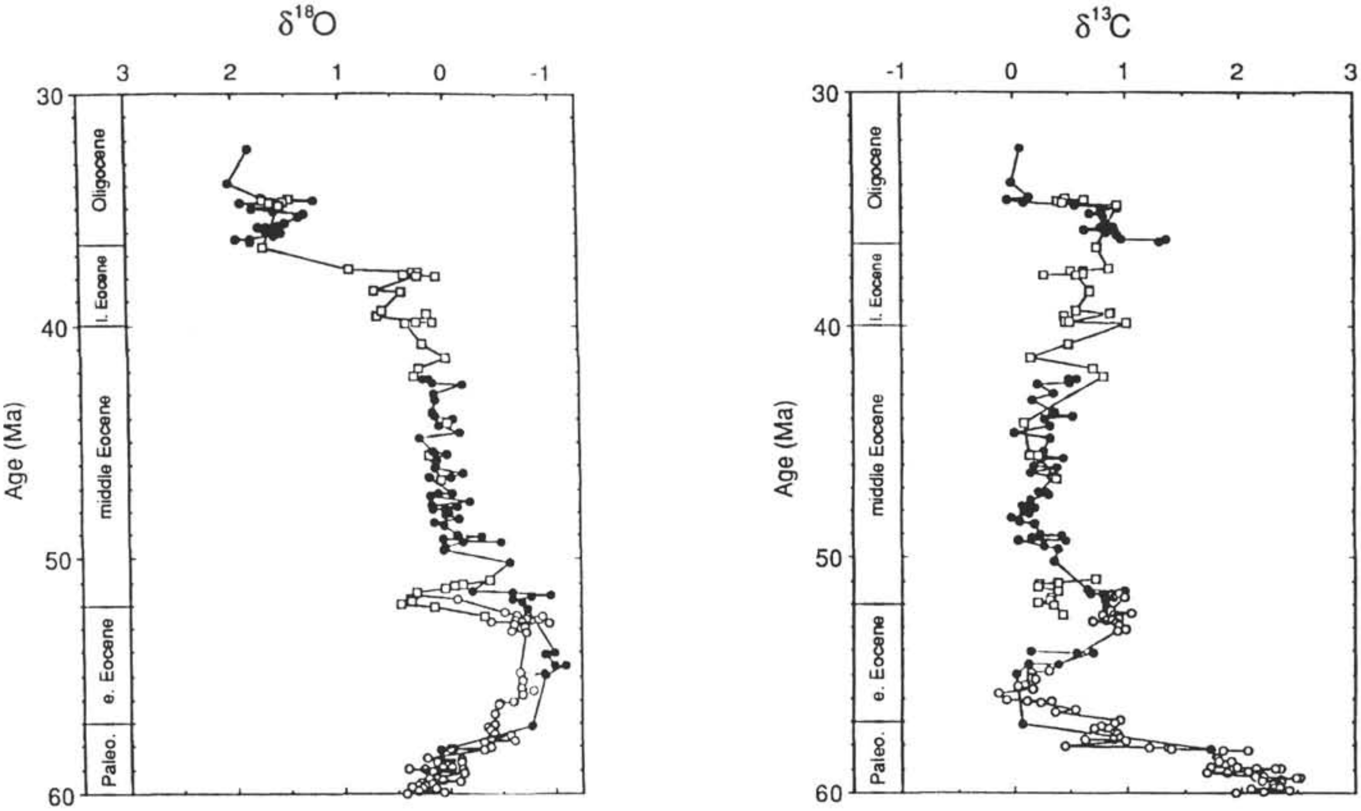

Figure 5. Oxygen and carbon isotope values of benthic foraminifers from Sites 883 (solid dots), 884 (open squares), and 577 (open circles). (From Pak and Miller, this volume.)

can be interpreted as not being redeposited. Claystone intraclasts in the deformed chalk are matrix-supported, red to brown in color, generally angular and tabular in shape, up to 8 cm in length, and have well-defined outlines. Some of the claystone intraclasts retain carbonate-filled burrows produced by bioturbation prior to reworking. These characteristics suggest that the claystone clasts have been transported only a short distance. The clasts are interpreted to have been eroded from intervals of consolidated altered volcanic ash, similar to those observed lower in the stratigraphic sections at the Detroit Seamount sites. The chalk matrix is similar to the overlying, less-disturbed material, but shows well-developed convolute laminations, suggesting emplacement by a highly viscous flow mechanism. The boundaries of individual flows are difficult to identify within this interval, but the vertical spacing of bioturbated ashy horizons (assumed to be in place), the spacing between clast concentrations, or the thickness of intervals with consistent clast orientations may provide some indications of flow thickness. The average spacing between these various types of indicators is 1–2 m or less, suggesting that this interval at Site 883 was deposited by a series of small, locally derived, viscous flows.

Although the overall thickness of redeposited sediment at Site 884 is more than twice the thickness of the redeposited sediments at Site 883, the general downhole increase in the abundance and size of mass-displacement structures is evident at both sites. At Site 884, the interval from 604 to 700 mbsf contains discontinuous and small-scale features, such as microfaults, parallel and convolute laminations, and microload structures. Small claystone intraclasts were first observed at approximately 700 mbsf, and intraclasts and larger scale features indicating redeposition are abundant between 730 and 771 mbsf (Fig. 6). As at Site 883, the surfaces of individual flows are not clearly defined; however, the presence of a 25-cm-thick nose of a recumbent fold and a 40-cm-thick nannofossil chalk intraclast suggest that flow thicknesses were also on the order of 50 cm to 2 m at Site 884.

The redeposited units recovered at Detroit Seamount are composed of pelagic sediment components (nannofossil chalk and claystone), mixed with varying amounts of volcanogenic constituents. Cook et al. (1976) recognized similar compositional variations in redeposited sediment recovered along the Line Islands during DSDP Leg 33, and grouped those sediments on the basis of both composition and physical structures. The sediment recovered at Detroit Seamount fall within three of the categories identified by Cook et al. (1976): graded units composed of only pelagic constituents, graded units composed of pelagic sediment plus minor to moderate volcanogenic material, and slumped/folded/parallel-laminated zones with a mixture of pelagic and moderate to abundant volcanogenic sediment. The first two categories represent sediment deposited by rapid, low-viscosity flows (i.e., turbidity currents), whereas the latter category represents sediment deposited by relatively slow, high-viscosity flows (i.e., slumps and/or debris flows).

The redeposited sediment at Detroit Seamount provides useful insights into the physical nature of sedimentation in that area during the Eocene, but the timing of this redeposition event also presents an interesting point for comparison with other sites in the Pacific. For example, Lithologic Unit III at ODP Site 802 in the Mariana Basin is composed of lower Miocene to upper Paleocene nannofossil chalks, with abundant graded beds, reworked nannofossils, and a 5.5-m-thick bed of redeposited material that contains horizontally sheared nannofossil chalk and abundant claystone intraclasts. Regional isopach patterns suggest that the source of the redeposited material was a shallow-water region (seamount), perhaps located to the northeast of Site 802 (Lancelot, Larson, et al., 1990). Less-obvious evidence for sediment redeposition during the Eocene was observed at Site 810 on the Shatsky Rise, where Lithologic Unit IV consists of upper Paleocene to lower Eocene nannofossil ooze that exhibits contorted bedding and size sorting (Storms, Natland, et al., 1991). Additional evidence for sediment reworking during the Eocene is described by Thiede

