

## Late Miocene and early Pliocene biosiliceous sedimentation along the California margin

**John A. Barron<sup>1,\*</sup>, Mitchell Lyle<sup>2</sup>, and Itaru Koizumi<sup>3</sup>**

<sup>1</sup> U.S. Geological Survey, Menlo Park, CA, 94025, USA,

<sup>2</sup> Center for Geophysical Investigation of the Shallow Subsurface, Boise State University, Boise, ID, 83725, USA,

<sup>3</sup> Division of Earth and Planetary Sciences, Graduate School of Science,  
Hokkaido University, Sapporo 060-0818, Japan

\* e-mail: [jbarron@usgs.gov](mailto:jbarron@usgs.gov)

### ABSTRACT

*Biogenic opal sedimentation is compared between offshore and onshore areas of the California margin during the late middle Miocene, the late Miocene, and the early Pliocene. The records from offshore ODP Sites 1010 and 1021 have declining opal abundance, with a dramatic three-fold decline at about 11.5 Ma and a second, less pronounced drop occurring at about 7.6 Ma. Thick stratigraphic sections of diatomaceous sediments dated between 11.5 and 10.0 Ma and between 7.6 and 6.5 Ma are found onshore in California, whereas coeval intervals in offshore deep sea sites display relatively low opal percentages. This suggests that during periods of reduced strength in the California Current, diatom production declined in offshore areas while it increased in more coastal regions. The early Pliocene and early part of the late Pliocene (4.6 to ca. 2.7 Ma) are marked by the near absence of diatoms in offshore sites, while diatoms are masked by clastic components in onshore sections. Diatom production was greatly reduced along the California margin during this climatically warm period of the Pliocene at the same time that production dramatically increased in the subarctic northwest Pacific, suggesting fractionation of opal to higher latitudes.*

*Key words: opal, diatom, Miocene, Pliocene, California*

### RESUMEN

*Se compara la sedimentación biogénica de ópalo, entre las áreas costeras y las marinas del margen de California, durante el Mioceno medio tardío, el Mioceno tardío y el Plioceno temprano. Los registros de los sitios marítimos ODP 1010 y 1021 muestran abundancia decreciente de ópalo, con una disminución dramática de tres veces a aproximadamente 11.5 Ma, y una segunda disminución, menos pronunciada a aproximadamente 7.6 Ma. Se han encontrado secciones estratigráficas gruesas de sedimentos diatomáceos fechados entre 11.5 y 10.0 Ma y entre 7.6 y 6.5 Ma en las costas de California, mientras que los intervalos contemporáneos en sitios marinos profundos muestran porcentajes relativamente bajos de ópalo. Esto sugiere que durante los periodos de poca intensidad de la corriente de California, la producción de diatomeas decreció en las áreas marinas mientras que aumentó en las regiones más cercanas a la costa. El Plioceno temprano y la parte temprana del Plioceno tardío (4.6 a 2.7 Ma) se caracterizó por la ausencia casi total de diatomeas en los sitios marinos, mientras que los diatomeas se encuentran enmascarados por componentes clásticos en las secciones costeras. La producción de diatomeas se encontró muy reducida a lo largo del margen de California durante este periodo climáticamente caliente del Plioceno, al mismo tiempo que la producción aumentó dramáticamente en el Pacífico nororiental subártico, sugiriendo fraccionamiento de ópalo a latitudes más altas.*

*Palabras clave: Ópalo, diatomeas, Mioceno, Plioceno, California.*

## INTRODUCTION

Abundant and geographically-extensive diatom production characterized the California margin during the middle and late Miocene, (Ingle, 1981; Barron, 1998), as illustrated by widespread outcrops of the diatom-rich Monterey Formation. Previous studies have noted that these California diatom-rich sediments were part of much more extensive biosiliceous facies that dominated vast regions of the Pacific Ocean during the middle and late Miocene (Ingle, 1981; Keller and Barron, 1983; Barron and Baldauf, 1990).

