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Paleotemperature oscillations in the Middle and Late Miocene of the northeastern Pacific

ABSTRACT

The paleoclimatic and paleoceanographic history of the Middle and Late Miocene marginal eastern North Pacific has been studied in a north-to-south transect encompassing DSDP Site 173, the Newport Beach surface section, and DSDP Site 470, based on quantitative diatom and planktic foraminiferal analyses. Fourteen cold and 12 warm events that show close agreement with other microfossil studies as well as oxygen isotope records from low-latitude Pacific sites have been identified. Hiatuses are recognized at 7 to 6.5 Ma, 9.8 to 8.5 Ma, and 12 to 11 Ma at the three reference localities, and they correspond to widely recognized deep-sea hiatuses in the World Ocean.

INTRODUCTION

In recent years, Miocene paleoclimatology and paleoceanography have received considerable attention in studies that include analyses of oxygen isotopes (Keigwin, 1979; Woodruff et al., 1981; Savin et al., 1981) and calcium carbonate (Dunn and Moore, 1981), quantitative studies of microfossils (Keller, 1980a, 1981a; Haq, 1980; Lohmann and Carlson, 1981; Bukry, 1981, in press) and the recognition of widespread deep-sea hiatuses (Keller and Barron, in press). Integration of these studies has resulted in refinements in biostratigraphy and in the paleoclimatic and paleoceanographic history of the Miocene oceans.

Most of these studies have concentrated on low-latitude areas where numerous sections with uncomplicated biostratigraphy have been cored by the Deep Sea Drilling Project. High species diversity, good preservation, and the ability to run oxygen isotope analyses on specific foraminiferal taxa have provided a high resolution biochronology and paleotemperature curve for the equatorial Pacific region. (For a summary of recent data analyses see Savin et al., 1981.) In contrast, the generally low species diversity among planktic foraminiferal faunas and intervals of carbonate dissolution have made it difficult to obtain a similar record for the middle to high latitudes in the North Pacific. New quantitative planktic foraminiferal analyses and diatom studies have considerably refined the biochronology and paleoclimatic history of middle latitudes and have provided detailed correlation with low latitudes (Ingle, 1973; Keller, 1980a; Barron, 1980, 1981; Keller and Barron, 1981). Biochronologic resolution of middle-latitude sequences is now comparable to that of low latitudes; the paleoclimatic history, however, is not. This is primarily due to carbonate dissolution and rarity of the necessary species for $\delta^{18}\text{O}$ analyses. To overcome this problem we have combined quantitative diatom and planktic foraminiferal studies in three Miocene sections including DSDP Sites 173 and 470 and the Newport Beach surface section and derived an integrated temperature curve for the marginal northeastern Pacific. The results of this study not only provide a detailed paleoclimatic history, but also permit interpretation of the complex depositional history of the Monterey Formation and related siliceous rocks around the North Pacific margin.

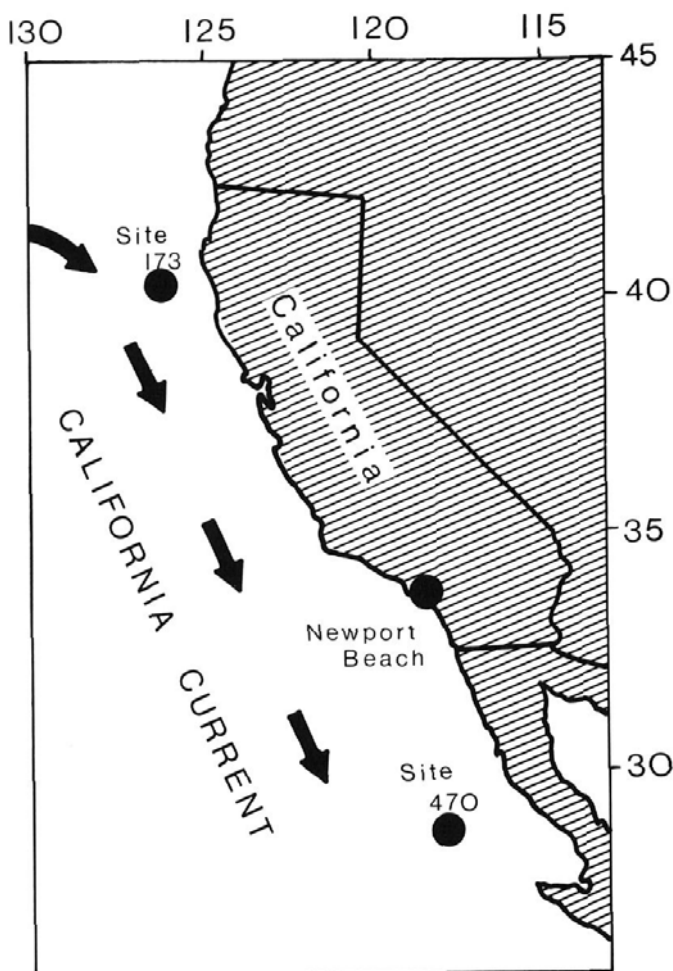
The Middle to Late Miocene marginal northeastern Pacific is an ideal region to monitor fluctuations in the pole-to-equator thermal gradient, as has been pointed out by Ingle (1973). The cool-water California Current has been active since at least the Cretaceous (Sliter, 1972), affecting the microfossil assemblages deposited between 40°N and 25°N along the coast of California and Baja California. Faunal and floral assemblages and the depositional history of the siliceous middle to

upper Miocene Monterey Formation are intimately tied to the fluctuations of the California Current (Ingle, 1973, 1981). Siliceous rocks of equivalent age are common around the North Pacific margin, and declining Neogene paleotemperatures accompanied by increased upwelling have been invoked to explain their widespread occurrence in the middle and upper Miocene (Ingle, 1981).

Deep Sea Drilling Project Sites 173 ($39^{\circ}57.71'N$, $125^{\circ}27.12'W$, water depth 2927 m) and 470 ($28^{\circ}54.46'N$, $117^{\circ}31.11'W$, water depth 3549 m) and the Newport Beach section of the Monterey Formation ($33^{\circ}38'N$, $117^{\circ}53'W$) in southern California form a north-to-south transect within the area of influence of the California Current (text-fig. 1). Bukry (1973), Ingle (1973), and Keller (1978, 1980a) have researched the paleoclimatic history at Site 173 using silicoflagellates and planktic foraminifers. At Newport Beach a detailed paleoclimatic study based on radiolarians has recently been completed by Weaver et al. (1981). Site 470, which is close (8 km) to the 1961 Experimental Mohole Drilling Site, is situated at the distal end of the California Current, which makes it ideal for paleotemperature studies. Nevertheless, only Bukry (1981) has published Miocene paleotemperature data based on silicoflagellates, although some speculations regarding paleoclimatic conditions were also made by Bandy and Ingle (1970) based on planktic foraminifers from the Mohole site.

Quantitative studies of planktic foraminifers have long been used as a tool for paleoclimatic interpretations (Ingle, 1967, 1973; Bandy and Ingle, 1970; Kennett, 1970; Kennett and Vella, 1975). These early studies and more recent reports by Srinivasan and Kennett (1981a, 1981b) and Keller (1980a, 1980b, 1981a, 1981b) of low- and middle-latitude assemblages of the Pacific provide a framework for identifying "warm", "temperate", and "cold"-water planktic foraminifers for the Miocene.

The use of diatoms for Miocene paleotemperature studies has lagged, owing to a lack of quantitative studies. Hence, quantitative diatom biostratigraphy and paleoclimatic interpretation are presented here for the first time. The present report and an unpublished quantitative study at equatorial Pacific DSDP Site 77B (Barron, unpublished data) allow interpretation of the paleoclimatic affinities of most of the Miocene diatom species. Qualitative studies such as those of Gombos (1975) and Burckle (1972, 1978) of equatorial assemblages and those of Schrader (1973), Koizumi (1973), and Barron (1980, 1981) of middle- to high-latitude assemblages have been helpful in establishing the basis for Miocene diatom paleotemperature studies.



TEXT-FIGURE 1

Location of DSDP Sites 173 and 470 and the Newport Beach surface section.

METHODS

Samples were collected for study from DSDP Sites 173 and 470. The Newport Beach samples of Barron (1976) were re-examined for diatoms and processed and examined for planktic foraminifers. Diatom processing followed the steps outlined in Barron (1976), with the exception of the Site 173 samples that were provided by L. H. Burckle. Diatom strewn slides were traversed at a magnification of 1250 by light microscope and the first 300 planktic diatoms were tabulated (tables 1–3). The counting techniques of Schrader and Gersonde (1978) were employed on vertical traverses across the slide. Care was taken to avoid abnormally thick or thin areas on the slide. Samples were processed and counted for planktic foraminifers following the procedure outlined in Keller (1980a).

BIOSTRATIGRAPHY

North Pacific diatom biostratigraphy, as developed by Koizumi (1973) and Barron (1980, 1981), was integrat-

TABLE 1

Percent abundance of planktic diatoms in middle and upper Miocene of Site 173. Three hundred specimens were counted in each sample. * = reworked.

[illegible] $(X = \leq 2X)$

TABLE 2

TABLE 2
Percent abundance of planktic diatoms in Middle Miocene to earliest Pliocene of Newport Beach section. Three hundred specimens were counted in each sample. Samples are Barron's (1976). * = reworked.

[illegible]

(X = < 2%)

TABLE 3

Percent abundance of planktic diatoms in middle and upper Miocene of Site 470. Three hundred specimens were counted in each sample. * = reworked.