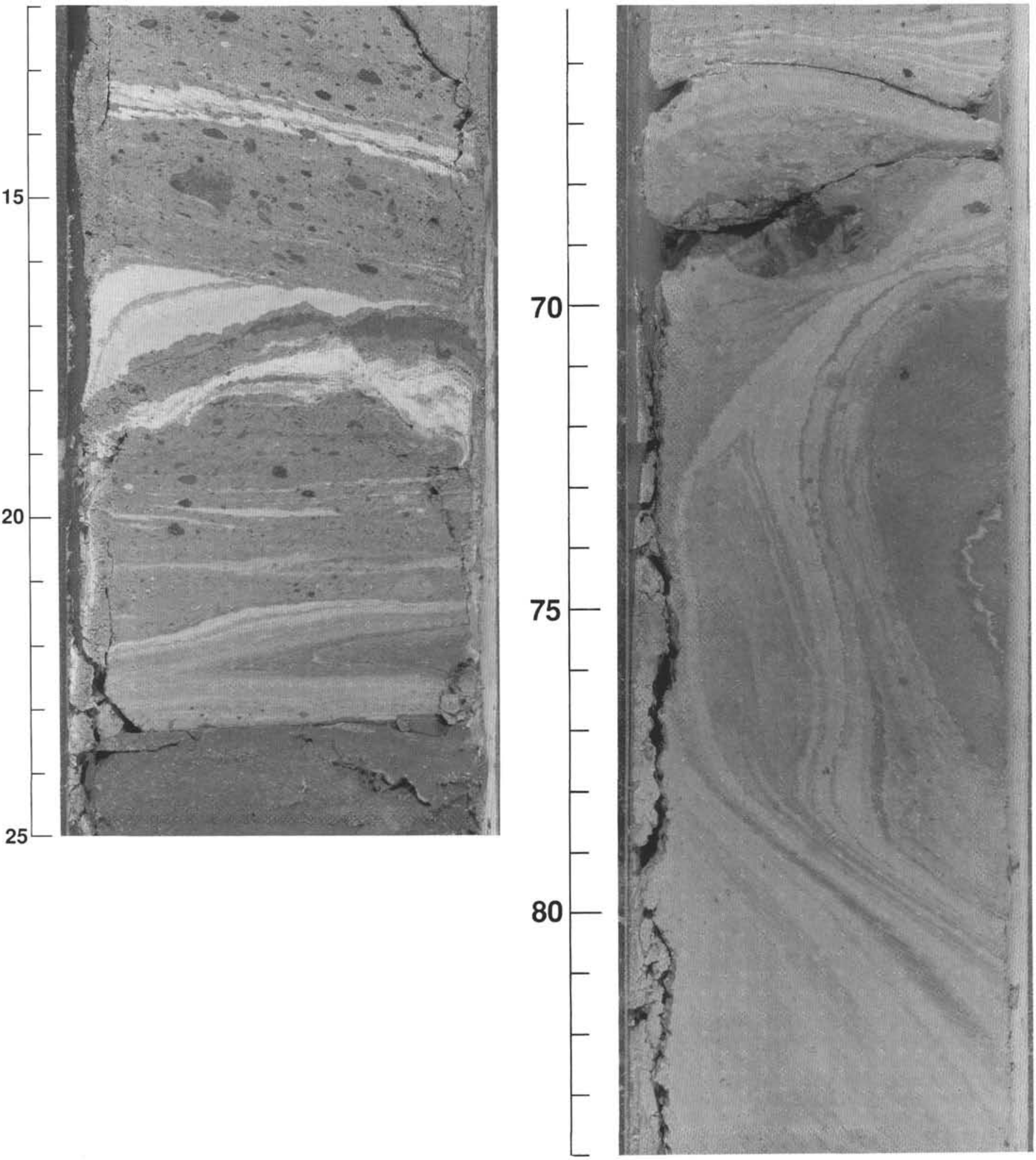

Figure 6. Sedimentary structures in the downslope transported sediments of Site 884. Left: Core 884B-81X-5, 12–25 cm, showing matrix-supported clasts at 11–16 cm, truncations at 16–17 cm, and a recumbent fold at 22–23 cm. Right: Core 884B-83X-3, 65–84 cm, showing the nose of a large recumbent fold.

(1981a, 1981b) from the occurrences of shallow-water (neritic) fossil debris in sediment recovered from deep-sea localities in the central and western Pacific.

The widespread geographic distribution of these redeposited sediments suggests that regional-scale mechanisms may have been responsible for displacing sedimentary masses during the Eocene. The pelagic nature of the biogenic component in the redeposited sediments argues against a lowered sea level as a possible explanation. Another possible cause for enhanced sediment instability is increased seismic activity, perhaps associated with increased rates of volcanism; an analogous explanation has previously been used to explain the abundance of redeposited Cretaceous sediment in the Pacific Basin (Schlanger and Premoli Silva, 1981). The early and middle Eocene was a time of significant tectonic activity in the northwestern Pacific Basin, including large shifts in the rate and direction of plate convergence (Rea and Duncan, 1986), the counter-clockwise rotation and eventual demise of the Kula-Pacific spreading center (Lonsdale, 1988), and the construction of the Aleutian volcanic arc (Scholl et al., 1987). Kennett et al. (1977) have identified the Eocene as a time of increased volcanic activity around the Pacific Basin; at Sites 883 and 884 this increase is recorded by the abundance of smectite-rich claystones, which probably represent altered volcanic ashes.

CALCITE COMPENSATION DEPTH IN THE NORTHWEST PACIFIC

The long-term history of the calcite compensation depth (CCD) in the Pacific Basin is well known for equatorial regions (Berger, 1973; van Andel and Moore, 1974; van Andel et al., 1975) and adequately known in the southeast Pacific (Rea and Leinen, 1985). Because of the lack of information there has been no reconstruction of the CCD history for the temperate or subpolar North Pacific. Beneath the equator, the CCD is about 600 m deeper than the general nonequatorial depth of 4100 to 4400 m (van Andel et al., 1975; Berger et al., 1976). The general history of the compensation depth displays a shallow CCD in the latest Cretaceous and early Tertiary, a deepening of 1000 to 1500 m at the Eocene/Oligocene boundary, a rise of as much as 500 m through the late Oligocene to a relative high in the early to middle Miocene, and a deepening of 300 to 400 m over the past 10 or 15 m.y. (Berger, 1973; van Andel and Moore, 1974; Rea and Leinen, 1985). Here we compare the CCD history derived from ODP drill sites in the far northwest Pacific to that for most of the Pacific Basin.

Three of the Leg 145 sites (882, 883, and 884) form a depth transect down the slopes of Detroit Seamount from 2385 m at Site 883 to 3244 m at Site 882 and 3826 m at Site 884. Site 881, about 350 km to the southwest, lies on the floor of the abyssal northwest Pacific at a depth of 5531 m (Fig. 1). One of the important goals of the leg was to conduct a depth transect at Detroit Seamount for the purpose of obtaining carbonate sediment and foraminifers as the basis of understanding the geological history of intermediate-depth waters in this region of the world ocean. In pursuit of this objective, drill holes at Sites 883 and 884 were cored continuously through the approximately 850 m of sediment to volcanic basement. Site 882, the intermediate depth site, was cored to a depth of about 400 mbsf.

Subsidence curves for the northwest Pacific sites are determined in the normal manner, using the relationship between the amount of subsidence and the square root of age: $\Delta z = k(t)^{1/2}$, where z is depth in kilometers and t is age in millions of years. The subsidence parameter, k, determines the rate of the subsidence and, for normal seafloor, falls in the range of 0.3 to 0.35. A useful discussion of this methodology can be found in Rea and Leinen (1986a). Detroit Seamount was erupted seafloor of the age of the Cretaceous magnetic quiet zone, perhaps 110 m.y. old, about 30–40 m.y. after its formation. Most of the thermally controlled seafloor subsidence would have already occurred at the time of seamount emplacement, so the rate of subsequent subsidence for Detroit Seamount sites, and so also the subsidence parameter, is relatively low. Determination of useful subsidence curves entails knowing initial depth and age. For the Detroit Seamount we assumed an eruptive age of 70 Ma based on Leg 145 onboard biostratigraphy and on the age of nearby Meiji Seamount (Creager, Scholl, et al., 1973). The radiometric age of 81 Ma determined by Keller et al. (this volume) for the basement basalts of Site 884 change the subsidence history very little, especially as essentially no Cretaceous sediment occurs on Detroit Seamount. Initial depths are constrained by the conclusion that the shallowest part of the seamount never reached sea level, yet was shallower than 500 m. This interpretation is based on the lack of shallow-water or reefal debris in any of the sediment units that accumulated by downslope redeposition, and paleodepths indicated by benthic foraminifer assemblages of the redeposited sediments.

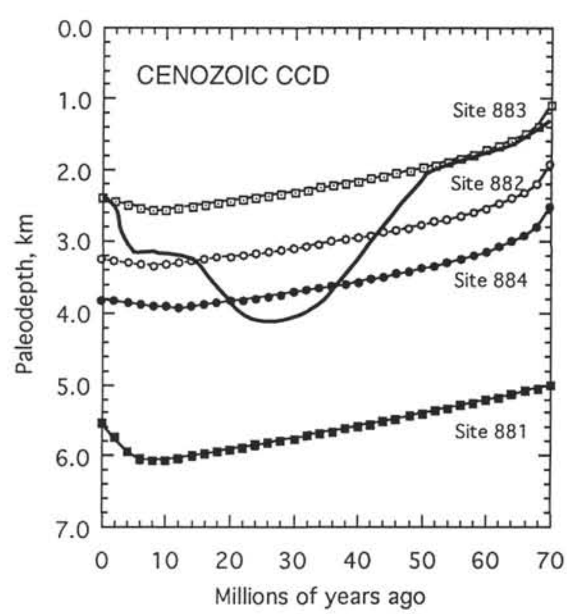

Figure 7. Age vs. depth curves for the northwestern Pacific drill sites (Leg 145) and the level of the CCD.

Site 883 is about 900 m deeper than the shallowest point on the seamount and so has been assigned an initial depth of 1100 m. Sites 882 and 884 are assigned initial depths according to their present (unloaded) basement depths in relation to that at Site 883 (Table 1). For Site 881 we have assumed a rather standard paleo ridge-crest depth of 2800 m. Correcting for sediment loading has been calculated using a simple two-rate model, earlier slow sedimentation succeeded by faster sedimentation, with the large sediment rate increase occurring in the middle Miocene. Because simple isostatic models demonstrate that basement is depressed by an amount equal to half the sediment thickness, the actual seafloor depth is reduced by only half of the sediment thickness (Berger, 1973; Rea and Leinen, 1986a). For the three Detroit Seamount sites, the sedimentation rate since the middle Miocene is more than twice the subsidence rate so the depths get shallower. At Site 881, recent shallowing is a result both of increased sedimentation rate and of the site being on the outer rise of the Kuril Trench. The resulting age-depth curves are plotted on Figure 7.

CCD in the Present Northwest Pacific

The upper sedimentary unit at Site 883, a gray clay with quartz and diatoms, contains 0% to 5% calcium carbonate, and most samples contain a few foraminifers. We conclude that Site 883, at its depth of 2385 m, lies at the present northwest Pacific CCD. The nearest drill sites (Site 192 on Meiji Seamount at 3014 m depth and Site 882 at 3244 m depth) are clearly below the CCD (Creager, Scholl, et al., 1973; Rea, Basov, Janecek, Palmer-Julson, et al., 1993). This observation means that the CCD is significantly shallower in the far northwestern Pacific than it is in the central gyre region. Shatsky Rise (Site 306 at 3399 m) and Hess Rise (Site 310 at 3516 m) both are characterized by silica-bearing nannofossil ooze of 60%–70% $CaCO_3$ (Larson, Moberly, et al., 1975; Dean, 1981). The northernmost site on Hess Rise, Site 464, at 39.9°N in a water depth of 4670 m, contains 11% $CaCO_3$ in its uppermost siliceous ooze unit (Thiede, Vallier, et al., 1981; Dean, 1981), twice as much as occurs at Site 883, only 1250 km to the north at 51.2°N and almost 2300 m shallower. Site 433, on Suiko Seamount in the Emperor Seamounts south of Detroit Seamount, at 44.7°N in a water depth of 1862 m, has 52 m of lower Miocene to Pleistocene carbonate ooze—occasionally silica-bearing carbonate ooze—on top. Site 433 has been above the CCD throughout its Cenozoic depositional history (Jackson, Koizumi, et al., 1980).