Barron (1998) constructed "diatom mass accumulation rate (MAR) records" for the late Neogene at ODP Sites 881, 882, 883, and 887 in the high-latitude northwest Pacific and compared them with records at DSDP Site 438 off northeast Japan and in coastal outcrops of the Monterey and Sisquoc Formations of southern California. Four major changes in diatom sedimentation patterns were identified in the North Pacific during the last 10 m.y.: 1) an apparently region-wide, early late Miocene (*ca.* 9.0-8.5 Ma) rise in diatom MAR; 2) a step-like, latest Miocene (6.5-5.5 Ma) increase diatom sedimentation that varied slightly in age between the high-latitude northwest Pacific and coastal regions of the middle-latitude north Pacific; 3) enhanced regional differences in production during the early Pliocene (4.5Ma) wherein diatom MAR increased dramatically in the high-latitude northwest Pacific while declining abruptly in middle-latitude coastal regions; and 4) a reversal in the early Pliocene North Pacific patterns in the late Pliocene (at 2.7 Ma), resulting in a sharp decline in diatom accumulation rates in the high-latitude northwest Pacific and resumption of biosiliceous sedimentation off California.

Barron (1998) suggested that shoaling of the Isthmus of Panama combined with high-latitude cooling was responsible for these late Neogene changes in diatom sedimentation in the North Pacific. As argued by numerous researchers (Berger, 1970; Keller and Barron, 1983; Maier-Reimer *et al.*, 1990), progressive restriction of deep, intermediate, and shallow water exchange through the Central American Seaway during the late Neogene enhanced North Atlantic-Pacific, basin-basin fractionation, probably leading to increased nutrient levels in the North Pacific and fueling increased diatom productivity.

Recent coring in the North Pacific by the Ocean Drilling Program has resulted in the collection of more quantitative and more detailed measurements of biosiliceous sedimentation that are better constrained to geologic time (Barron, 1998; Haug *et al.*, 1999; Lyle *et al.*, 2000). These data necessitate a reassessment of patterns of biosiliceous sedimentation off the California margin.

## IMPROVED CHRONOLOGICAL FRAMEWORK

ODP Leg 167 provided the first continuous paleomagnetic stratigraphies along the California margin at

ODP Site 1010 off northern Baja California, Mexico and at Site 1021 off northernmost California (Figure 1). When combined with high resolution calcareous nannofossil, planktonic foraminiferal, diatom, and radiolarian stratigraphies and high resolution correlation of magnetic susceptibility, GRAPE bulk density, and color reflectance records, unprecedented stratigraphic control for the upper Neogene and Quaternary has been achieved in the 52 holes drilled at 13 sites during Leg 167 throughout the 29°N to 40°N latitudinal transect (Lyle *et al.*, 2000).

Janecek (2000) determined the weight percent of biogenic opal content of sediment from seven of the ODP Leg 167 sites using the reduction colorimetric technique of Mortlock and Froelich (1989). Although Janecek (2000) provided down core plots of opal percent versus depth and estimated age, he did not attempt any interpretation. The opal data of Janecek (2000) is shown for Site 1010 off northern Baja California and Site 1021 off northern California, on Figure 2. Weight percent opal values of both sites display considerable variation down core, with values ranging from almost 50% to 2%. When time lines are placed on the opal data using updated biostratigraphy and magnetostratigraphy (Lyle *et al.*, 2000), considerable similarity is revealed in the trends of weight percent opal of the two sites, even though they are separated by nearly 10° of latitude and more than 1100 km. The overall trend is declining opal values during the late

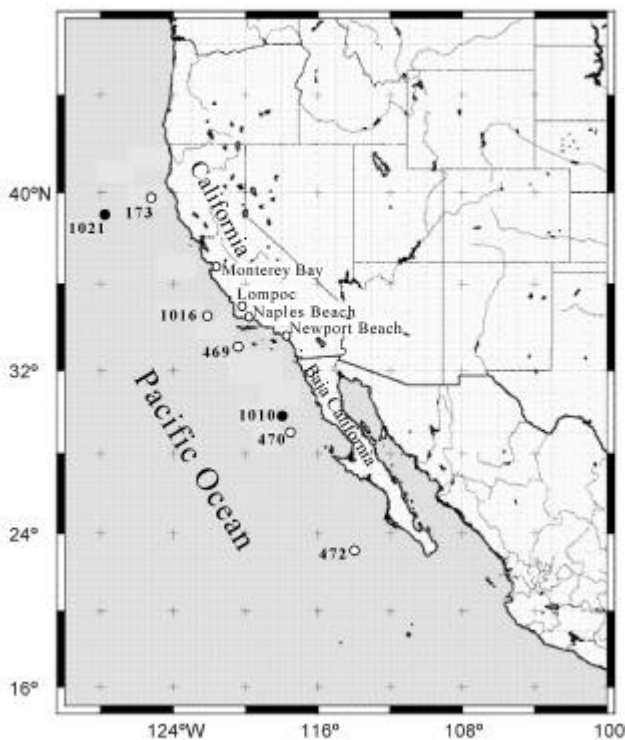


Figure 1. Map showing the DSDP and ODP sites and onshore sections discussed. Key ODP Sites 1010 and 1021 off Baja California and northern California, are marked by filled circles.