DSOP SITE 470		ACTINOCYCLUS ELLIPTICUS	A. INGENS	A. spp.	ASTEROMPHALUS spp.	COSCINODISCUS LEWISIANUS	C. MARGINATUS	C. NODULIFER	C. Plicatus s. ampl.	C. TABULARIS s. ampl.	C. TEMPEREI var. DELICATA	C. TUBERCULATUS	C. spp.	CRASPEDODISCUS COSCINODISCUS	DEUTICLOPUS DIMORPHA	D. HUSTEDTII	D. HYALINA	D. LAITA	D. NICOBARICA	D. PRAEDIMORPHA	D. PUNCTATA var. HUSTEDTII	HEMIDISCUS CUNEIFORMIS	MITZSCHIA spp.	RHIZOLENIA BARBOI	R. PRAEBARBOI	R. spp.	ROSSIELLA PALEACEA	ROUXIA spp.	SYNEDRA JOHNSONIA	THALASSIONEMA HIPOKARTENSIS	T. NITZSCHIOIDES	T. sp. 1	THALASSIOSIRA ANTICUA	T. BURCKLIANA	T. ECCENTRICA	T. LEPTOMIS	T. NATIVA	T. sp. 1	THALASSIOTRICH LONGISSIMA	TRICERTATIUM CINNAMOMUM	Miscellaneous spp.		
SAMPLE	ZONE/SUBZONE																																										
8-2 (12-14 cm)	T. antiqua		X	X		7						X		6			X	*	*			2	X	5			9	7	38		9	X							2	X	7		
8-3 (12-14 cm)				X		10	X	X				X		3								X	X	X	4		5	4	42	10	2		X	X				3	X	10			
8 cc		X	X	X		5	X					X		X				*	*	*		X	2	X	2		7	12	41	14	X	X							2	X	7		
9-1 (40-42 cm)			X	X	X	4	X	*				X		4			X					X	3	X	10		12	18	27	9	X	X	X								X	6	
9-2 (40-42 cm)			X	X	X	7	X		X			2		2			X					X	2	2	5		10	20	33	7	X	X		X						X	4		
9-3 (40-42 cm)			X	X	X	3	X					X		X								3	X	X			X	36	35	8	X	X		X						7			
9 cc		X	X	X		4	3				2		2									4	6	7		X	20	3	32	7	X	X	X	X				X	X	8			
10-1 (40-42 cm)	D. hustedtii a	X	X	X		X	X	X	X	X		X		43								X	X	3	3		X	X	38	X									4	X			
10-2 (40-42 cm)		X	X	X		2	X							37			X					X	X	7	3		2	X	42	X								X	X	X			
10-2 (73-75 cm)		X	X	X	X	3	X	X			X		17									X	X	11	2		4	4	50	X								X	3	X	X		
11-1 (40-42 cm)	d	X	4			9	X	X	X		2	X	18			X						X	5	4		X	25	28	X								X		X	3			
11-2 (40-42 cm)			X			8	X	X	X		2	X	17			X						X	12	7		X	3	41											6	X			
11-3 (40-42 cm)		X	X	X		28	X		X		X	2	24			X	X	X				X	X	7	2	X	X	28	X										X	3	X		
11-4 (40-42 cm)			X			12	X	X			X	X	15			X						X	5	2		X	4	48	X										2	6			
11-5 (40-42 cm)		X	X			14	X	X	X		X	X	14			X	X	X				X	6	X		X	6	47	X							X			X	5	X		
11-6 (40-42 cm)			X			20	X	X	X		X	X	8			X	X					X	9	8		X	2	38	X							X			7	X			
11-7 (40-42 cm)	D. hustedtii + D. lauta	3	2	X		4	X	X			X		11			X	*	X				X	X	8	3		7	47							X				6	X			
12-1 (14-16 cm)		X	X			X	X	X	X		2		29	X	X	X						X	X	18	X		X		33	10							X			6			
12-2 (40-42 cm)		2				X	X	X			X	2	26	X	X	3						X	11	2		2	45	2											5	X			
12-3 (40-42 cm)		X	X			3	X	X	3				27	X	X	3						X	7	2		2	45	X											3				
12-4 (40-42 cm)		X	X	X	X	X	X	X	X		2		20	X	X	3						X	14	7		X	X	*	38	X									5	X			
12-5 (40-42 cm)		X	X			X	X	X	X	X		X		24	X	X	5					X	X	14	5		X		34	X									10				
12-6 (40-42 cm)		2				2	X	X	X	X		X		32	X	X	4					X	14	3		X	*	31	4										4				
12-8 (40-42 cm)		2				6		X					28	X	2	6						2	4	6		X	2	*	32	X									6				
13-1 (40-42 cm)		3				2	X	X					39			3	*	X				X	X	X	2				43	X										4	X		
13-2 (40-42 cm)		X				2	2				X		36	X	X	6	X					2	2	9		X		32												4	X		
14-1 (40-42 cm)		X	3			3	X	X	X		X	X	9			4	60	X				X	3	2		X	X	19	X											2			
14-2 (40-42 cm)		X	2	X	X	2	2	X	X		X	2	27	X	X	7	X					X	X	X	15		X		30	2										5			
15-1 (40-42 cm)		b	X	5	2	X	6	X	2	3		X	X	12	X	2	X	14	2			X		7	X		X	X	27	X										9	X	X	
15-2 (40-42 cm)			X	3	X	X	3	X	X	X		X	X	20			3	X	20	X			4	2			X		27	2										6			
15-3 (40-42 cm)			X	3	X		3	X	X	X		X		18			X	X	21	X		X	X	2			2	35	2												6	X	
15-4 (40-42 cm)				5	X	X	X	X	X	X	X		X	X	15			4	20				X	3	3		X	X	X	35	X										5	X	
15-5 (40-42 cm)			X	6	X	X	3	X	X	3		X		38	X	2	X	9	X							2	X	X	18												13	X	
15 cc				3	X	X		X	X	X	2		X	X	18			3	X	42			X	X	4				17	X											5		
16-1 (40-42 cm)		a	X	2	X		11		X	2		X	X	53			5	X	5			X	X	2			3	5													6		
16-2 (40-42 cm)			X	5	X		9		X	2		X		52	X	X	X	X				X	X	4		X	X	10												12	X		
16-3 (40-42 cm)				13	X	2	2	3					3	X	20			X	7				X	X	4		X	X	29	X											8		
17-1 (40-42 cm)			X	12	X	X	3	3		X			X	X	26			X	X	6			X	X	4		X	2	28												9		
17-3 (40-42 cm)				25	X	X		11		X	X		X	3	12			X	X	10			X		2			2	17													13	
17-3 (79-80 cm)	D. lauta b		5		X		4	X				X	X	X	72	5									X			X	5	X											2		

(X = <2%)

ed with middle-latitude planktic foraminiferal biostratigraphy (Keller, 1980a) to provide a detailed biostratigraphy for Site 173, the Newport Beach section, and Site 470 in Keller and Barron (1981). Direct (Burckle, 1978a) and indirect (Barron, 1980, 1981) correlation of diatom datum levels (first and last occurrences) to paleomagnetic stratigraphy allow assignment of absolute ages to these sequences (see Keller and Barron, 1981). We employ the paleomagnetic time scale of Mankinen and Dalrymple (1979) and note that other paleomagnetic time-scales will result in slightly different absolute age estimates. In the following sections age calibration of datum levels allows us to compare variations

in the sediment accumulation rates of the three sites and their depositional history within the California Current system. We then discuss the quantitative aspects of diatom and planktic foraminiferal analyses and derive a paleoclimatic index curve based on cold-water faunal and floral elements.

Sediment accumulation diagrams

Construction of sediment accumulation rate (or age vs. depth) diagrams for sedimentary sections is a convenient graphical means of extrapolating the age of selected intervals and of displaying hiatuses or uncon-

formities. Such diagrams may be considered a variation of the graphical correlation technique employed by Shaw (1964). The resulting composite standard section is subsequently used as a time-scale which assumes constant rates of sediment accumulation between the plotted ages of individual microfossil datum levels.

Because detailed paleoclimatic studies require rigorous ties to an absolute time-scale, construction of sediment accumulation rate diagrams for Site 173, the Newport Beach section, and Site 470 is a necessary step which also facilitates interpretation and evaluation of data.

Text-figures 2–4 show the sediment accumulation rate diagrams for Site 173, the Newport Beach section and Site 470. Assignment of absolute age to the individual datum levels follows Keller and Barron (1981).

The plots for Site 173 and Newport Beach (text-figs. 2, 3) show many similarities. The Middle Miocene between 15 and 12 Ma has a relatively high sediment accumulation rate (30 m/m.y. at Site 173, 65 m/m.y. at Newport Beach) compared with those of the Late Miocene prior to 6.5 Ma (15 m/m.y. at Site 173, 23 m/m.y. at Newport Beach). Hiatuses are observed at around 11.5 and 7.0 Ma in both sections. The older hiatus ranges in age from about 12.0 to 11.0 Ma at Site 173 and from about 12.4 to 11.3 Ma at Newport Beach. The younger hiatus spans the interval from about 7.6 to 5.8 Ma at Site 173 and from about 7.2 to 6.5 Ma at Newport Beach, where its existence is supported by benthic foraminiferal studies (K. McDougall, oral communication, 1981) that show a pronounced shoaling at 255 m in the section. Above the younger hiatus at Newport Beach, the sediment accumulation rate increases dramatically to 105 m/m.y., a four-fold increase. This increase is typical of the uppermost Miocene of the California area (Barron, 1980; Rowell, 1981) and most likely reflects an increased terrigenous input (Ingle, 1973). Uppermost Miocene sediments above the hiatus at Site 173 are hemipelagic. Typically, this sedimentation change occurs immediately above the Monterey Formation, coincident with the change from laminated to massive and more terrigenous diatomaceous sediments. At Newport Beach, however, the increase occurs 100 m below the top of the Monterey Formation.