Shoaling of the CCD toward highly productive subpolar regions and coastal upwelling zones, such as those off the west coasts of South America and Africa, is a well known phenomenon in the modern ocean (Berger, 1973, 1989). It occurs because much of the biological productivity in these regions is siliceous material and organic carbon. The ensuing breakdown of the organic carbon enhances the rate of dissolution of calcite produced in these regions, thus raising the CCD to shallow depths. The northward shoaling of the CCD by more than 2 km observed in the North Pacific between about 40°N to 50°N appears to be a good example of this particular kind of productivity/dissolution control of carbonate preservation on the seafloor.

Cenozoic History of the CCD

During the last several million years of the Cretaceous, the Paleocene, and most likely the Eocene, Site 884 lay below the central North Pacific CCD (Fig. 7). Shallower Site 883 displays pelagic carbonates in the Eocene, but perhaps not in the Paleocene or Maastrichtian. These data imply a shallow CCD, perhaps 2 km deep, beneath the North Pacific subtropical gyre for the latest Cretaceous and Paleocene. During Eocene time the CCD is better constrained at a depth intermediate to that of Site 883 and 884, perhaps 2500 to 3000 m paleodepth. At the time of the Eocene/Oligocene boundary, about 35 Ma, the level of the CCD dropped to deeper than 3700 or 3800 m, resulting in the deposition of the Oligocene chalk at Site 884. During the early Miocene the CCD rose above 3700 m in a manner similar to the rest of the Pacific (Berger, 1973; van Andel and Moore, 1974; Rea and Leinen, 1985).

The middle Miocene to Quaternary history of the CCD in the northwest Pacific is markedly different from that in the equatorial and subtropical gyre regions. Since the Oligocene CCD low, common to all oceans, the northwest Pacific CCD has risen 1300 to 1600 m to its present level of about 2400 m. The difference evolved since the middle Miocene when the CCD level began to drop elsewhere in the Pacific but continued to rise in the Detroit Seamount region. If the area of this different behavior is defined by the modern CCD situation, then it is confined to region north of 40°N. Sediment recovered at Site 887 in the northern Gulf of Alaska at a depth of 3631 m indicates a younger shallowing of the CCD, perhaps limited to late Pliocene and Quaternary time, as well. The Site 887 information also suggests that the CCD rises at least 1 km from east to west, not nearly as dramatic a gradient as the latitudinal change observed in the northwestern Pacific. Thus, the CCD history so well displayed at Detroit Seamount seems to characterize all of the northernmost Pacific Ocean.

The timing and location of the regional offset in the CCD implicates the renaissance of deep-water circulation in the middle Miocene as the potential cause of the observed changes. The North Pacific subpolar region, and particularly the northwest corner of the Pacific, presumably became the end of a coherent global deep-water flow path during the middle Miocene. This increased flow of deep water would have brought nutrients and dissolved CO_2 to the North Pacific, resulting in a shallower CCD and high sea-surface productivity beginning in the middle Miocene. Both the shallow CCD and the enhanced productivity that have characterized the North Pacific since the middle Miocene are therefore a dynamic effect of ocean deep-water circulation in the present mode.

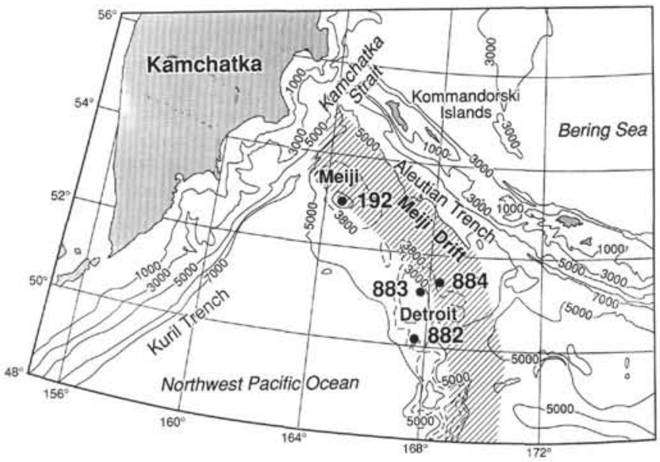

Figure 8. Map of the northwesternmost Pacific showing the location of the Meiji Drift and nearby drill sites. The location of the Meiji Drift is shown by the shading.

MEIJI DRIFT

Documentation of the Meiji sediment tongue as a drift deposit was the major new paleoceanographic discovery of Leg 145. The Meiji sediment tongue lies along the northeast side of the northernmost Emperor Seamounts, Meiji and Detroit (Fig. 8). This deposit is over 1000 km long, about 350 km wide, and is up to 1800 m thick at its northwestern end near the Kamchatka Strait (Fig. 7; Scholl et al., 1977). It was first identified on the sediment thickness maps compiled at Lamont-Doherty Earth Observatory in the 1960s (Ewing et al., 1968) and drilled in 1971 by Leg 19 at Site 192 (Creager, Scholl, et al., 1973). Results of that cruise identified the Meiji sediment accumulation as a deposit formed by sediment-laden currents moving south through the Kamchatka Strait from the Bering Sea to the northwest Pacific (Creager, Scholl, et al., 1973; Scholl et al., 1977). Scholl et al. (1977) documented the Siberian mineralogy of the terrigenous component of this deposit and suggested that its formation began in early Miocene time. Further analysis of seismic reflection profiles from the region allowed Mammerickx (1985) to suggest that the Meiji deposit extended southeast and south along the eastern flank of the Emperors for 2000 km from its origin at the Strait of Kamchatka. She also noted small- (10–100 m) and medium-scale (100–1000 m) features indicative of bottom transport in the region, such as ripple marks, current lineations, pavements, channel-like structures, etc. (Mammerickx, 1985). Mammerickx observed that the Meiji sediment tongue has many features in common with the North Atlantic drift deposits and concluded that it was deposited under the same conditions, by southward-flowing deep-ocean currents.

Our primary objective in drilling Site 884 was to test Mammerickx's hypothesis that the Meiji tongue was a North Atlantic–type drift deposit. We selected a site based on survey data from the U.S. Geological Survey (Fig. 9) where the deposit was expected to be thin enough (less than 800 m thick) to recover it completely. At Site 884 the Meiji Drift forms the upper 695 m of the 854-m-thick sedimentary sequence (Rea, Basov, Janecek, Palmer-Julson, et al., 1993) and is Oligocene to Quaternary in age. The pelagic component of the Miocene to Quaternary portion of the deposit is dominated by diatom ooze,

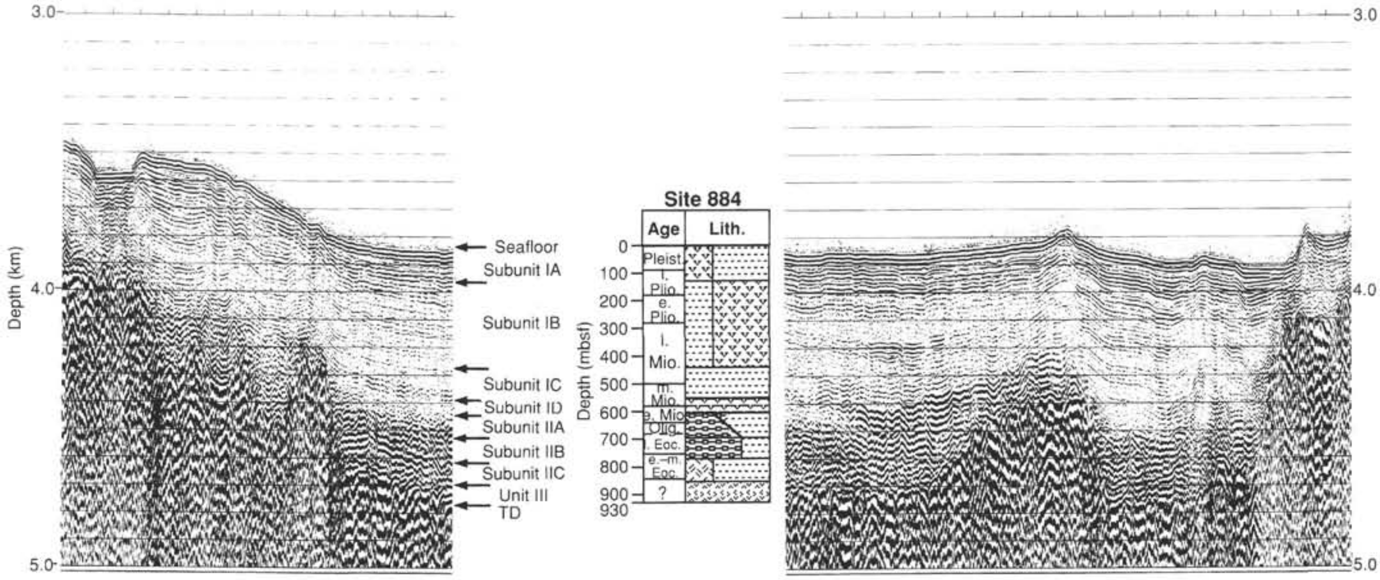

Figure 9. Seismic reflection profile at Site 884 in the Meiji Drift. (Processed by S. Dadisman and D. Scholl of the U.S. Geological Survey.)

with varying amounts of terrigenous silt. Chalk occurs as the pelagic component in the Oligocene portion of the drift. Sedimentation rates of the entire deposit range from low Oligocene values of 6 m/m.y. to high Pliocene values of 60 m/m.y. Corresponding mass accumulation rates (MAR) of the terrigenous component range from 400 to 1400 $mg(cm^2 \cdot k.y.)^{-1}$ (Rea, Basov, Janecek, Palmer-Julson, et al., 1993), which are values that commonly denote hemipelagic sedimentation rates (Rea, 1993, 1994). X-ray diffraction analysis of the sediment recovered at Site 884 showed a remarkably constant composition of the terrigenous component from the sediment surface down to about 685 mbsf (Arnold, this volume; Fig. 10).