Miocene. At both sites the most dramatic drop in weight percent opal occurs at about 11.5 Ma. This drop represents an approximately three-fold decline in opal content from values averaging about 35-40% prior to 11.5 Ma to values of 10-15% between about 11.5 and 10.0 Ma. A second, less pronounced drop occurs at about 7.6 Ma, where weight percent opal declines upsection by approximately two fold from values of 20% or more to less than 10%.

Sediment accumulation rates must be considered before further evaluating these trends. Prior to 11.5 Ma at Site 1010, sediment accumulation rates average about 30 m/m.y., whereas after 11.5 Ma, they decline to an average of about 12 m/m.y. Thus, at Site 1010, the 11.5 Ma drop in opal content is even more dramatic in terms of opal mass accumulation rates. At Site 1021, on the other hand, sediment accumulation rates average about 18 m/m.y. during the late middle and early late Miocene but increase to about 30 m/m.y. at about 7.6 Ma and remain relatively constant thereafter (Lyle *et al.*, 2000).

In addition to the major step-like reductions in weight percent opal at 11.5 and 7.6 Ma, the weight percent opal plots show considerable similarity between Sites 1010 and 1021 (Figure 2). Relatively low opal values without high amplitude fluctuations characterize the intervals between 11.5 to 10.0 Ma, 7.6 to 6.5 Ma, and after 4.6 Ma. These intervals alternate with the periods of relatively increased, but highly variable opal percent

between 10.0 to 7.6 Ma and 6.5 to 4.6 Ma.

As shown on Figure 3, each of these intervals is readily identifiable by diatom biostratigraphy. Thus, the character of opal sedimentation during these intervals can be compared in numerous onshore (Barron, 1986a) and offshore (Barron, 1981; Maruyama, 2000) sections along the California margin (Table 1).

### 13.0 - 11.5 Ma

The late middle Miocene interval of relatively high opal values extends from 11.5 Ma at least back to about 13 Ma (Lyle *et al.*, 2000) at Site 1010. The opal record at Site 1021, unfortunately does not continue beyond 12 Ma. No other quantitative opal data are available from other offshore California sites during this time interval. It should be noted, however, that this interval, which is equivalent to diatom subzones NPDZ5B and 5A, is represented by diatom-rich sediments at DSDP Sites 472 and 470 off Baja California and Sites 469 and 173 off California (Schrader, 1973; Barron, 1981).

### 11.5 - 10.0 Ma

Weight percent opal values at Sites 1010 and 1021 drop sharply at 11.5 Ma from values averaging about 35-40% prior to 11.5 Ma to values of 10-15% between about 11.5 and 10.0 Ma. The 11.5 to 10.0 Ma interval spans the middle Miocene-late Miocene boundary and coincides with diatom subzone NPDZ5C (the *Thalassiosira yabei* Zone) (Figure 3). This interval is typically compressed or eroded at unconformities (hiatus NH4 of Keller and Barron, 1983) along the California margin (Barron, 1986 a, b; 1989). Where the section is not compressed offshore, it is typified by poorly preserved diatoms, as at DSDP Sites 470 and 472 off Baja California (Barron, 1981) (Table 1). Onshore in California, the only places where relatively thick diatomaceous sections have been documented containing this interval are the Monterey area (Barron, 1986a) and the Grefco Quarry (see Jenkins, 1982) near Lompoc (Barron, unpublished data on samples provided by A. Sarna-Wojcicki).

In contrast, this interval, the *Thalassiosira yabei* Zone, is well represented in sections from Japan (Akiba, 1986), suggesting that diatom production and/or preservation may have been preferentially greater there.