Significantly higher sediment accumulation rates in the latest Miocene (6.4 to 5.0 Ma) as compared to the middle and early Late Miocene (10.0 to 6.5 Ma) have been observed throughout the North Pacific (Keller, 1980a). A similar marked difference has been noted in the Indian Ocean by Vincent et al. (1980). Both Keller (1980a) and Vincent et al. (1980) invoked increased biologic productivity as the cause for the increased

rate. Hence, it is possible that at least part of the increased rate in the Monterey Formation at Newport Beach reflects increased upwelling and increased productivity of diatoms. However, the benthic foraminiferal evidence of shoaling in the Newport Beach section and an abrupt increase in terrigenous input in other California sections at this time (Barron, 1980; Rowell, 1981) argue for a regional tectonic event at about 7.0 to 6.6 Ma.

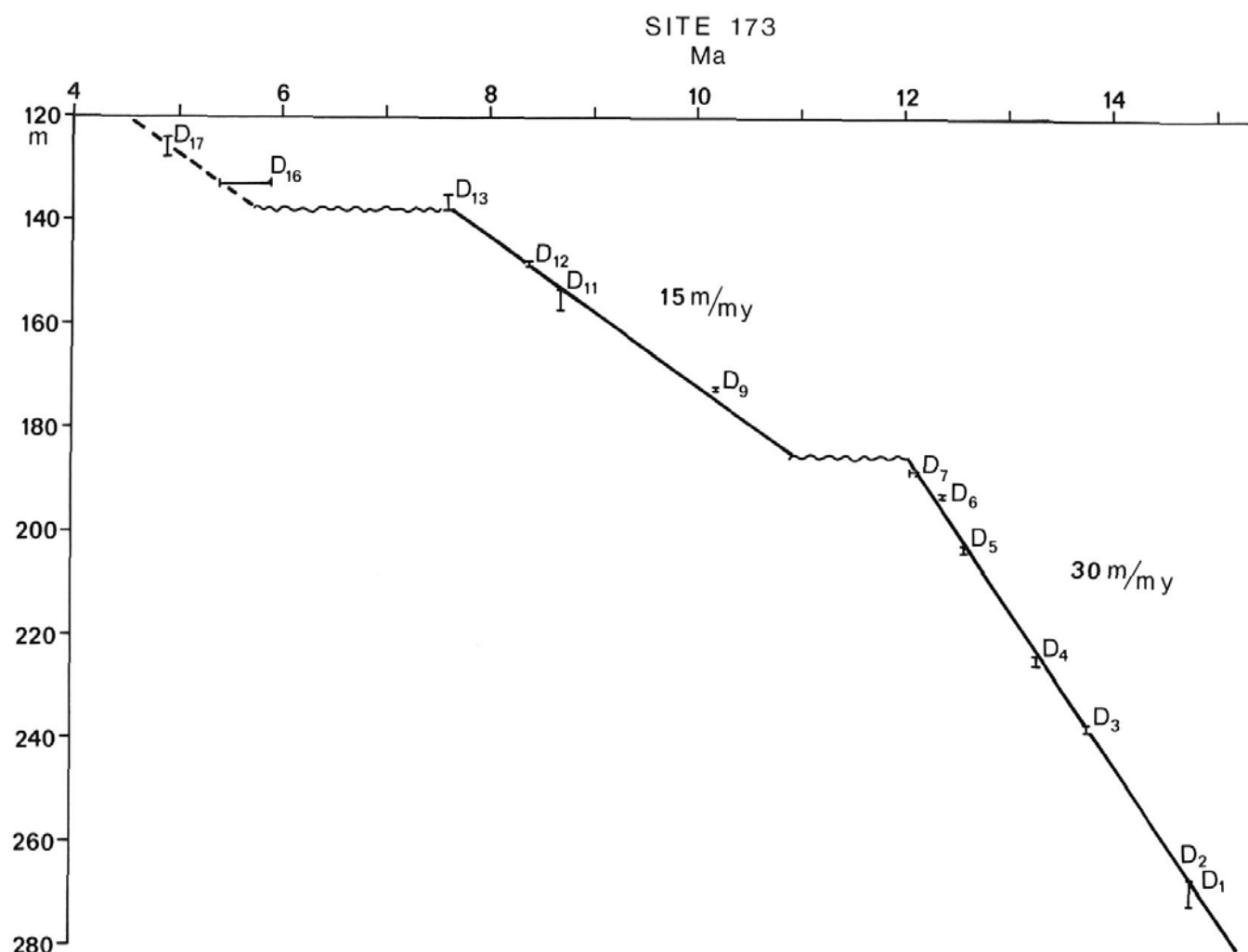
The sediment accumulation rate diagram for Site 470 (text-fig. 4) also shows two hiatuses, although only the younger one (from 7.2 to about 5.5 Ma) (Keller and Barron, 1981) coincides with hiatuses in the Site 173 and Newport Beach sections. The older hiatus at Site 470 encompasses an interval from about 9.8 to 8.5 Ma, an interval which is represented by sediments at Site 173 and Newport Beach. The sediment accumulation rate for the Middle and early Late Miocene at Site 470 is about 19 m/m.y., and presumably, the rate for the middle Late Miocene is comparable. Basalt was encountered at 167 m subbottom depth at Site 470 (Core 18 of Hole 470 and Core 7 of Hole 470A), and the extrapolated age of the base of the sediment section at Site 470 is 14.4 Ma (see also Barron et al., 1981).

The hiatuses noted at Site 173, Newport Beach, and Site 470 correspond with intervals of widespread deep-sea hiatuses recognized throughout the World Ocean (Keller and Barron, in press). The younger hiatus in the three sections correlates with hiatus NH 6,* which spans the interval between about 7.5 and 6.2 Ma. The older hiatus at Site 173 and Newport Beach is equivalent to hiatus NH 4 (12.0 to 11.0 Ma), and at Site 470 the older hiatus corresponds with hiatus NH 5 (10.0 to 9.0 Ma).

Quantitative diatom biostratigraphy

In a companion paper (Keller and Barron, 1981) we demonstrated how diatom and planktic foraminiferal biostratigraphy based on datum levels could be further refined at Site 173, Newport Beach, and Site 470 by quantitative planktic foraminiferal analyses. Quantitative diatom biostratigraphy has yet to be attempted for the Miocene; however, the quantitative diatom data in tables 1–3 and the sediment accumulation rate diagrams (text-figs. 2–4) allow us to test the biostratigraphic utility of quantitative diatom data. Text-figure 5 presents the quantitative distributions of stratigraphically significant diatoms in the Site 173, Newport Beach and Site 470 Miocene sections. It is immediately apparent that the quantitative diatom distribu-

* Neogene hiatus, i.e., NH 1–7, denotes seven Miocene hiatuses with widespread occurrence as identified by Keller and Barron (in press).



TEXT-FIGURES 2-4

Sediment accumulation rate diagrams for DSDP Site 173, the Newport Beach section, and DSDP Site 470. Diatom datum levels: D₁ = last appearance of *Anellus californicus*; D₂ = first appearance of *Denticulopsis hyalina*; D₃ = transition from *D. hyalina* to *D. hustedtii* (first predominant *D. hustedtii*); D₄ = first appearance of *D. praedimorpha*; D₅ = first appearance of *Coscinodiscus temperei* var. *delicata*; D₆ = first appearance of *Rhizosolenia barboi*; D₇ = last appearance of *Craspedodiscus coscinodiscus*; D₈ = first appearance of *D. dimorpha*; D₉ = last appearance of *D. dimorpha*; D₁₀ = first appearance of *Nitzschia fossilis*; D₁₁ = first appearance of *Thalassiosira burckliana*; D₁₂ = first appearance of *T. antiqua*; D₁₃ = last appearance of *T. burckliana*; D₁₄ = last appearance of *Thalassionema hirosakiensis*; D₁₅ = last common appearance of *Rouxia californica*; D₁₆ = overlap of *Thalassiosira miocenica* and *N. miocenica*; D₁₇ = first appearance of *T. oestrupii*. C = coccolith datum level: last appearance of *Sphenolithus heteromorphus*. Dashed line = inferred plot; wavy line = hiatus.