A complete sequence of all North Pacific diatom zones from late Quaternary to late Oligocene occurs at Site 884. The intervals between 12.0 and 13.5 Ma and approximately 17.5 to 20 Ma are condensed sections. Shipboard nannofossil biostratigraphy allows definition of the Oligocene/Miocene boundary at 640 mbsf and the Eocene/Oligocene boundary between 680 and 693 mbsf. Stratigraphic control in the upper 600 m of the cored section is greatly enhanced by a magnetic reversal stratigraphy coherent back to about 13.5 Ma. The diatom assemblage at Site 884 includes an Arctic-boreal component characteristic of portions of the Bering Sea the late Miocene. Additionally, a benthic form that lives only in the shallow waters of the Aleutian-Bering region occurs consistently, although in low abundance, throughout the drift deposit. These unusual diatom occurrences indicate relatively long-distance, generally southerly transport of the containing sediment (Barron and Gladenkov, this volume).

The Leg 145 drilling at Detroit Seamount confirmed the suggestions of Scholl et al. (1977) and Mammerickx (1985) that the Meiji tongue is the result of deposition by southerly flowing bottom currents moving south from the Bering Sea. This depositional process began at the time of the Eocene/Oligocene boundary, which is identical in timing to its North Atlantic drift-current cousins (Kidd and Hill, 1987). Our discovery means that there has been a continuous, 35-m.y. history of bottom waters entering the deep North Pacific from the Bering Sea, with all its attendant consequences for the requisite physical oceanography and abyssal flow pathways.

Flow is southerly through the Kamchatka Strait (Fig. 8) and occurs as a result of shallower inflow to the Bering Sea from the Alaska Gyre along the eastern and central Aleutians. Today there is a seasonally varying flow of 10 to 20 Sv (1 Sv = 10^6 m^3/s) moving south out of the Bering Sea through the 4200-m-deep Kamchatka Strait at average speeds of up to 90 cm/s (Arsenjev, 1967; Verkhunov and Tkachenko, 1992; Taft et al., 1993). Chemistry of the deeper waters of this flow link it to surficial waters in the Bering Sea (Taft et al., 1993). For comparison, North Atlantic Deep Water (NADW) forms at rates of 15 to 20 Sv (Schmitz and McCartney, 1993) and current speeds in the deep flows along the western boundary of the North Atlantic Basin are in the range of several tens of centimeters per second (Richardson et al., 1981; Pickering et al., 1989).

Backtracking Site 884 along the Hawaiian trend for the past 35 m.y. places it at about 40°N and 165°W in early Oligocene time (Rea and Duncan, 1986). Mineral fluxes in the Oligocene portion of the section are about 400 $mg(cm^2 \cdot k.y.)^{-1}$, 20 to 40 times greater than mid-Cenozoic eolian fluxes to the ocean (Janecek and Rea, 1983; Janecek, 1985; Snoeckx et al., this volume); hence, the Meiji deposit is clearly hemipelagic in origin. The question thus arises how such long-distance hemipelagic transport can be accomplished. One possibility is that the northwestward continuation or extension of the Hawaii-Emperor Ridge acted as bathymetric a flow guide for North Pacific thermohaline circulation, diverting bottom water flowing south from the Bering Sea to the southeast along the proposed (now subducted) Meiji extension. If so, the history of the Hawaii-Emperor-Meiji Ridge, hence the life of the Hawaiian hot spot, is extended by about 40 m.y.

The assembled data suggest that the deposition of the Meiji Drift was occurring by early Oligocene time. Northern-source minerals and diatoms have accumulated at moderate to high rates, generally increasing throughout the middle and late Cenozoic, in an elongate deposit on the northeast flank of the northwest or Meiji extension of the Emperor Ridge. The supply of terrigenous material increased markedly at times of known climate change in the middle Miocene and late Pliocene and thus may be related to the enhanced physical erosion of the North Pacific rim caused by deterioration of climate in those regions. Work in eastern Kamchatka by Gladenkov and Shantser (1989) and Gladenkov et al. (1991) has shown that the beginning of the middle Miocene and the latest Pliocene are marked by erosion and subsequent accumulation of thick conglomerates

The early Oligocene onset and continuing deposition of the Meiji Drift entails important consequences to the physical oceanography of the North Pacific. Southerly flow of bottom waters from the Bering Sea into the North Pacific basin has been occurring for at least 35 m.y. Presumably this flow has been controlled geographically by the location of deep western passages through the Aleutian Ridge. At present, and perhaps since the last important change in direction and

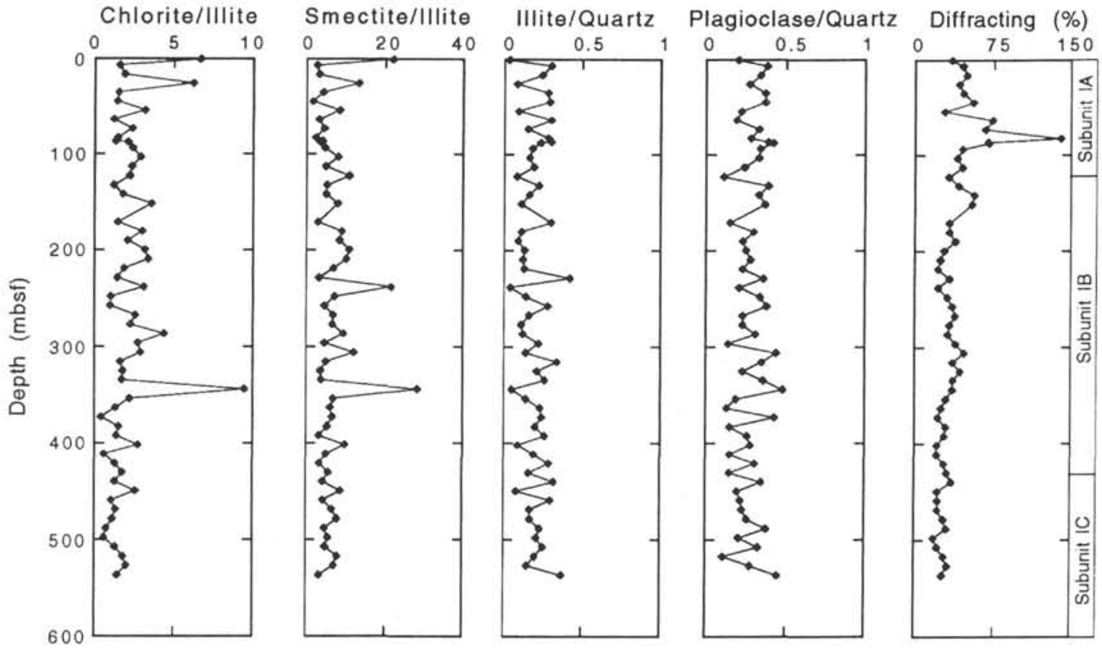

Figure 10. Mineralogy of the 2- to 20-μm terrigenous component of sediments recovered from the Meiji Drift at Hole 884B. The uniform composition suggests an unchanging source of the sediment. (From Arnold, this volume.)

rate of plate convergence in the region in Eocene time (Rea and Duncan, 1986), the deep passage is at the western end of the Aleutian chain, the Kamchatka Strait. At present the dominant transform plate boundary at the western end of the Aleutian Trench lies along the northern side of the Aleutian Ridge, so the Kommandorski Islands (Fig. 8) are moving toward Kamchatka with the Pacific plate (Geist et al., 1994; Geist and Scholl, 1994). This process will probably close the Strait of Kamchatka within 1 or 2 m.y. In all likelihood there has been one or a series of deep passages though the former western Aleutian Ridge, all of which are now subducted beneath (collided with) Siberia.

The basins of the Bering Sea serve as catchments for the voluminous clastic detritus, mostly turbidites that derive from Siberia and Alaska, allowing a bypassing of the finer, hemipelagic component to the North Pacific. Without such a large catchment basin, the clastic debris entering the northwest Pacific directly from North America and Siberia would have formed vast turbidite abyssal plains similar to those of the Gulf of Alaska.

In a broader sense, the onset of drift deposition in the North Pacific at generally the same time as in the North Atlantic suggests a similar oceanographic and probably climatic setting. The paleolatitude and paleodepth of the Bering Sea and the basins between the Iceland-Faeroes Ridge and the Charley-Gibbs Fracture Zone are quite similar. Pelagic sediment in the North Atlantic is more calcareous, but the mid-Tertiary supply of clastic sediment appears to have been greater in the North Pacific. The response of both of the northern oceans to the onset of Southern Hemisphere glaciation in the earliest Oligocene seems to involve a fundamental change in deep circulation. It remains a fruitful area of research.

NEOGENE OPAL DEPOSITION, THE "SILICA SWITCH," AND PALEOPRODUCTIVITY

Silica Switch

One of the important objectives of Leg 145 was to further quantify the nature and timing of silica deposition in the northernmost Pacific. Over a decade ago Keller and Barron (1983), in a stratigraphic overview of extant Neogene DSDP sites, outlined the "silica switch"—

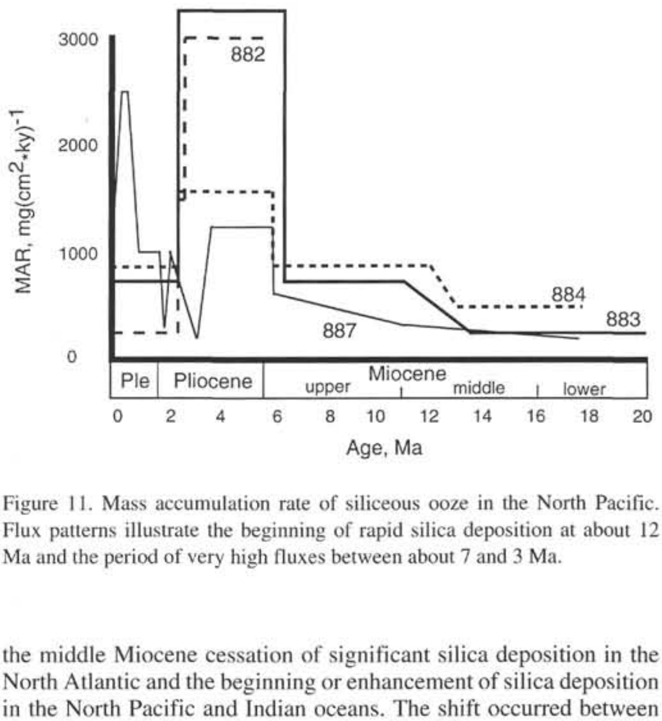

Figure 11. Mass accumulation rate of siliceous ooze in the North Pacific. Flux patterns illustrate the beginning of rapid silica deposition at about 12 Ma and the period of very high fluxes between about 7 and 3 Ma.

the middle Miocene cessation of significant silica deposition in the North Atlantic and the beginning or enhancement of silica deposition in the North Pacific and Indian oceans. The shift occurred between about 15 and 12 Ma on the time scales of both Berggren et al. (1985) and Cande and Kent (1992). The information assembled by Keller and Barron (1983) is the relative abundance data provided by smear-slide descriptions made by the shipboard sedimentologists on the *GLOMAR Challenger*.