### 10.0 - 7.6 Ma

Moderate concentrations of opal (averaging about 20% at Site 1010 and slightly higher at Site 1021) are seen again beginning at about 10.0 Ma. Thereafter, weight percent opal at both sites displays strong cycles with means close to 20% until about 7.6 Ma (Figure 2). This early late Miocene interval coincides

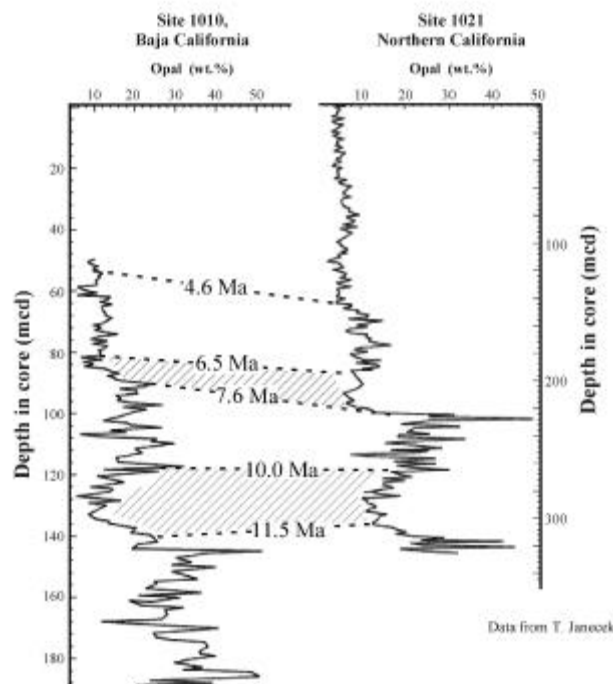


Figure 2. Comparison of weight percent opal measured by Janecek (2000) at Sites 1010 and 1021 with time lines from the age models of Lyle *et al.* (2000). Diagonal-lined areas show intervals of reduced weight percent opal.

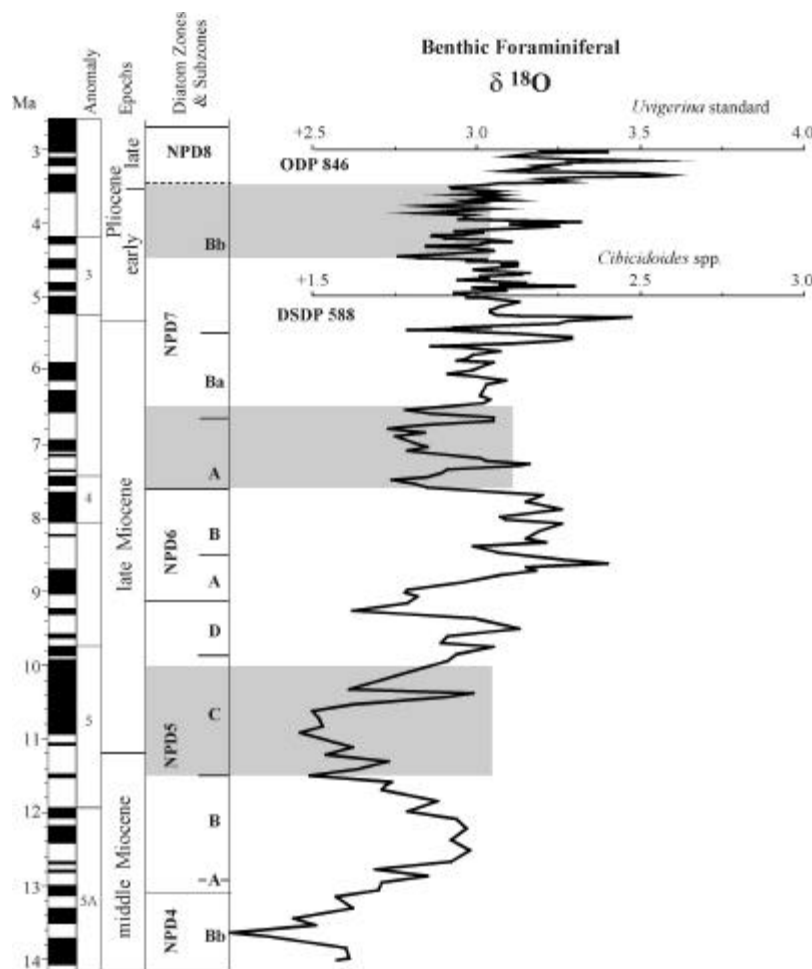


Figure 3. Spliced oxygen isotope record from DSDP Site 588 (Kennett, 1986) and ODP Site 846 (Shackleton, 1995) compared with age and the diatom zonation of Maruyama (2000). Shaded areas represent intervals of reduced opal accumulation in offshore waters of the California margin. Note that the shift in  $\delta^{18}\text{O}$  between the records of Site 588 and Site 846 is due to different water depths of the sites and different fractionation effects of the foraminifers used.