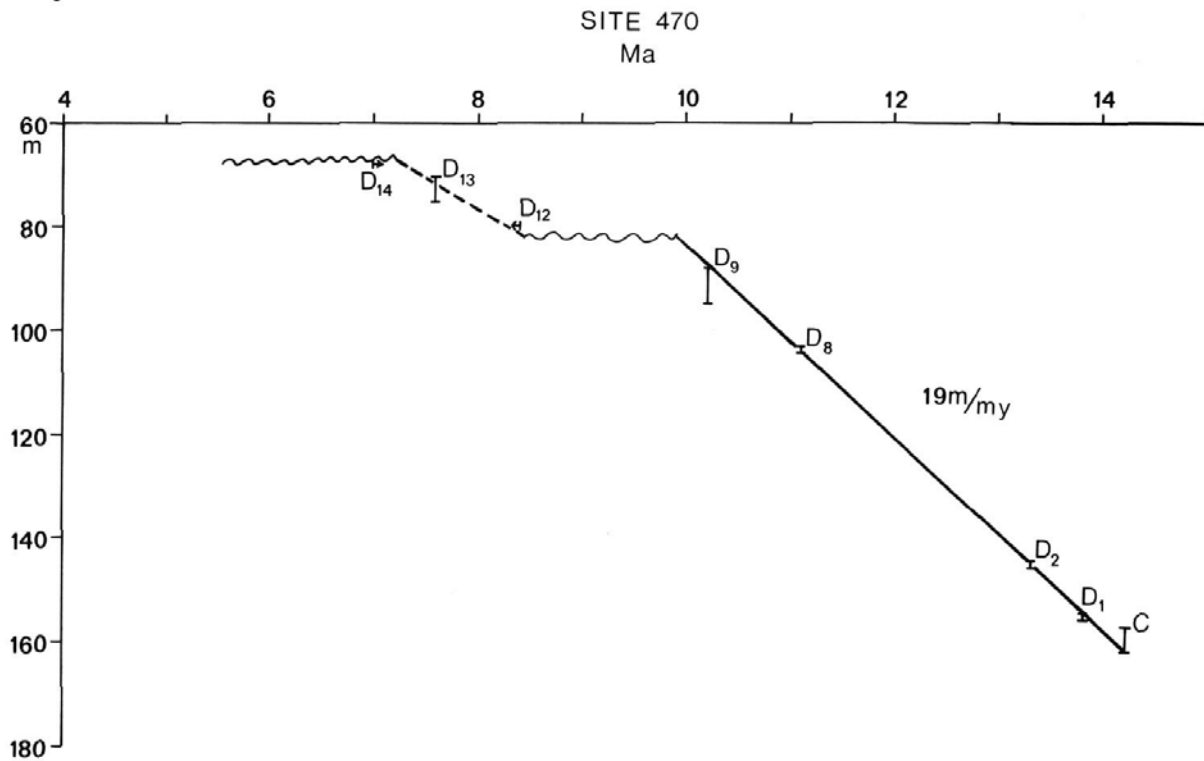
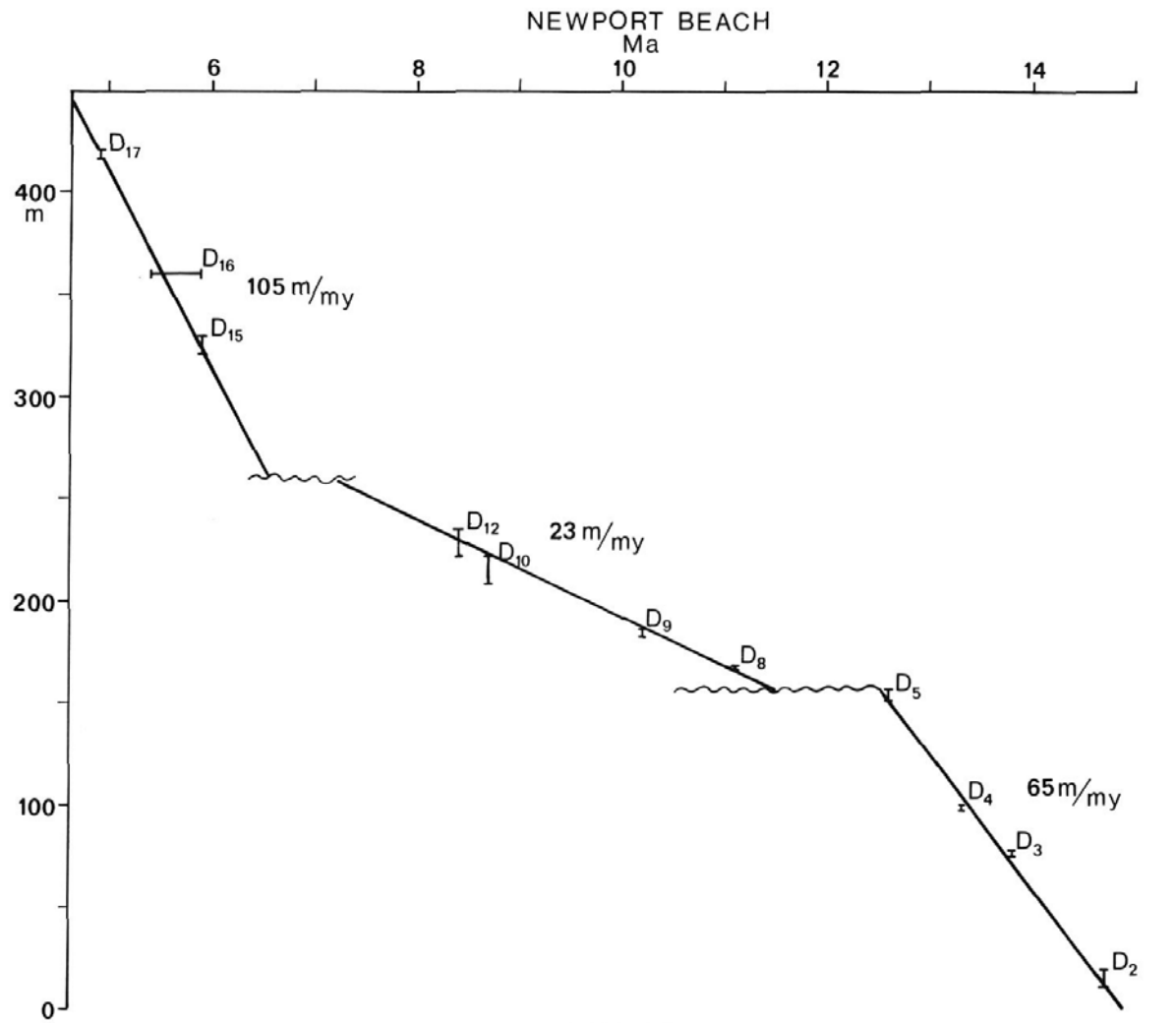
tions of the three sections are markedly similar, implying similar floral response to major oceanographic changes in the California Current system. Lines of correlation based on datum-level diatom biostratigraphy provide the means to compare selected intervals within the sections which, for convenience, will be discussed in terms of the diatom zones and subzones in the following paragraphs.

Subzone a of the *Denticulopsis lauta* Zone is characterized by common *Denticulopsis lauta* (Bailey) Simonsen and *Synedra jouseana* Sheshukova-Poretzka (tables 1, 2; text-fig. 5). Both species decline sharply above the subzone, a relationship which also holds

true in the type section of the Luisian Stage in central California (Baldauf and Barron, 1982).

Denticulopsis hyalina (Schrader) Simonsen is the most distinctive diatom of Subzone b of the *D. lauta* Zone. At both Site 173 and Newport Beach an initial increase in *D. hyalina* is followed upsection by a minor decline (at 14.5 Ma) and a substantial increase (at 14.3 Ma). Planktic assemblages in the upper half of the subzone are dominated by 70 to 80% *D. hyalina*.

The dominance transition from *D. hyalina* to *D. hustedtii* (Simonsen and Kanaya) Simonsen (i.e., first common, consistent *D. hustedtii*) in the lower part of



the *Denticulopsis hustedtii*-*D. lauta* Zone (13.8 Ma) is sharp at Site 173, Newport Beach and Site 470 (text-fig. 4), and available correlations suggest it is isochronous throughout the middle-latitude (25–40°N) North Pacific (Barron, 1980, 1981; Keller and Barron, 1981).

Subzone a of the *D. hustedtii*-*D. lauta* Zone is characterized by relatively common *D. hustedtii*. At both Sites 173 and 470 *Actinocyclus ingens* Rattray is common in the lower part of the subzone but declines in the upper part (tables 1, 3).

In all three sections *D. hustedtii* has an abundance peak across the Subzone a/Subzone b boundary within the *D. hustedtii*-*D. lauta* Zone. A second abundance peak in *D. hustedtii* upsection in Subzone b is correlatable with Site 173 (at 208 m) and the Newport Section (at 140 m) and has an extrapolated age of 12.8 Ma (text-figs. 1, 2). Within Subzone b, *D. praedimorpha* (Akiba) Barron fluctuates in abundance in all three sections. Abundance peaks at 140 m at Site 470 and at 122 m at Newport Beach each have an extrapolated age of 13.0 Ma; however, no apparent peak is found at an equivalent horizon (ca. 214 m) at Site 173. It is unclear whether this discrepancy is due to the limits of sampling and recovery at Site 173 or whether it reflects a difference in ecologic conditions between Site 173 and the southern sites.

Site 470 is the only section with a complete Subzone c of the *D. hustedtii*-*D. lauta* Zone. The upper portions of Subzone c are removed at a hiatus at 185 m at Site 173, whereas the lower portions of the subzone are removed at a hiatus at 159 m at Newport Beach (text-figs. 2, 3). Both Sites 173 and 470 show an abundance peak in *D. praedimorpha* near the base of the subzone (text-fig. 5). The sediment accumulation rate curves for these sites (text-figs. 2, 4) both give estimates of 12.2 Ma for this abundance peak. Above the peak, *D. praedimorpha* declines rapidly in abundance in Subzone c. This decrease coincides with an increase in the abundance of *Thalassionema nitzschioides* Grunow from values around 30% to values around 50% at Site 470 (table 3). Although Subzone c is truncated at Site 173 and Newport Beach, a similar increase through this interval is also apparent (text-fig. 5).