We determined the mass accumulation rate of opal at each of the Leg 145 drill sites (Rea, Basov, Janecek, Palmer-Julson, et al., 1993; Fig. 11); more detailed accumulation rate studies have been carried out on the diatom oozes of Site 882 (Haug et al., this volume; Maslin et al., this volume), at Site 885/886 (Snoeckx et al., this volume), and in the northeast Pacific at Site 887 (Rea and Snoeckx, this volume). Site 883 is probably most representative of the northwest Pacific, as it has a much longer record than either Site 881 or 882 and it is not influenced by the deep-ocean processes that deposited the Meiji Drift. At Site 883, Oligocene and older sediment is calcareous in its pelagic component. Opal input in percent becomes an important, although still minor, part of the sediment beginning in the early Miocene and becomes the dominant component by about 16 Ma. The MAR of biogenic opal at Site 883 is low, perhaps 200 $mg(cm^2 \cdot k.y.)^{-1}$, prior to about 14 Ma. At about 12 Ma the first of two large flux increases to about 700 $mg(cm^2 \cdot k.y.)^{-1}$ takes place. In the latest Miocene, at 6.8 Ma, the flux of opal increases to over 3000 $mg(cm^2 \cdot k.y.)^{-1}$ and remains high until about 2.6 Ma (Fig. 11). At the onset of major Northern Hemisphere glaciation at 2.6 Ma, silica fluxes at Site 883 return to about 700 $mg(cm^2 \cdot k.y.)^{-1}$. This two-step increase in silica flux is mimicked at Site 884, with an earlier increase at roughly 12 Ma and a later one at 6.2 Ma, declining at 2.6 Ma. The high-resolution record from Site 882 (Haug et al., this volume) is not old enough to define the onset of the latest Miocene silica pulse, but shows the end of that episode very well. At this site silica fluxes decline from about 3000 $mg(cm^2 \cdot k.y.)^{-1}$ to about 200 $mg(cm^2 \cdot k.y.)^{-1}$ at 2.75 Ma. In the northeast Pacific at Site 887, silica fluxes are low, about 200 $mg(cm^2 \cdot k.y.)^{-1}$, prior to 11 Ma but ramp up to 600 $mg(cm^2 \cdot k.y.)^{-1}$ at 6.0 Ma and reach a maximum from about 6 to 3.5 Ma (Rea and Snoeckx, this volume). Site 885/886, situated beneath the oligotrophic gyre, records an increase in opal accumulation at about 8 Ma and a relative maxima at 3.5 to 2.5 Ma (Snoeckx et al., this volume).

The overall picture presented by these results is as follows. The North Pacific changes from a carbonate-depositing ocean to a silica-depositing ocean beginning in the early Miocene. By the beginning of the middle Miocene carbonate is virtually absent from all but the shallowest regions. The mass flux of silica to the seafloor, however, remains low until the middle of the middle Miocene when values in the northwest Pacific increase by a factor of two to three at about 12 Ma. This increase may be more gradual and begins slightly later in the northeastern Pacific. In the latter part of the late Miocene, between 7 and 6 m.y. ago, the mass accumulation rate of silica increases greatly all across the North Pacific. This pulse of high silica flux ends suddenly and dramatically 2.75 m.y. ago, as the oceanic regime enters the glacial mode.

Biogenic Fluxes and Paleoproductivity

By far the dominant biogenic component of the northern Pacific Miocene and younger sediment is opaline silica, and the mass accumulation rate of opal is assumed to be a reliable record of past sea-surface biological productivity. All sites show a maxima in silica deposition rates during the late Miocene and early Pliocene, extending into the late Pliocene. In the northwest Pacific, this rapid accumulation rate of opal declined to much lower values at or just before the onset of major Northern Hemisphere glaciation. Maslin et al. (this volume) and Haug et al. (this volume) show at Site 882 a decline in opal flux from about 3000 $mg(cm^2 \cdot k.y.)^{-1}$ to a few hundred $mg(cm^2 \cdot k.y.)^{-1}$ (Fig. 11). Calcite fluxes also decline, and the flux of organic carbon is reduced several fold after the ice buildup event at about 2.6 Ma. Rea and Snoeckx (this volume) in their examination of sediment fluxes at Site 887 in the Gulf of Alaska find a several fold decline in the mass accumulation rate of opal at about 2.8 Ma. Site 885/886 beneath lower productivity waters, also shows a two-fold decline in silica flux at about 2.6 Ma. Fluxes generally stay at their new lower values throughout the late Pliocene and Quaternary in the central and western North Pacific, but increased during the last million years in the Gulf of Alaska to the highest values of the last 18 m.y. (Rea and Snoeckx, this volume).

The obvious decline in sea-surface biological productivity that just precedes or accompanies the onset of major Northern Hemisphere glaciation at 2.6 Ma must somehow reflect a significant decline in the delivery of nutrients to the northwestern Pacific. Because we know that fluxes of materials from the continents (both IRD and hemipelagic sediment) have increased greatly beginning at 2.6 Ma, and that the input of eolian dust also increased several-fold higher beginning 3.5 to 3.8 Ma (Snoeckx et al., this volume; Arnold et al., this volume), we conclude that most of the nutrients fertilizing phytoplankton growth in the northwest Pacific are not derived from the surrounding land masses. The other source of nutrients is the diffuse upwelling of ocean deep and bottom waters originating in the North Atlantic and in the Southern Ocean that occurs in the North Pacific at the end of the global transport pathway (Dodimead et al., 1963; Broecker et al., 1988). These old waters are nutrient- and CO_2-rich and oxygen poor, corrosive to calcium carbonate and, when they reach the surface, conducive to high biological productivity. The onset of major Northern Hemisphere glaciation at 2.6 Ma resulted in the suppression of NADW formation (Sikes et al., 1991; Raymo et al., 1992). (North Atlantic ice cover during glacial regimes inhibits the sea-surface cooling. Further, the more southerly course of the North Atlantic drift current during glacial regimes results in less salt delivered to high latitudes. The combination of less salt and inhibited cooling serves to reduce the formation rate of deep waters in the Norwegian and Greenland seas during times of glacial advance.) The reduction in NADW formation slowed the advection of deep-water nutrients to the North Pacific and resulted in a large decrease in the amount of biological productivity there.

Opal fluxes at Site 882 remain low until about 1.6 Ma, then recover somewhat to a cyclic accumulation pattern, although they never approach their middle Pliocene values (Haug et al., this volume). At Site 887 in the Gulf of Alaska, the low opal fluxes of the latest Pliocene increase somewhat between 1.8 and 1.6 Ma, and also show a pronounced younger flux maxima in excess of 2500 $mg(cm^2 \cdot k.y.)^{-1}$ between 0.8 and 0.2 Ma (Rea and Snoeckx, this volume). During this period the northeast Pacific behaved oceanographically very differently from the northwest Pacific. Today, Site 887 lies on the northeast margin of the Alaska Dome, the upwelling system associated with the center of the Alaska gyre (Dodimead et al., 1963, and presumably records the history of this more focused subpolar upwelling system. The Site 887 opal flux record suggests that in the latter part of the Quaternary, the upwelling of deep waters that did occur happened in conjunction with the Alaska Dome, and that this more localized productivity response to upwelling in the Gulf of Alaska did not extend to the vicinity of Detroit Seamount, 3000 km to the west.

MIDDLE PLIOCENE WARM PERIOD

A rather brief period of the middle Pliocene, corresponding to 3.29 to 2.98 Ma on the Cande and Kent (1992) time scale, has been identified as unusually warm. Leg 145 drill sites provide a glimpse of the effects of that warming in the high latitude North Pacific.

The middle Pliocene warm period is characterized by enhanced deposition of calcium carbonate in both the northwestern (Site 882) and northeastern (Site 887) Pacific. At Site 882, calcite fluxes are relatively high and cyclic between 3.5 and 2.95 Ma, reaching values similar to the late Quaternary equatorial Pacific high-productivity zone (Haug et al., this volume). A similar phenomenon occurs at Site 887 where lower-resolution data show that carbonate fluxes were high in the time period 3.6 to 2.9 Ma (Rea and Snoeckx, this volume). Haug et al. (this volume) interpret the increased $CaCO_3$ fluxes associated with the mid-Pliocene warm interval as reflecting enhanced productivity responding to stronger upwelling of ocean deep waters in the northernmost Pacific.