with diatom subzones NPDZ5D and zone NPDZ6 (Figure 3). It is characterized by abundant diatoms at DSDP Sites 173 and 469 (Barron, 1981; Barron and Keller, 1983) and typically is represented by a calcareous diatomaceous sediments in onshore sections of the Monterey Formation (Table 1).

### 7.6 - 6.5 Ma

Opal at Sites 1010 and 1021 undergoes a second dramatic drop in concentration at about 7.6 Ma, where weight percent declines upsection from average values of  $\geq 20\%$  to values less than 10% (Figure 2). Qualitative data at offshore DSDP Site 469 (Figure 1) also suggests a decline in diatom productivity between 7.6 and 6.5 Ma (Barron, 1981; Table 1). A hiatus (NH6 of Keller and Barron, 1983) is present at DSDP Site 173 off northern California. Whereas, hiatus NH6 may be associated with a sea level fall and a possible tectonic event in onshore

sections (Barron, 1986b), reduced diatom sedimentation during this interval may contribute to the development of a hiatus offshore.

As pointed out by Barron (1998), there is evidence that opal accumulation rates actually increased in onshore sections of southern California during this 7.6 to 6.5 Ma interval. In the Naples Beach section near Santa Barbara, California, this interval coincides precisely with the  $\text{CaCO}_3$ -poor, informally-named clayey-siliceous member of the Monterey Formation of Isaacs (1983) and marks an upsection doubling of silica accumulation rates (Isaacs, 1985). A similar relationship may hold true for the Monterey Formation at Newport Beach south of Los Angeles, where the sediment accumulation rates doubles (from about 40 m/my to 80 m/my) at about 7.6 Ma coincident with the onset of a  $\text{CaCO}_3$ -poor interval (Barron and Keller, 1983). At Lompoc, the most pure (mineable) deposits of the Manville Quarry occur between about 7.6 and 6.5 Ma, implying enhanced diatom production.

Table 1. Comparison of quantitative and qualitative measures of diatom accumulation in offshore and onshore stratigraphic sections in California along the Pacific margin of California and Baja California. MAR = mass accumulate rates.

| OFFSHORE SITES   |                | North   |  |   | South                                     |
|------------------|----------------|---|--|---|---|
| Ma               | Zone           | 1021  | 173  | 1016/469                                | 1010                                      |
| 4.6-3.5          | NPD7B upper    | <5% opal                                      | hiatus                                       | very rare diatoms                       | <<10% opal                                |
| 6.5-4.6          | NPD7B lower    | ~12% opal                                     | abundant diatoms                             | abundant diatoms                        | ~12% opal                                 |
| 7.6-6.5          | NPD7A          | <10% opal                                     | hiatus                                       | few diatoms                             | <10% opal                                 |
| 10.0-7.6         | NPD5D and NPD6 | >20% opal                                     | abundant diatoms                             | abundant diatoms                        | ~20% opal                                 |
| 11.5-10.0        | NPD5C          | ~15% opal                                     | hiatus                                       | hiatus                                  | ~10% opal                                 |
| ONSHORE SECTIONS |                |   |  |   |   |
| Ma               | Zone           | Monterey Bay                                  | Lompoc                                       | Naples                                  | Newport                                   |
| 4.6-3.5          | NPD7B upper    | hiatus  | Foxen Mdst. -<br>clastics mask diatoms       | Puente Fm. -<br>clastics mask diatoms   | Capistrano Fm? -<br>clastics mask diatoms |
| 6.5-4.6          | NPD7B lower    | Purísima Fm. -<br>clastics increase at 5.9 Ma | Sisquoc Fm. -<br>thick, diatom-rich sections | Sisquoc Fm. -<br>opal MAR increase x 3  | Capistrano Fm. -<br>increased clastics    |
| 7.6-6.5          | NPD7A          | hiatus  | Monterey Fm. -<br>(Lompoc Quarry)            | Monterey Fm. -<br>opal MAR increase x 2 | Monterey Fm. -<br>increased sed. Rate     |
| 10.0-7.6         | NPD5D and NPD6 | Santa Cruz Mdst.                              | Monterey Fm. -<br>(calcareous)               | Monterey Fm -<br>(calcareous)           | Monterey Fm -<br>(calcareous)             |
| 11.5-10.0        | NPD5C          | Monterey Fm. -<br>Toro Rd. section)           | Monterey Fm. -<br>(Grefco Quarry)            | condensed or<br>hiatus                  | condensed or<br>hiatus                    |