The abundances of stratigraphically important diatoms within Subzone d of the *D. hustedtii*-*D. lauta* Zone show certain differences from section to section. Northern Site 173 has relatively common *Denticulopsis dimorpha* (Schrader) Simonsen in this subzone, whereas the abundance of this taxon drops off sharply to the south. Correspondingly, southern Site 470 contains an abundance peak (25%) of *Thalassionema hirosakiensis* (Kanaya) Schrader (at 10.5 Ma) within this subzone, but abundance values for this species are considerably less (no more than 7%) in the more

northern Newport Beach section and Site 173. Both taxa are strongly resistant to dissolution, so it is unlikely that selective dissolution is the cause of these differences. Abundance values of *Thalassionema nitzschioides* remain high (50%) throughout most of Subzone d, although the extreme fluctuations (27 to 91%) within this interval at Newport Beach (table 2) may be due to local conditions or downslope transport.

Subzone a of the *Denticulopsis hustedtii* Zone is characterized by a high abundance of *Denticulopsis hustedtii* (30–40%) in its lower half and a rapid decline in *D. hustedtii* midway through the subzone at about 9.3 Ma. This rapid decline is apparent in all three sections (text-fig. 5). Above this interval, there is an abundance peak in *Thalassionema hirosakiensis* (at 9.0 Ma) followed by an abundance peak in *Rouxia* spp. (at 8.5 Ma) at Site 173 and Newport Beach (text-fig. 5). This interval in the upper half of Subzone a of the *D. hustedtii* Zone has been truncated by a hiatus at about 82 m (between Cores 10 and 9) at Site 470 (text-fig. 4).

The *Thalassiosira antiqua* Zone is truncated at its top at Site 173 (at 138 m), Newport Beach (at 255 m) and Site 470 (at 67 m) (text-figs. 2–4). All three sections, however, contain an abundance peak of *Thalassiosira hirosakiensis* in the lower half of the zone at 8.0 Ma.

Following Barron (1976) and the sediment accumulation rate curve (text-fig. 3) the base of the *Nitzschia reinholdii* Zone (6.5 Ma) is placed at about 255 m in the Newport Beach section. The nominate species, however, is rare in the Newport Beach section. At Newport Beach the *N. reinholdii* Zone has increased abundances of *T. antiqua* (Grunow) Cleve-Fuller (4–9%) in its lower half and two peak abundances of *Rouxia* spp. (at about 6.1 and 5.9 Ma) in its middle portion. The section shown in text-figure 5 does not extend to the top of the *Nitzschia reinholdii* Zone (418 m) (text-fig. 3) at Newport Beach. The highest sample (Sample N 13) on text-figure 5 correlates with Sample 173-15-4, 40–41 cm which overlies the latest Miocene hiatus at Site 173 (text-fig. 2). This correlation is suggested by the presence of *Nitzschia miocenica* Burckle and *Thalassiosira miocenica* Schrader, low-latitude species which are restricted to a narrow horizon just below the Miocene/Pliocene boundary in California (Harper, 1977; Burckle and Opdyke, 1977; Barron, in Addicott et al., 1978).

Quantitative planktic foraminiferal biostratigraphy

In discontinuous sequences, or in the absence of datum level species due to dissolution and low species diversity, quantitative planktic foraminiferal analyses can provide paleoclimatic information as well as clues

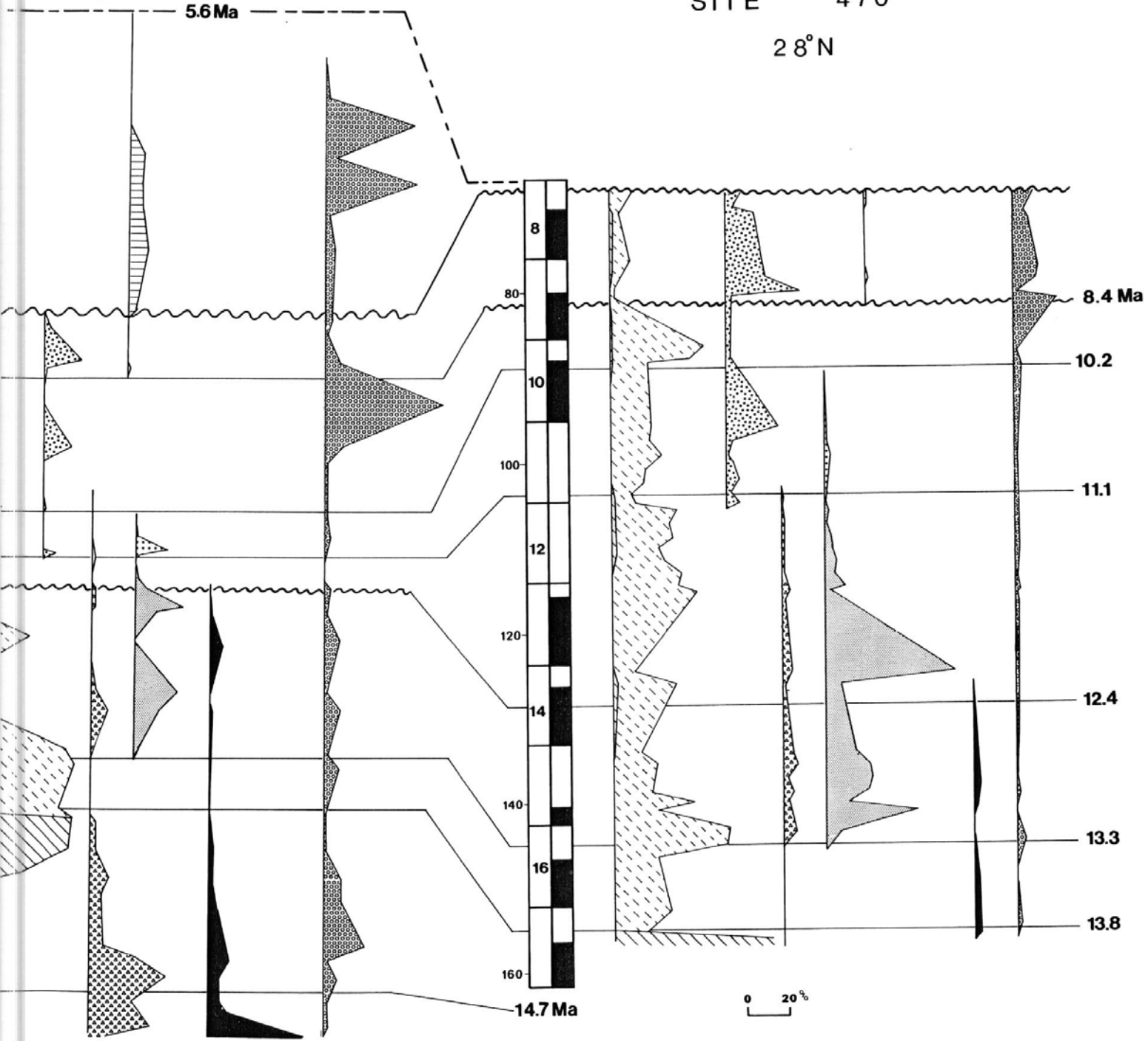
ORT BEACH

33°N

5.6Ma

SITE 470

28°N



nd 470 and the

TABLE 4

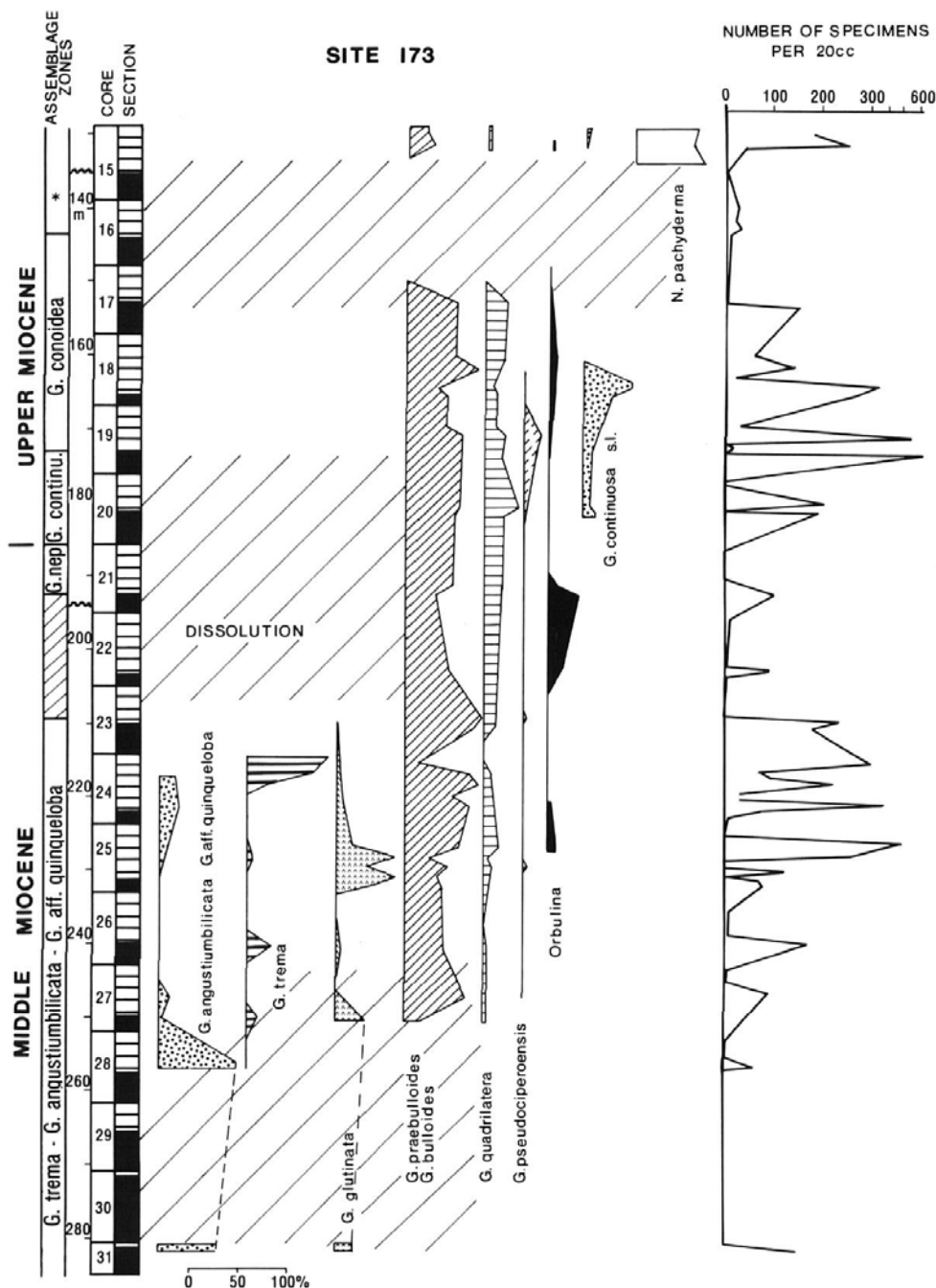
TABLE 4
Percent abundance of planktic foraminifers in the middle and upper Miocene of Site 173. Parentheses indicate raw counts, rather than percentage for fewer than 90 specimens.