Barron (this volume) presents paleotemperature estimates derived from diatom assemblages for this warmer time. Along a south to north transect from DSDP Site 580 (41.6°N) to Site 881 (47.1°N) and Site 883 (51.2°N), summer temperatures were 2° to 3°C warmer than present at Sites 580 and 881 and as much as 4°C warmer at Site 883. Wintertime temperatures were much warmer at Site 580, 4° to 5°C, somewhat warmer at Site 881, up to 5°C, and showed no change or even became slightly colder at Site 883 (Barron, this volume). Dowsett and Ishman (this volume) examined assemblages of planktonic and benthic foraminifers taken from Sites 883 and 887. They find that Site 883 assemblages are similar to modern ones, indicating middle Pliocene oceanographic conditions in the Detroit Seamount area were similar to the present. At Site 887, the middle Pliocene foraminifer assemblages suggest slightly warmer surface conditions (Dowsett and Ishman, this volume). However, paleotemperature estimates based on $\delta^{18}O$ values of foraminifers suggest that the middle Pliocene sea-surface temperatures were as much as 7.5°C warmer than those since 2.75 Ma (Maslin et al., this volume).

In eastern Siberia the middle Pliocene climatic optimum is recorded by an increase in the relative abundance of thermophilic elements in plant assemblages and by northward retreat of taiga beyond the Arctic Circle. Average annual temperature then may have been about 14°C, with July maxima reaching 18°C (Velichko et al., 1994).

NORTH PACIFIC RECORD OF ICE-RAFTING AND EVENTS OF 2.6 MA

History of Ice Rafting

In marine settings at mid to high latitudes and away from continental margins, the presence of anomalously coarse-grained terrigenous clasts within a finer grained pelagic or hemipelagic matrix is an indicator of iceberg transport away from tidewater glaciers. The MAR of coarse-grained IRD can be used to identify times of glacial expansion, and the geographic distribution and the composition of the IRD can be used to locate source areas. On top of a high-latitude bathymetric high, such as a seamount, where sediment supply by abyssal currents is unlikely, ice rafting is a major mode of terrigenous sediment supply. In these settings the total terrigenous MAR records may be a proxy for the regional importance of ice rafting. The Neogene history of ice rafting in the North Pacific can thus be evaluated by examination of the MAR of coarse-grained IRD from Sites 881, 883, and 887 (Krissek, this volume), total terrigenous MARs from Sites 882 and 883 (Detroit Seamount) and Site 887 (Patton-Murray Seamount; Rea and Snoeckx, this volume), and IRD compositional data is available from Sites 881, 882, 883, 884, and 887 (McKelvey et al., this volume). These data consistently indicate a major increase in the importance of ice rafting at 2.6 Ma across the North Pacific, with major ice expansion along the eastern side of the Kamchatka Peninsula, the Koryak highlands to the north of the Bering Sea, and the Gulf of Alaska drainages.

Sand-sized IRD is present in limited amounts in sediment older than 2.6 Ma at Sites 881, 883, and 887 (Krissek, this volume), and a small number of macroscopic dropstones were observed in upper Miocene and lower Pliocene sediment during shipboard description of the Leg 145 cores. These data indicate that ice-rafting began by 5.5–6.0 Ma from both the Alaskan and Siberian IRD sources, an interpretation supported by a correlative increase in total terrigenous MARs at Site 887 (Rea and Snoeckx, this volume). The age of the oldest IRD at a site in the North Pacific is strongly affected by the location of that site with respect to major circulation pathways and latitude. The oldest IRD generally becomes younger at sites farther south. In particular, DSDP Sites 177, 579, and 580 are 400–500 km south of Leg 145 sites, and contain no IRD older than late Pliocene in age (Kulm, von Huene, et al., 1973; Krissek et al., 1985).

Previous studies of outcrops and nearshore boreholes in coastal Alaska and Kamchatka (Lagoe et al., 1993; Gladenkov et al., 1991) have identified an interval of early glacial effects from 6 Ma to approximately 4.2 Ma, followed by a mid-Pliocene warm interval with reduced glacial effects from approximately 4.2 Ma to 3.0–3.5 Ma. The IRD MAR records from Sites 881 and 887 are generally consistent with this pattern, showing decreased glacial influence from 4.2 Ma to 3.0–3.5 Ma. Shipboard mineralogical data also support this paleoclimatic interpretation; at Sites 882, 883 and 887, smectite (an indicator of chemical weathering) is relatively more abundant in sediment dated at 3.0 to 4.2 Ma than in older or younger deposits. At the same sites, the relative abundances of chlorite, illite, and plagioclase (indicators of physical weathering) reach minima in sediment dated at 3.0 to 4.2 Ma.

The largest and most widespread change affecting the ice-rafted terrigenous fraction during the Neogene is a major increase in abundance at, or very close to, the Matuyama/Gauss paleomagnetic boundary (2.6 Ma on the time scale of Cande and Kent, 1992). This change is recorded by (1) the increased abundance of macroscopic dropstones at Sites 881, 882, 883, 884, and 887 (Rea, Basov, Janecek, Palmer-Julson, et al., 1993); (2) the two- to ten-fold increase in total terrigenous MARs at Sites 882, 883, and 887 (Rea, Basov, Janecek, Palmer-Julson, et al., 1993; Rea and Snoeckx, this volume); and (3) the rapid increase in IRD MARs at Sites 881, 883, and 887 (Krissek, this volume). A similar age for the first significant appearance of IRD was reported previously elsewhere in the North Pacific (Kent et al., 1971; Krissek et al., 1985; Rea and Schrader, 1985), in the North Atlantic (Shackleton et al., 1984; Ruddiman et al., 1987; Raymo et al., 1987), and in the Norwegian Sea (Krissek, 1989; Jansen et al., 1990; Jansen and Sjøholm, 1991). This increase has generally been interpreted as recording the onset of continental-scale glaciation in the Northern Hemisphere, an interpretation that is consistent with a variety of other indicators of a major change in Northern Hemisphere paleoclimates at approximately 2.6 Ma (e.g., Raymo et al., 1989).

In sediment younger than 2.6 Ma, IRD MAR maxima are highest at Site 887, intermediate at Site 881, and least at Site 883 (Krissek, this volume). This spatial pattern suggests that major ice sources were located on the perimeter of the Gulf of Alaska and along the Kamchatka-Koryak margin, as interpreted previously by Conolly and Ewing (1970). Detailed petrographic and geochemical studies of macroscopic dropstones (McKelvey et al., this volume) confirm this dual provenance. One dropstone assemblage, a diverse suite of relatively pristine arc-derived volcanic and volcaniclastic debris, tectonized/metamorphosed arc volcanic rocks and sandstone, fine-grained metasediment, chert, and rhodochrosite-rock clasts, is derived from the complex assemblage of tectonic terranes in eastern Kamchatka and the Koryak region, and is predominant in the northwestern Pacific (Sites 881, 882, 883, and 884). The second dropstone assemblage is composed predominantly of arkosic and mixed-provenance sandstone, foliated metasediments and metamorphic rocks, plutonic rocks, and minor basalt pebbles. These clasts are derived from southeastern Alaska and dominates the dropstone population at Site 887 (McKelvey et al., this volume).

In sediment younger than 2.6 Ma, at least eight episodes of increased IRD MARs can be correlated between two or more Leg 145 sites, and most of these can be correlated farther south and west to IRD abundance maxima at DSDP Sites 579 and 580 (Krissek, this volume). Three of these increases are also evident as maxima in the total terrigenous MAR at Site 887 (Rea and Snoeckx, this volume), confirming the role of ice rafting as the predominant supplier of all terrigenous material at this location. The synchronous increases in IRD abundance at Sites 579, 580, 881, 883, and 887 (Fig. 1) also correlate well with North Pacific–wide periods of increased ice rafting previously identified by Kent et al. (1971) and by von Huene et al. (1976), indicating that the major characteristics of North Pacific paleoclimatic history are well represented in the Leg 145 records.

The high-resolution history of North Pacific ice rafting since 2.6 Ma is not well known, and its linkages to other components of the Northern Hemisphere ocean/atmosphere/cryosphere system are poorly understood. Results of several Leg 145 post-cruise studies, however, suggest that sediment recovered during Leg 145 contain valuable high-resolution paleoclimatic records suitable for further study. Rea and Snoeckx (this volume) compare the total terrigenous MAR record at Site 887 for the past 3 m.y. to an indicator of the amplitude of glacial cycles (the amplitude of benthic oxygen isotope variations) for the same interval. This comparison indicates that terrigenous flux maxima (at 2.6, 1.5, and 0.6 Ma) immediately follow an increase in the ice-volume amplitude of glacial-interglacial cycles, whereas the terrigenous flux decreases during successive cycles of equal amplitude. Rea and Snoeckx (this volume) hypothesize that the first glacial advance of increased magnitude removes most of the easily erodible material, leaving a generally more resistant substrate exposed to subsequent advances. This hypothesis can be tested in future studies by examining compositional changes through these cycles (especially mineralogical indicators of physical vs. chemical weathering); if the hypothesis is correct, chemically weathered components should be most important during times of high terrigenous flux, and physically weathered components should dominate the intervals of lower terrigenous flux.

The IRD MAR records presented by Krissek (this volume) also suggest that Leg 145 sediment contains a high-resolution paleoclimatic record suitable for future study. In particular, the IRD MAR records from Sites 881 and 887 exhibit quasi-periodic fluctuations with average durations near orbital values; these fluctuations should be investigated further with more detailed sampling and refined age vs. depth models. Such high-resolution IRD records would be the first from the North Pacific comparable in detail to those available from the North Atlantic (Shackleton et al., 1984), and would contribute significantly to interocean comparisons of behavior during glacial/interglacial fluctuations.