### 6.5 - 4.6 Ma

Beginning at about 6.5 Ma, near the boundary between diatom subzone NPD7A and 7B, weight percent opal increases by about 5% at Sites 1010 and 1021 and begins to display increased variability (Figure 2). This interval, which lasts until about 4.6 Ma, is characterized by abundant, well-preserved diatoms at offshore DSDP Sites 173 and 469 (Barron, 1981; Barron and Keller, 1983). Onshore it coincides with the Sisquoc Formation of southern California and mixed terrigenous, diatomaceous formations that immediately overlie the Monterey Formation (*i.e.*, the Capistrano and Purísima Formations) in coastal California (Barron, 1986 a, b; 1998).

During this interval, clastic components increase in a step-like fashion, almost completely masking diatoms by the Miocene-Pliocene boundary (5.32 Ma) in most onshore basins (Barron, 1992).

### 4.6 - 3.5 Ma

The early Pliocene interval from 4.6 to about 3.5 Ma is notable by greatly reduced opal sedimentation offshore (Barron, 1981, 1998; Figure 2). Onshore it coincides with terrigenous-rich sedimentation that completely masks any diatoms (Barron, 1992). The interval between about 5 and 3.5 Ma also tends to be an interval almost barren of foraminifers and calcareous nannofossils (Lyle, *et al.*, 2000; Fornaciari, 2000; Kennett *et al.*, 2000).

## DISCUSSION

A composite benthic foraminiferal isotope plot for the late middle Miocene through the early Pliocene has been constructed (Figure 3) from the data of Kennett (1986) from DSDP Site 588 in the southwest Pacific and the data of Shackleton *et al.* (1995) from equatorial Pacific ODP Site 846. Although the DSDP 588 data of Kennett (1986) is fourteen years old, it remains the only Pacific isotope curve for the entire late Miocene that is tied directly to paleomagnetic stratigraphy. The early Pliocene data of Shackleton (1996) is offset from the DSDP 588 data by about 1‰, reflecting differences in the benthic foraminifers used and differences in the water depth of the two sites.

It is immediately apparent that intervals of relatively high opal production along the California margin (13.0-11.5 Ma, 10.-7.6 Ma, and 6.5-4.6 Ma) coincide with higher average  $\delta^{18}\text{O}$  values than the intervals immediately preceding and following them (11.5-10.0, 7.6-6.5 Ma, and 4.6-3.5 Ma). A simple explanation for such a relationship involves a direct correspondence between the level of opal production in offshore California waters and the strength of the California Current. Higher benthic oxygen isotope values are indicative of high latitude cooling or increased polar ice caps, both conditions which would contribute to strengthening of the California Current and related coastal upwelling.

However, without sufficient nutrients in near-surface waters, coastal upwelling cannot drive diatom production. Studies of late Quaternary and Holocene

sediment demonstrate that opal production is enhanced along the California margin during interglacial periods relative to glacial intervals, due to increased levels of nutrients in the intermediate waters of the northeastern Pacific (Gardner *et al.*, 1997; Lyle *et al.*, 2000). Due to basin-basin fractionation, nutrient levels in the northeastern Pacific rise when production of North Atlantic Deep Water (NADW) is increased (Berger, 1970; Broecker and Peng, 1982). Indeed, numerous researchers have linked enhanced diatom production along the California margin during the interglacials of the late Quaternary and the Holocene with increased production of NADW.

What role does basin-basin fractionation play in shaping the late middle Miocene to early Pliocene record of opal deposition along the California margin? Let us look at published studies documenting the Miocene and Pliocene production of NADW (and its ancestor, Northern Component Water (NCW)).