[illegible]

to age based on relative abundances of common and long-ranging species. A biostratigraphic scheme for the eastern North Pacific region based on abundance fluctuations of selected planktic foraminifers was presumed by Keller and Barron (1981), and the reader is referred to that study for a complete discussion and application of quantitative biostratigraphy in this region. In this study we introduce abundance fluctuations of all major planktic foraminiferal species at Sites 173, 470, and Newport Beach in order to illustrate the similarities and differences between sections, dem-

onstrate the ability to correlate between sections and develop a paleoclimatic curve. Planktic foraminiferal species characteristic of the middle and upper Miocene marginal northeastern Pacific are illustrated in plates 1–3.

Faunal analyses of Sites 173 and 470 and Newport Beach are illustrated in text-figures 6 and 7 and tables 4 to 7 along with the zones proposed previously in Keller and Barron (1981). These figures illustrate the low diversity of middle-latitude faunas as well as a



TEXT-FIGURE 6a

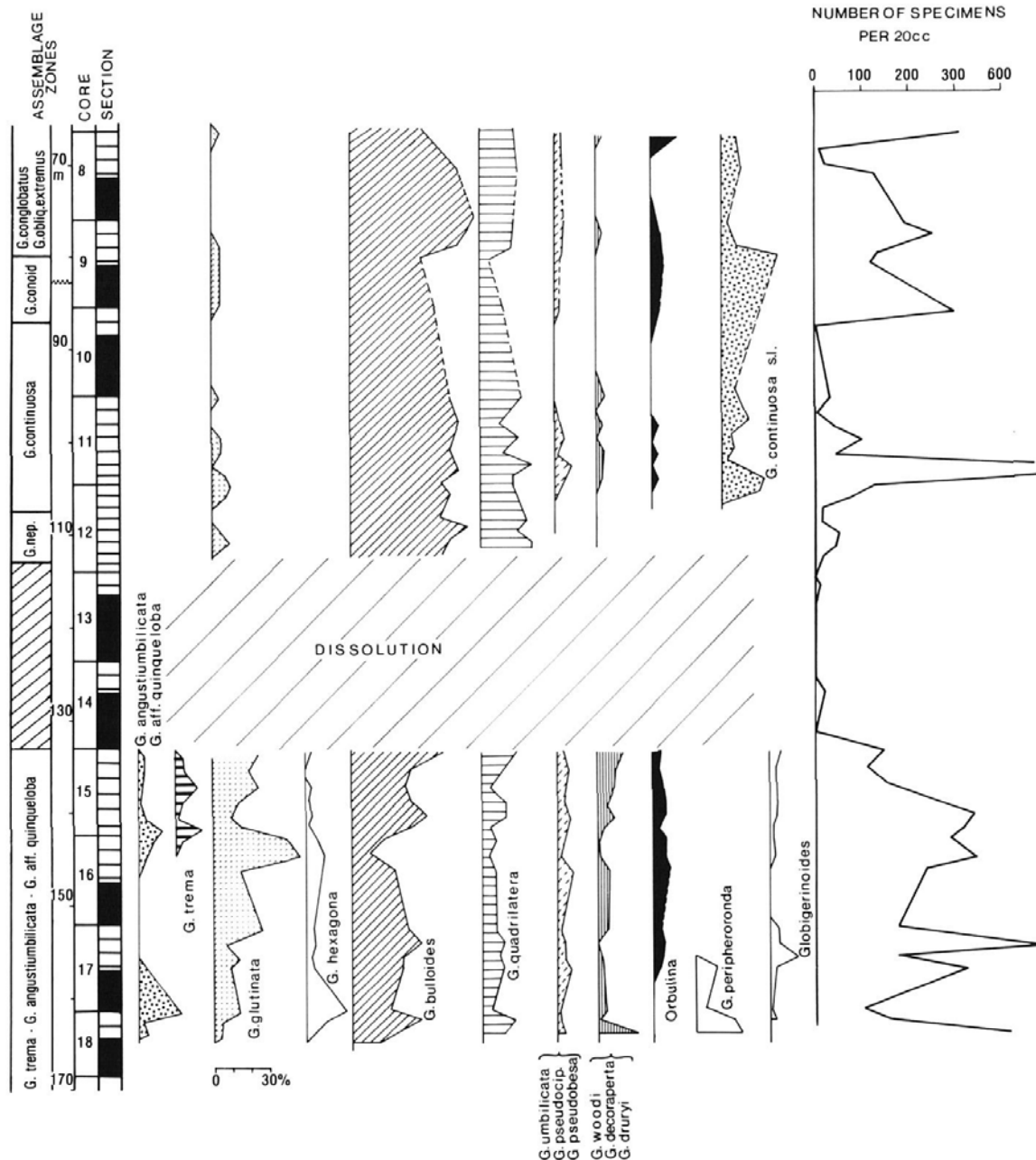
Quantitative distribution of common planktic foraminifers in the middle and upper Miocene of DSDP Site 173 and abundance of foraminifers in a 20 cc sample. Diagonal lines = dissolution; wavy lines = hiatus. * *G. conglobatus*-*G. obliquus extremis*.

systematic occurrence of intervals with nearly complete carbonate dissolution (diagonal lines). A sporadic preservation record is also indicated in the graph which plots the number of specimens present in a sample of 20 cm³. Hiatuses are often associated with dissolution intervals (zig-zag lines, text-figs. 6, 7) and have been discussed earlier.

Characteristic faunal assemblages are separated by in-

tervals of dissolution which are nearly coeval in time; hence such well-defined dissolution intervals can aid in regional correlations. For instance, the Middle Miocene *Globorotaloides trema*-*Globigerina angustumbilicata*-*G. sp. aff. G. quinqueloba* assemblage Zone is terminated in all three sequences by carbonate dissolution which removed nearly all species in Site 470 and Newport Beach, but retained the more dissolution

SITE 470



TEXT-FIGURE 6b

Quantitative distribution of common planktic foraminifers in the middle and upper Miocene of DSDP Site 470 and abundance of foraminifers in a 20 cc sample. Diagonal lines = dissolution; wavy lines = hiatus.

resistant species *Globigerina bulboides* d'Orbigny and *G. quadrilatera* d'Orbigny in Site 173.

A faunal change indicating cooler conditions and increased provincialism is apparent in the upper Miocene sediments above the middle Miocene dissolution interval, with the introduction and increasing abundance of *Globorotalia continuosa* Blow s.l. (*G. continuosa* Zone), reaching a peak at about 9.3 Ma (*G.*

conoidea Zone, Keller and Barron, 1981). The more temperate species *Globorotaloides trema* Lipps, *G. hexagona* (Natland), and *Globigerina angustiumbilitata* Bolli disappear, whereas the cool temperate species *Globigerina bulboides* and *G. quadrilatera* generally increase in abundance. The apparent similarities of the faunal sequences, dissolution intervals and hiatuses, are also illustrated in text-figure 5 of Keller and Barron

Quantitative distribution of common planktic foraminifers and planktic foraminifer abundance in middle and upper Miocene of Newport Beach section. Diagonal lines = dissolution. Wavy lines = hiatus.