Change in Bottom-water Activity in the Abyssal North Pacific—Site 881

Presently, in the triangular area of the northwest Pacific deep-ocean floor west of the Emperor Seamounts, east of the Kuril-Kamchatka trench and north of about Shatsky Rise, abyssal sediment shows evidence of current-related redeposition. Echo-character mapping from seismic reflection profiles (Damuth et al., 1983) indicates that strong bottom-current activity influences modern depositional processes in this region, but there was no way to determine when this process became important. Drilling at Site 881 (5531 m present depth) allowed definition of the time of onset of the present current-influenced seafloor depositional processes. Seismic reflection profiles collected by the *JOIDES Resolution* during the presite occupation survey established that the lower part of the sediment column drapes over the original abyssal topography, and that the younger section exhibits parallel, horizontal reflectors (Rea, Basov, Janecek, Palmer-Julson, et al., 1993; Hamilton, this volume). This transition occurs at a depth of about 165 mbsf, at the stratigraphic position of the Matuyama/Gauss magnetic reversal at 2.6 Ma. These results demonstrate that the deep ocean floor of the northwest Pacific became affected by more energetic bottom currents at the time of the 2.6-Ma climatic transition. This is the opposite sense of the slowdown in diffuse upwelling recorded for this time in the North Pacific, and implies that the deepest regions of the northwestern Pacific were part of a different, higher-energy circulatory regime than the lesser depths sampled on the flanks of the Emperor Seamounts.

Pacific Rim Volcanism

Throughout the northwest Pacific drill sites and in the Gulf of Alaska, ash layers are common in sediment younger than 2.6 Ma. At all five of these drilling locations (Sites 881–884 and 887) the deposition of volcanogenic material increased suddenly by an order of magnitude at the exact time of (within a few meters of) the Matuyama/Gauss reversal, and the increase in ash-layer abundance always precedes the (macroscopic) increase in IRD. For example, macroscopic description of Core 145-882A-11H shows the first thick (5 cm) ash layer at 11H-4, 133–138 cm, the Matuyama/Gauss magnetic reversal (at 2.6 Ma) at 11H-3, 80 cm, and the first dropstone at 11H-1, 88–93 cm, 4.9 m (60 or 70 k.y.) above the first thick ash layer. Similar relationships occur at other northwest Pacific sites and at the Gulf of Alaska Site 887 (Fig. 12; Rea, Basov, Janecek, Palmer-Julson, et al., 1993).

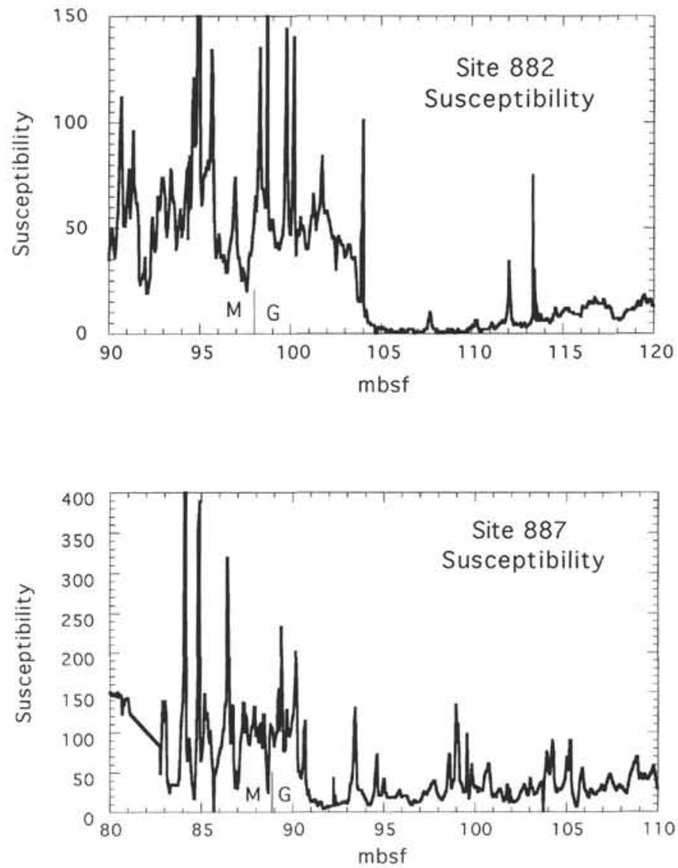

Figure 12. Magnetic susceptibility records from Sites 882 and 887 spanning the time of onset of major Northern Hemisphere glaciation. The background level is an indication of the amount of terrigenous sediment in the diatom oozes and the sharp peaks generally correspond to ash layers. The horizon of the Matuyama/Gauss magnetic reversal boundary at 2.6 Ma is indicated by the vertical line. At the sedimentation rates that characterize these locations, the sediments change from preglacial character to glacial character in only a few thousand years. Further, the timing of glacial onset coincides with the presence of multiple ash layers in the sediment.

The Kamchatka volcanic province is the site of the most voluminous late Pliocene and Quaternary explosive volcanism (Cao et al., this volume), lies at a climatically sensitive latitude, 50° to 60°N, and began its present eruptive cycle at exactly 2.6 Ma. Two decades ago Kennett and Thunell (1975; see also Stewart, 1975) noticed a worldwide increase in the number of ash layers in the late Pliocene and suggested that the episode of volcanism they represented may be somehow associated with Northern Hemisphere glaciation. Bray, in a series of papers (1974, 1977, 1979a, 1979b), linked explosive volcanism with both hemispherical and global cooling and glacial advances. A Pacific-wide summary of Neogene and Quaternary volcanism indicated larger eruptive episodes at 0–2 Ma and 14–16 Ma with lesser events centered near 5 and 10 Ma (Kennett et al., 1977). Kennett et al. (1977) suggested that cooling events may be associated with each maxima. The APC cores recovered on Leg 145, with their clear evidence for glaciation in the IRD record, their multiple and thick (up to 2.5 m at Site 884) ash layers, and excellent stratigraphy are the first cores collected by DSDP/ODP suitable for a detailed investigation of the suggestion of Kennett and Thunell (1975, 1977). The shipboard data suggest that the discussion begun 20 years ago by Kennett and Thunell (1975) and by Stewart (1975) that linked extreme volcanic activity to the rapid buildup of continental ice should be reopened.

PELAGIC CLAY AT SITE 885/886

An objective of Leg 145 was to recover pelagic clay from the central North Pacific to examine the record of eolian deposition at a location 10° of latitude farther north than the clay sampled at DSDP Site 576 and piston core LL44-GPC3 (Fig. 1). This objective was accomplished at Site 885/886, where a 72-m-thick sedimentary section was cored, the lower portion of which was about 18 m of red-brown pelagic clay and, in the lower part, hydrothermal ooze.

The stratigraphy for this site is based on (1) biostratigraphic and magnetostratigraphic information in the upper 50 m; (2) the 80-Ma age of the basement rock (Keller et al., this volume); (3) the stratigraphic position of the K/T boundary based on an iridium anomaly in the sediment (Kyte et al., this volume); and (4) Sr^{87}/Sr^{86} isotope data on ichthyoliths (Ingram, this volume; Snoeckx et al., this volume) that are comparable to the seawater strontium curve. This last data set is still somewhat experimental (see Staudigel et al., 1985) but the work of Leg 145 has brought it closer to being a useful stratigraphic tool.

Rutledge et al. (this volume) examined the geotechnical properties of the sediment from Hole 885A and found an overconsolidated interval between 15 and 20 mbsf. Dickens et al. (this volume) compiled a composite depth section for these holes, basing their initial correlations on magnetic susceptibility and verifying the results with biostratigraphic, lithostratigraphic and chemostratigraphic information. They report a compressed interval between Cores 145-885A-2H and -3H, at about 19 mbsf, the same depth as Rutledge et al.'s identified overconsolidation. Casting all of the stratigraphic information onto an age/depth curve, Snoeckx et al. (this volume) estimate the ages of two hiatuses at Site 885/886 as between 11 and 21 Ma, and a second break lower in the core between 45 and 64 Ma. Thus, the interesting stratigraphic record of the early and middle Miocene and Paleocene through middle Eocene are missing from the record of Site 885/886.

Arnold et al. (this volume) examined the clay mineralogy and rock magnetic properties of the mineral component of sediment from Site 885/886. They found a reduction in the kaolinite-rich assemblage beginning in the late Miocene and an abrupt change in mineralogy to a chlorite and illite-rich assemblage at about 3.8 Ma. Dust grain size, as interpreted from the rock magnetic properties, also increases about 3.8 Ma suggesting an increase in zonal wind speed then (Arnold et al., this volume). Both Arnold et al. (this volume) and Snoeckx et al. (this volume) calculate the mass accumulation rate of eolian dust as very low fluxes, 5 to 30 $mg(cm^2{\cdot}k.y.)^{-1}$ prior to the Miocene hiatus, a peak of about 125 $mg(cm^2{\cdot}k.y.)^{-1}$ at about 7.5 Ma, and initiation of a permanent increase to fluxes of 100 to 150 $mg(cm^2{\cdot}k.y.)^{-1}$ beginning between 3.7 and 3.5 Ma. The change in mineralogy and increase in eolian fluxes at about 3.6 Ma signifies the rapid drying of east-central Asia. This middle Pliocene event, seen in other North Pacific eolian records (Rea, 1994), precedes both the onset of major Northern Hemisphere glaciation and the onset of loess deposition in China by 1 m.y.

CHINOOK TROUGH RIFTING AND HYDROTHERMAL ACTIVITY

The Chinook Trough is a pronounced bathymetric feature that extends WSW-ENE across the central North Pacific. The trough has been interpreted as a lithospheric scar resulting from the initiation of north–south seafloor spreading within the old North Farallon Plate (Rea, 1970; Rea and Dixon, 1983; Mammerickx and Sharman, 1988). The new rift formed in the Late Cretaceous and separated the Kula plate to the north from the Chinook plate to the south (Rea and Dixon, 1983).

Drilling results from Legs 92 (in the southeastern Pacific) and 121 (in the eastern Indian Ocean) have demonstrated that extremes of seafloor hydrothermal activity occur in association with ridge jumps and the formation of new spreading centers in old lithosphere (Owen and Rea, 1985; Rea and Leinen, 1986b; Lyle et al., 1987; Owen and Zimmerman, 1991). Site 885/886 lies about 60 km from the southern margin of the Chinook Trough and was intended to be used to discover the hydrothermal history of the newly forming Chinook-Kula spreading center. At Site 885/886, XCB drilling bottomed in a basalt flow that is much younger than the expected middle Cretaceous age of the igneous ocean crust, and since has been dated at 80 Ma by Keller et al. (this volume). We assume that the 80-m.y.-old basalt dates the height of rifting activity along the Chinook Trough and corresponds to the age for the Late Cretaceous plate boundary rearrangement widely recorded in the Pacific Basin (Rea and Dixon, 1983; Mammerickx and Sharman, 1988).