### **Influence of northern component water**

Wright *et al.* (1992) argue that Atlantic-Pacific benthic foraminiferal  $\delta^{13}\text{C}$  differences were enhanced between 12.0 and 10.0 Ma (ages updated by Roth *et al.*, 2000), suggesting increased production of NCW in the North Atlantic. Under such conditions, nutrient levels should have increased in North Pacific waters, possibly leading to enhanced diatom production off the California margin. However, opal production in California waters was typically low during most of this 12.0 to 11.0 period of enhanced NCW (Figure 2, Table 1). Clearly, interpretation of the 11.5 to 10.0 Ma interval of reduced opal production in offshore California waters is complicated. Lyle *et al.* (2000) point out that this interval coincides with the late and middle Miocene carbonate crash seen in equatorial sediments around the Isthmus of Panama, but Roth *et al.* (2000) argue that severe carbonate dissolution began at about 12.0 Ma in the Caribbean but did not begin until about 11.0 Ma in eastern equatorial Pacific Site 846. They argue that the Isthmus of Panama was temporarily closed between about 11.0 and 9.0 Ma during a low stand in eustatic sea level.

According to Wright *et al.*'s (1992)  $\delta^{13}\text{C}$  benthic foraminiferal data, NCW production was reduced between about 9.9 and 8.6 Ma, and then increased until it peaked (for the late Miocene) during the interval from about 7.6 to 6.7 Ma (ages updated). As NCW production reached its acme between 7.6 and 6.7 Ma, opal production in offshore California margin waters declined (Figure 2) at the same time that it appears to have increased in onshore sections of southern California (Table 1). Although increased NCW production should lead to increased nutrient levels in North Pacific deep waters, regional variations in upwelling and the depth of the nutricline determines where diatom production and opal sedimentation occurs. Increased onshore fractionation of opal during this 7.6 to 6.7 Ma interval may be

related to a slackening and narrowing of the California Current, as this interval apparently was characterized by relatively lower  $\delta^{18}\text{O}$  values at DSDP 588 (Figure 3) and a reduced latitudinal thermal gradient.

The 6.5 to 4.6 Ma interval of increased opal sedimentation roughly coincides with Farrell *et al.*'s (1995) "latest Miocene-earliest Pliocene biogenic bloom", which is characterized by significant increases in both  $\text{CaCO}_3$  and opal MAR's in the eastern equatorial Pacific. In the northwest Pacific Barron (1998) argued that diatom accumulation rates increased slightly later at 6.2 Ma, but Haug *et al.* (1999) report an even younger increase at Site 882 at 5.6 Ma; so it is unclear whether these north Pacific opal events were related.

Farrell *et al.* (1995) point out the widespread nature of this "latest Miocene-earliest Pliocene biogenic bloom" in the low-latitude Indo-Pacific region. Berger *et al.* (1993) suggest that this latest Miocene-earliest Pliocene biogenic bloom was caused by greater nutrient concentrations in Pacific waters due to increased production of NADW (increased basin-basin fractionation), but Farrell *et al.* (1995) argue for regional fractionation of nutrients, rather than a global increase in the supply of nutrients to the ocean, because of their observation of sharp intra-basinal differences of opal and  $\text{CaCO}_3$  in the eastern equatorial Pacific.

At least the Messinian (6.8 to 5.3 Ma) part of this interval might be presumed to have been a time of reduced NCW production, because of isolation of the Mediterranean. This interval is characterized by highly fluctuating oxygen isotope values and rapidly changing paleoceanographic conditions (Hodell *et al.*, 1994). A major  $\delta^{18}\text{O}$  increase in Morocco at 6.8 Ma is correlated by Hodell *et al.* (1994) with the base of the Tripoli Formation and the onset of crisis conditions in the Mediterranean.

Keigwin (1982) noted increased contrast between Pacific and Caribbean benthic foraminifer  $\delta^{13}\text{C}$  beginning at 6.8 to 6.6 Ma (equivalent to the end of the late Miocene carbon shift), which he interpreted to be evidence of termination of deep-to-intermediate-water exchange across the Central American Seaway caused by shoaling of the sill. Wright *et al.* (1991), however, did not record increased contrast between North Atlantic and Pacific benthic foraminifer  $\delta^{13}\text{C}$  at this time, so it is unclear whether there was an overall increase in basin-basin fractionation.