PALEOCEANOGRAPHY AND PALEOCLIMATOLOGY

Paleoclimatic interpretations using faunal and floral assemblages are generally based on species with known temperature affinities. Abundance fluctuations of cold-water planktic foraminifers have long been used to reconstruct the paleoclimatic and paleoceanographic history of the northeastern Pacific (Ingle, 1967, 1973; Bandy and Ingle, 1970; Keller, 1978, 1980a). In these studies paleoclimatic interpretation was primarily based on abundance fluctuations of *Neogloboquadrina pachyderma* (Ehrenberg) and its coiling ratios in Pliocene to Pleistocene sequences and on the abundance of the cool temperate species *Globigerina bulloides*, *G. quadrilatera* and *Globorotalia continuosa* in the Middle to Late Miocene. These cool- to cold-water species abundance fluctuations together with the sporadic occurrence of cool-temperate to warm-temperate and subtropical species reveal major paleoclimatic fluctuations within the California Current system. Unfortunately, the record is interrupted by poor preservation and dissolution intervals. A more complete paleocli-

Planktic foraminifer paleotemperature interpretations

Planktic foraminiferal faunas of the eastern North Pacific (Sites 173, 470, Newport Beach) are characterized by cool-temperate Middle Miocene and generally colder Late Miocene assemblages. The temperate faunal aspects of the Middle Miocene faunas consist of *Globorotaloides trema*, *G. hexagona*, *Globigerina angustumbilicata* and *G. sp. aff. G. quinqueloba* Natland, which are considered characteristic of the intermediate latitude water mass. These species disappear by late Middle Miocene time and are replaced by only sparse and episodic incursions of temperate species such as *Globorotalia conoidea* Walters, *G. acostaensis* Blow, *Globigerinoides bollii* Blow, *G. trilobus* (Reuss), *Globigerina nepenthes* Todd, and *Orbulina*. Subtropical species including *Globorotalia fohsi* Cushman and Ellis, *G. peripheroacuta* Blow and Banner, *G. praemenardii* Cushman and Stainforth, and *Globigerinoides sacculifer* (Brady) represent brief incursions of subtropical water masses at this latitude (28°N). Absence of subtropical species in sequences younger than 13.5 Ma is further evidence of the general cooling trend and increased provincialism beginning in the latest Middle Miocene (see also Keller and Barron, 1981).

Cool- to cold-water species (*Globigerina bulloides*, *G. praebulloides* Blow, *G. quadrilatera*, *G. pseudociperoensis* Blow) dominate the Middle and Late Miocene faunas. Moreover, the abundance of this group increases in the Late Miocene coincident with the decline in the abundance of cool temperate species (textfigs. 6, 7). In addition, the coolest faunal component during the Late Miocene appears to be the *Globorotalia continua* s.l. group* which includes the precursor of the cold-water species *Neogloboquadrina pachyderma*. *Neogloboquadrina pachyderma* s.s. is rare or absent in these sequences due to a hiatus that removed the uppermost upper Miocene.

During the Middle Miocene, abundance fluctuations of *Globigerinita glutinata* Egger at Sites 470 and 173 also suggest that this species reflects cool climatic condi-

* Some of these morphotypes were assigned to *Neogloboquadrina pachyderma* in earlier studies (Ingle, 1967, 1973).

Percent abundance of planktic foraminifers in middle Miocene of Site 173. Parentheses indicate raw counts, rather than percentage for fewer than 90 specimens per sample.

[illegible]

tions (Ingle, 1973; Keller and Barron, 1981) (text-fig. 6; tables 5, 7). In the Early and Late Miocene, however, *G. glutinata* is also common in the equatorial Pacific (Keller, 1980a, 1980b, 1981a). It is not clear at this time whether the cosmopolitan distribution of this species is due to vertical migration in the water mass or to factors other than temperature. We feel confident, however, that the late Middle Miocene abundance peak of *G. glutinata* at about 13.4 Ma records a cool climatic event which is also observed in the $\delta^{18}\text{O}$

isotope curves of low-latitude sites (Keigwin, 1979; Woodruff et al., 1981; Keller and Barron, 1981). In this study, therefore, we include *Globigerina glutinata* as a cool-water indicator, as has been done previously by Ingle (1973).

A paleoclimatic signature for the northeastern Pacific regions can thus be provided by abundance fluctuations of the "cold-water" planktic foraminifers: *Globigerina bulloides*, *G. praebulloides*, *G. quadrilata*, *G.*

TABLE 6

Percent abundance of planktic foraminifers in middle and upper Miocene of Newport Beach section. Parentheses indicate raw counts rather than percentage for fewer than 90 specimens per sample. Samples were collected by Barron (1976). See table 2 for stratigraphic interval.

	NEWPORT BEACH X = < 2%										NEWPORT BEACH X = < 2%										NEWPORT BEACH X = < 2%										NEWPORT BEACH X = < 2%									
GLOBIGERINA	N 7A	N 7	N 6	N 5	N 4A	N 4	N 3	N 2B	N 2A	N 2	N 1	NEW 61	NE 20	NE 19	NEW 51	NE 16	NEW 48	NE 15	NE 13	TM 18	TM 17	NE 12	NE 11	N 10	TM 14	TM 9	NE 9	NE 8	NE 7	NE 6	NE 5	NE 1	NEW 5							
G. ANGUSTIUMBILICATA											X																													
G. BULLOIDES	17	36	19	37	38	63	37	29			39	40	12	23		29	29		(50)						(9)	14	34	33	30	(18)	21									
G. FALCONENSIS				5	4		3	X			2	5	X	3		X	2																							
G. PRAEBULLOIDES	10	25	43	25	38	8	14	43			8	18	13	16		21	21		(11)						(2)	11	20	8	34	(24)	29									
G. PSEUDOCIPEROENSIS	49	25	2	11	3	4	10	X			11	12	X	4		10	32								(6)	6	27	10	6	(1)	20									
G. PSEDOBESA		6	X	2	X		X	X				2	X			3	X								(1)	X		3	X	(2)	6									
G. QUADRILATERA	10	9	29	10	13	19	14	27			17	14	13	13		16	13		(4)						(5)	9	8	6	3	(2)	22									
G. QUINQUELOBA						X	X									X												X												
GLOBIGERINITA GLUTINATA		4				4							X			X	X		(2)																					
G. UVULA						X										X																								
GLOBIGERINOIDES BULLOIDEUS					X						X																													
GLOBOROTALIA CONTINUOSA	2	2		X		10					17	8	56	38		18																								
G. MINUTISSIMA																																(1)								
G. OBESA				X	X						X																					X								
GLOBOROTALOIDES HEXAGONA																										54	12	38	25	(9)	X									
G. TREMA																X																								
NEOGLOBOQ. ACOSTAENSIS			X		X		6				4	X																												
ORBULINA UNIVERSA	14											X		X																										
NO. SPECIMENS COUNTED	326	253	345	242	326	401	367	379	0	0	0	307	330	360	324	0	0	406	330	0	0	68	0	0	23	387	351	429	478	57	344	0	0	0						

pseudociperoensis Blow, *Globorotalia continua* s.l., *Neogloboquadrina pachyderma*, and *Globigerinita glutinata* (text-fig. 8). These species, with the exception of *G. glutinata*, appear to be indigenous to cool middle-to-high altitudes, and the chronologic ages of major abundance peaks correspond to isotopically determined cold events at low-latitude sites (Keigwin, 1979; Woodruff et al., 1981; Savin et al., 1981; Keller and Barron, 1981), as will be discussed later.

Resolution of the paleoclimatic curves presented in text-figure 8 depends largely on faunal preservation, which unfortunately is poor in some intervals, as is indicated by diagonal lines marking intense carbonate dissolution. Only major abundance fluctuations, or abundance changes that are apparent in two or more sections can therefore be assigned to climatic events with confidence. Minor fluctuations, which alone might have been considered as due to dissolution or counting bias, are viewed as significant if found consistently in two or more sections and expressed by both faunal and floral groups. Combining planktic foraminiferal and diatom data, we have been able to identify 12 warm and 14 cold events within the Middle and Late Miocene of the northeast Pacific margin. Ten of these warm events and 11 of these cold events are identifiable in the planktic foraminiferal curves (text-fig. 8), where they are labeled with notation identical to that used in the diatom discussion. Because of hiatuses

and carbonate dissolution, however, no single sedimentary sequence contains a complete record of these events, and the paleoclimatic history must be pieced together from all three sections.

Diatom paleotemperature interpretations

In order to monitor fluctuations in the California Current and develop a paleoclimate curve for the Middle and Late Miocene of the California area, it is necessary to separate predominantly "cool"-water diatoms from predominantly "warm"-water diatoms. Literature on the quantitative distribution of modern diatoms in surface sediments of the North Pacific (Kanaya and Koizumi, 1966; Jousé et al., 1971) is useful, as are qualitative studies on Miocene diatoms from the equatorial (Burckle, 1972, 1978a; Gombos, 1975; Bukry and Foster, 1973) and North Pacific (Schrader, 1973; Koizumi, 1973; Barron, 1980, 1981). Quantitative data on Miocene diatoms from various parts of the equatorial and North Pacific, however, are of far greater value in determining the temperature affinities of Miocene diatoms. The quantitative data of the north-to-south transect formed by Site 173, the Newport Beach section and Site 470 and unpublished quantitative data by Barron from equatorial Pacific Site 77B form the basis for inferring the paleotemperature and paleoceanographic associations of the Middle and Late Miocene diatoms of Site 173, the Newport Beach section and Site 470.

TABLE 7

Percent abundance of planktic foraminifers in middle and upper Miocene of Site 470. Parentheses indicate raw counts, rather than percentage for fewer than 90 specimens per sample.