The rifting-associated sediment, low in the recovered section, represents a nearly pure hydrothermal ooze with minimal biogenous and terrigenous (eolian) components (Dickens and Owen, this volume). Hydrothermal sediment fluxes decrease exponentially from the base of the core to about 3 m above the K/T boundary iridium anomaly (Kyte et al., this volume), representing a span of 15 to 20 m.y. Other rifting-associated hydrothermal anomalies have an apparent duration of 1 or 2 m.y. Therefore, either the hydrothermal activity associated with the Late Cretaceous crustal rifting in the North Pacific was much more intense than observed elsewhere, or the lack of other sedimentary dilutants allows a more complete history of this event to be recovered than has been possible at other locations.

HIGH-RESOLUTION STUDIES AT SITE 882

Among the most important accomplishments of Leg 145 investigations is the generation of an orbitally tuned time scale for the past 4.0 m.y of sedimentation at Site 882 and the application of this time scale in high-resolution studies of the paleoceanographic and paleoclimatic variability in the northwestern Pacific (Tiedemann and Haug, this volume; Haug et al., this volume; Maslin et al., this volume). Tiedemann and Haug (this volume) began with the composite section constructed for Site 882 and presented in the *Initial Reports* volume (Rea, Basov, Janecek, Palmer-Julson, et al., 1993), and used the GRAPE (gamma-ray attenuation porosity evaluator) bulk-density data of the diatom oozes as the basis for tuning. The results were tested by applying them to the magnetic susceptibility data for the same composite section. By this exercise, the concentration of spectral variance was improved for both the GRAPE and susceptibility records. Tiedemann and Haug (this volume) extracted the spectral variability for 1-m.y. windows along the 4.0-m.y. record. For the GRAPE data, precessional variability at both 19- and 22-k.y. periods is most important in the past 1.0 m.y., and tilt and eccentricity power are strong. All variability is coherent with summer insolation curves at 65°N as indicated by the determinations of Berger and Loutre (1991). In the 1- to 2-Ma interval, precession power is low and the spectral variability is dominated by tilt. Between 2.0 and 2.7 Ma, only tilt is coherent with northern summer insolation. In the 2.8 to 4.0 Ma part of the record, precession and tilt are present in subequal amounts. Overall sedimentation rates determined from the new orbital time scale are 2 to 5 cm/k.y. between 0 and 1.75 Ma, 1 to 4 cm/k.y. from 1.75 to 2.75 Ma, and 7 to 15 cm/k.y. in sediments older than 2.75 Ma (Tiedemann and Haug, this volume).

Haug et al. (this volume) use the tuned time scale developed by Tiedemann and Haug (this volume) to generate a high-resolution record of the MAR of the biogenic components, $CaCO_3$, opal, and organic carbon. To the extent that the mass accumulation rate of biogenic sediment is a measure of biological productivity in the surface waters, these fluxes can be used as an estimator of paleoproductivity. Calcite and opal fluxes are generally covariant and are higher during interglacial periods. This leads to an Atlantic-type calcite preservation signal in the northwestern Pacific, something observed before by

Hovan et al. (1991). All biogenic fluxes decline dramatically at about 2.75 Ma, a several-fold reduction in mass accumulation rate that denoted the end of the late Miocene–Pliocene productivity maximum noted above.

Haug et al. (this volume) note that all local sources of nutrients to the North Pacific, dominantly runoff and possibly dust, are higher during glacial times, not interglacials. High interglacial productivity entails a greater supply of nutrients, a supply that must be from upwelling deep and bottom waters at the end of their global transit to the northernmost Pacific. Deep-ocean circulation responds to the rate of formation of NADW and is stronger during interglacial times and reduced during glacials (Shackleton et al., 1988). Enhanced deep water advection may also explain the high $CaCO_3$ fluxes during the middle Pliocene warm interval, 3.8 to 2.75 Ma, and at 5.2 to 4.8 Ma at Site 882 (Haug et al., this volume).

Maslin et al. (this volume) examined the same data set, including magnetic susceptibility, to document the details of the onset of major Northern Hemisphere glaciation in the northwestern Pacific region. They show a sudden increase in the flux of terrigenous grains as reflected in the susceptibility data, at 2.75 Ma, which they interpret as being an increase in IRD. The timing of this event coincides with a rapid decrease in sea-surface temperature of 7.5°C and the end of the late Miocene to Pliocene opal flux maxima. Maslin et al. (this volume) interpret the cooling, increase in terrigenous flux, and decline in productivity as representing the beginning of glaciation. These events are associated with a reduction in the advection of deep waters to the North Pacific, resulting from changes in the North Atlantic source region. They attribute the ultimate cause of Northern Hemisphere glaciation to changing orbital parameters, particularly the increasing amplitudes of both obliquity and precession during the critical period of the middle Pliocene.

SUMMARY

Leg 145, the North Pacific Transect, achieved most of the objectives set for it by the JOIDES planning bodies. The Neogene paleoceanographic history of the region is controlled by advection of deep-ocean waters to the North Pacific and their upwelling against the bathymetric restraints of the Aleutian Island Arc and adjacent continental margins. The volume of this regional upwelling, and thus the associated nutrient flux, increases with increased formation rate of deep waters in the North Atlantic. Events of the "silica switch" began with a modest increase in opal flux at about 12 Ma succeeded by a large increase at 6 to 7 Ma that matched in time the periods of NADW enhancement. Further, a decline in the rate of NADW formation immediately preceding the onset of major Northern Hemisphere glaciation terminates rather abruptly the latest Miocene to late Pliocene episode of high opal deposition rates. Opal fluxes never recover in the northwestern Pacific, but in the Gulf of Alaska upwelling (doming) area associated with the Alaska Gyre, a second, brief period of very high silica fluxes occurred 0.8 to 0.2 Ma. The period of extreme biological productivity coincides with the only significant carbonate deposition in the North Pacific since the Oligocene and with the middle Pliocene warm interval, about 3.8 to 2.8 Ma. It is considerably younger than the middle Miocene age of the Monterey and similar siliceous formations in western North America.

The history of the CCD in the northwest Pacific is also linked to changes in the abyssal circulation pattern. Today old, highly corrosive, deep waters upwell in the area. This causes the modern CCD to shoal more than 2 km in the 1300 km between northern Shatsky and Hess rises, where it is deeper than 4 km, to Detroit Seamount, where the CCD is just deeper than 2 km. The CCD may also rise to the west, because it is about 1 km deeper in the Gulf of Alaska region of Site 887 than at Detroit Seamount. During the Cenozoic, the CCD in the North Pacific follows the global pattern of being shallow, probably near 2 km, in the early Cenozoic, and deepening to nearly 4 km in the early Oligocene. Beginning in the early Miocene the CCD became continually shallower in the North Pacific, apparently a reflection of the increasing flux of highly corrosive bottom and deep waters to the region.

Documentation of the Meiji sediment tongue as a classic, North Atlantic–type drift deposit is a major paleoceanographic accomplishment of Leg 145. The Meiji Drift, with its northern-source diatoms and minerals, has been accumulating since the early Oligocene, indicating that southerly flowing bottom waters have prevailed in the North Pacific for 35 m.y. The source and feeder of this water to the North Pacific must have been the Bering Sea, which has a present circulation pattern similar to the North Atlantic. Surface waters enter the Bering Sea through the several passages in the Aleutian Island chain, and all the deep water flows out through the Kamchatka Strait. Presently 10 to 20 Sv of water move south through the Kamchatka Strait, flow volumes identical to the formation rate of NADW. The Oligocene Bering Sea and North Atlantic were of similar size, depth, and latitude. Both began producing drift deposits at the same time, most likely a record of the Northern Hemisphere response to cooling and ice buildup on Antarctica.

Other records documenting late Cenozoic changes in climate and ocean circulation were recovered by drilling the North Pacific transect. Ice-rafted debris appears in the North Pacific in the latest Miocene or earliest Pliocene, indicating that alpine glaciers had then reached sea level at both Siberian and Alaskan drainages. Ice rafting is minimal during the middle Pliocene warm episode and begins in significant volume at about 2.6 Ma. Alaska has supplied several times more IRD to the Pacific proper than has Siberia during the Pliocene-Pleistocene glacial ages. The MAR of all terrigenous sediment increases several fold at 2.6 Ma, reflecting increased continental erosion rates associated with continental glaciation and climatic deterioration. In the deep northwestern Pacific, the present current activity that modifies seafloor depositional patterns also began at this time. At Site 881 sediments older than 2.6 Ma drape the underlying topography, whereas younger beds are flat-lying and tend to fill the lows and pinch out over highs. Finally, the number and volume of ash layers increase suddenly by an order of magnitude within meters of the Matuyama-Gauss magnetic reversal boundary at 2.6 Ma. The spatially intimate association of greatly increased volcanic activity and the rapid onset of major Northern Hemisphere glaciation (Fig. 11) suggest that the long-discounted relation between the two should be reexamined by paleoclimatologists.

Finally, the construction of an orbitally tuned time scale for the past 4.0 Ma for the diatom oozes of the northwestern Pacific is a significant paleoceanographic accomplishment. This time scale permits comparison of the details of oceanographic and climatic change among North Pacific and other, commonly low-latitude sites where time scales of similar refinement have been constructed. Application of this time scale to determine sedimentation and the mass accumulation rates of the several sediment components demonstrates that the production rate of biogenic sediment is commonly greater during interglacial times than during the glacial episodes. Because local nutrient supply from runoff or dust is greater during glacial times, this observation means that a distal nutrient source, presumably the upwelling deep-ocean waters, controls biological productivity in the North Pacific on orbital time scales.

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