The 4.6 to 3.5 Ma interval of greatly reduced opal sedimentation off California coincides with a period of high NADW production (Billups *et al.*, 1998). Kwiek and Ravelo (1999) argue that North Pacific Intermediate Water (NPIW) ventilation from the North Pacific was enhanced during this time, resulting in a deeper nutrient maximum in intermediate waters of California margin Sites 1014 and 1018. A deeper nutricline, coupled with a probable reduction in wind-driven upwelling along the California margin during climatically warm interval (Figure 3), would have caused reduced diatom productiv-

ity during the early and middle part of the Pliocene (Barron, 1998).

The period of reduced diatom sedimentation off the coast of California (4.6-2.7 Ma) coincides exactly with a period of enhanced biogenic opal mass accumulation rates at subarctic northwest Pacific ODP Site 882 (Barron, 1998; Haug *et al.*, 1999). Haug *et al.* (1999) argue that a major step in the closure of the Central American Seaway occurred at 4.6 Ma and that the interval from 4.6 Ma to about 3.7 Ma marked a period of increasing thermohaline circulation (based on comparison of their opal record at Site 882 with  $\delta^{13}\text{C}$  values of the epibenthic foraminifer *Cibicidoides wuellerstorfi* at Caribbean ODP Site 999).

In contrast to the decline of opal during the early Pliocene, high production of  $\text{CaCO}_3$  characterized the interval between 3.5 and 2.6 Ma (Ravelo *et al.*, 1997; Lyle *et al.*, 2000). Ravelo *et al.* (1997) attribute this mid Pliocene carbonate event to increased carbonate productivity, not reduced dissolution. They argue for increased offshore upwelling caused by an enhanced wind stress curl along the California margin during the middle part of the Pliocene. Increased offshore winds, however, are unlikely because of the scarcity of diatoms, an indicator for coastal upwelling.

Diatom productivity strengthened only during the late Pliocene (at about 2.7 to 2.4 Ma) after a period of major high latitude cooling led to enhanced upwelling along the California coast (Barron, 1998; Maruyama, 2000; Janecek, 2000).

## CONCLUSIONS

Biostratigraphic and magnetostratigraphic data (Lyle *et al.*, 2000) allow correlation of the weight percent opal records (Janecek, 2000) at ODP Site 1010 off northern Baja California, Mexico and Site 1021 off northernmost California. These data reveal that biosiliceous sedimentation declined by a factor of three at about 11.5 Ma and again by a factor of two at about 7.6 Ma in offshore waters of the California margin, as part of a late Miocene trend of decreasing diatom content. These declines appear to coincide with increasing fractionation of opal to nearshore regions, as evidenced by limited data on diatom sedimentation from onshore California sections. Specifically, Isaacs (1983, 1985) reports a doubling of biosilica accumulation at about 7.6 Ma at the base of her clayey siliceous members of the Monterey Formation in the Naples Beach section, near Santa Barbara, precisely at the time when weight percent opal experienced a two-fold decline at offshore Sites 1010 and 1021.

In addition to the major drops in offshore opal sedimentation starting at 11.5 and 7.6 Ma, the Site 1010 and Site 1021 weight percent opal records display considerable similarity. Relatively low opal values without high amplitude fluctuations characterize the intervals

between 11.5 to 10.0 Ma, 7.6 to 6.5 Ma, and after 4.6 Ma, whereas periods of relatively increased, but highly variable opal content occur from 10.0 to 7.6 Ma and from 6.5 to 4.6 Ma. Periods of reduced opal deposition in offshore sections tend to coincide with times of reduced latitudinal thermal gradients and higher production of Northern Component Water in the North Atlantic. Although one might assume that nutrient levels North Pacific in intermediate waters were greater during such intervals, reduction in the southward flow of the California Current and deepening of the nutricline probably combined to reduce offshore diatom production during these climatically warm intervals. Conversely, periods of increased opal in offshore sediments (10.0 to 7.6 Ma and 6.5 to 4.6 Ma) coincided with increased latitudinal thermal gradient and intensified southward flow of the California Current.

The early Pliocene and early part of the late Pliocene (4.6 to *ca.* 2.7 Ma) are marked by the near absence of diatoms in offshore sites, while diatoms are masked by clastic components in onshore sections. Diatom production was greatly reduced along the California margin during this period of reduced latitudinal thermal gradients at the same time that production dramatically increased in the subarctic northwest Pacific, suggesting fractionation of opal to higher latitudes

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