DSDP SITE 470

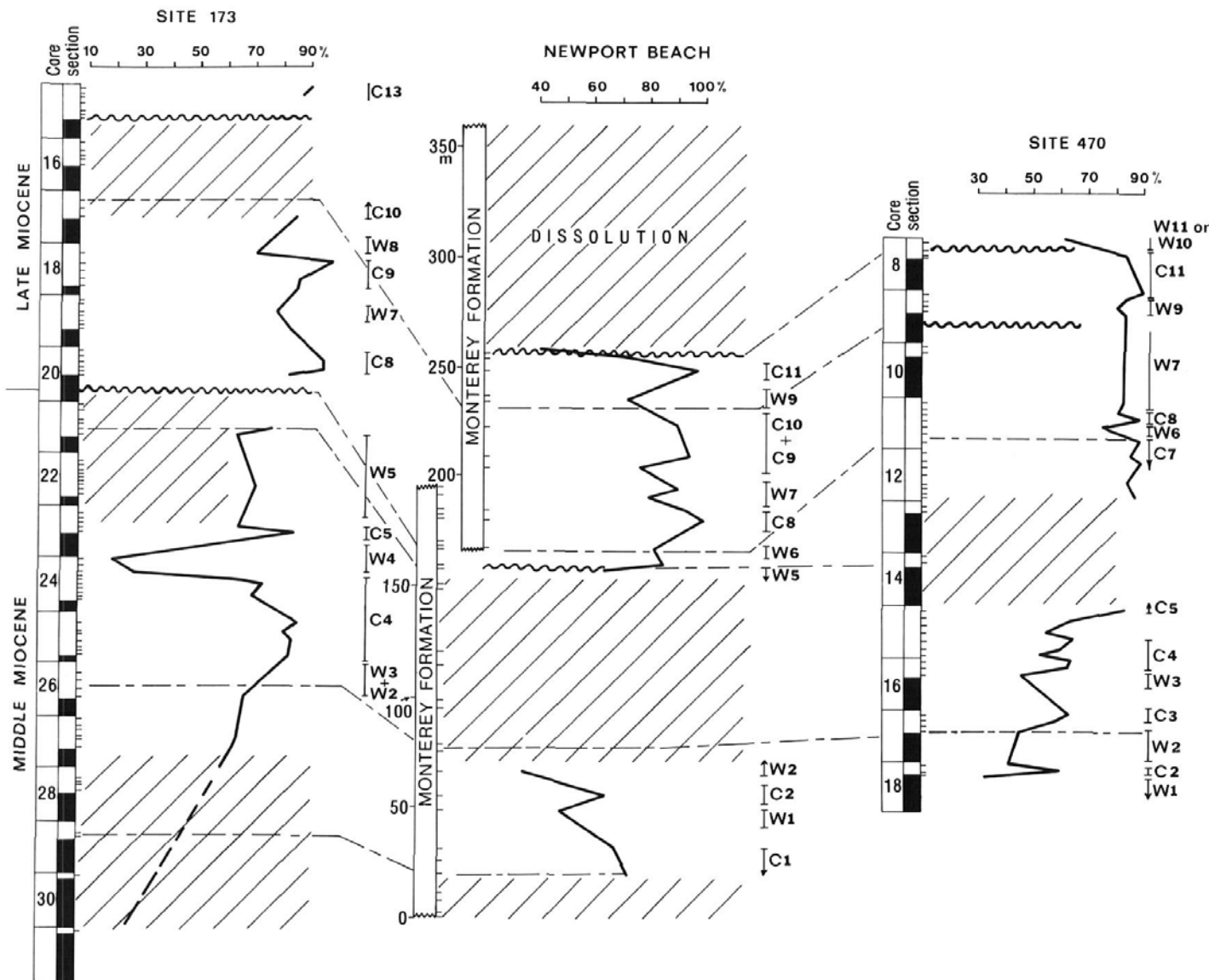
 $\chi^2 = < 2\%$

GLOBIGERINA

G. ANGUSTIUMBILICATA		X			X				X X	X		X																																			
G. APERTURA		X			X																																										
G. BULBOSA																																															
G. BULLOIDES	37 (6) (11) 56 73	63 57 36 45 (3)	52 (3) 57 55 52	54 56 47 52 (28)	(14) 61 52 (19)	(8)	47	32 28 33 40 33	18 10 23 31 38	28 28 21 39 19																																					
G. cf CIPEROENSIS									X	X																																					
G. CONNECTA									X	X																																					
G. cf DECORAPERITA			X		X X		3	X	X X	X 2 3																																					
G. DRURYI	2	X	X X X	X (1) X X 3	X X X (1)	(3)	9	3 6 5 5 3	X 5 4	X X																																					
G. FALCONENSIS		X	(1) X	X X	(3) X			2	2 X 3 5	4 X X																																					
G. FOLIATA									2	X																																					
G. NEPENTHES	3	X 2 2 X	X	5 X X	(3) X																																										
G. PRAEDIGITATA		X						X X	X X X	X X X																																					
G. PSEUDOCIPEROENSIS			X X	X			3	2	3 X 4 X 5	2 2 3																																					
G. PSEUDOBESA	(3)	3 2 X X	X 2 X	2 X 2	X		2	4 4 3 3 2	4 X 7	3 3 X X X																																					
G. QUADRILATERA	17 (2) 18 16	17 14 5 13	22 10 20 13	26 17 16 20 (1)	(9) 20 27		16	13 4 12 11 5	6 4 8 6 13	10 11 5 17 11																																					
G. QUINQUELOBA				X					X X	X 14 2 5																																					
G. aff QUINQUELOBA							3	3 X X 4 12	8 4 X X X	X 4 8																																					
G. UMBILICATA	2 (2)	3 X 2 3 2	X X 3	6 X X X			X	3 X X 4 3	X	3																																					
G. WOODI	2	X 2	3 X X X	X			X	3 3 2	X	X 2 X 18																																					
GLOBIGERINITA GLUTINATA	4	2 X	X 4 4 2	3 X 5 5	X 6 10 7	5 10	24	19 25 14 10 14	40 49 16 26 8	14 7 15 5 3																																					
GLOBIGERINOIDES BULLOIDEUS		X X 2		X			2	X X X		X																																					
G. CONGLOBATUS	X	X																																													
G. OBLIQUUS OBLIQUUS	X	X	X 3	X	X																																										
G. OBLIQUUS EXTREMUS	X	X																																													
G. SACCOLIFER		X X X X	3 X X	X X X		(1)	2	X X X X	X 2 2	2 X X																																					
G. SUBQUADRATUS										X																																					
G. TRILOBUS	X	X	X X	X	X 2	X	4	X 2	X X 2 3	10 2 X X																																					
GLOBOQUADRINA ALTISPIRA	X		(1)	3 X 4 2			2	2 3 2 X X	X 5 5 4 X	X																																					
G. DEHISCENS								X	X	X X X X X																																					
G. VENEZUELANA		X					2	2 2 2 X X	2 X 3 X X	2 4 X X																																					
GLOBOROTALIA ACROSTOMA								X																																							
G. BAUERENSIS	X								X X	X X X																																					
G. CONOMIOZEA	X																																														
G. CONOIDEA	X	X X X																																													
G. CONTINUOSA	3 (4) 7	3 6 38 20	6 14 4 5	2 11 13 12			X X X		X X																																						
G. FOHSI FOHSI								X X																																							
G. FOHSI PRAEFOHSI								X X																																							
G. JUANAI										X																																					
G. MAYERI				X	(1)			X																																							
G. MENARDII	X	X							X																																						
G. MIOZEA																																															
G. MINUTISSIMA								X	X 2	X X																																					
G. OBESA	(1)			X				X X	X X	X																																					
G. PERIPHEROACUTA							X	X		6 X																																					
G. PERIPHERORONDA										X 18 4 20 27																																					
G. PRAEMENARDII							X	X	X X	2																																					
G. PRAESCITULA								X																																							
G. SCITULA	3	X	X X	X X	X	X	X		X X																																						
G. SP. W								X X 3 2 X	X																																						
GLOBOROTALOIDES HEXAGONA	X	X	X X X X	X X X	X	(1)	3	X 2 2 3 2	7 9 9 3 5	3 5 18 11 4																																					
G. TREMA						X	4	5 12 4 X 14	4 X	X																																					
HASTIGERINA BERMUDEZI		X																																													
NEOGLOBOQ. ACOSTAENSIS	4	3	X 5	X	X 5 5	(2)																																									
N. PACHYDERMA	(1)	3				(1) (1)		1																																							
ORBULINA UNIVERSA	5	X 3	4 5 X 3	X	X	(2)	X	3 X X	X 4 5 X 3	4																																					
O. SUTURALIS	7 (2) X X	X X X		3 3	2		(1)	2	3 2 6 6 X	5 2 3 3 2																																					
SPHAERODIDINELLA DISJUNCTA									X X	X 2																																					
S. SEMINULINA	2	X X	X X		X X				X X																																						
S. SUBDEHISCENS	3	X X			X	(1)																																									
NO. SPECIMENS COUNTED	322	11	19	128	389	379	285	238	300	4	67	5	88	194	90	289	392	248	162	30	34	48	41	24	0	0	10	0	0	299	232	347	285	378	246	288	398	231	360	422	348	347	205	298	365		
(40 cc SAMPLE)																																															

NO. SPECIMENS COUNTED

(40 cc SAMPLE)



TEXT-FIGURE 8

Planktic foraminifer paleotemperature curves for middle and upper Miocene of Sites 173 and 470 and Newport Beach section. Cold ('C') and warm ('W') climatic events recognizable in more than one curve and/or in diatom curves, labelled C1 to C13 and W1 to W11. Cold-water taxa include *Globigerina bulloides*, *G. praebulloides*, *G. quadrilata*, *G. pseudociperoensis*, *G. continuosa* s.l., *Neogloboquadrina pachyderma* and *Globigerinita glutinata*. Correlation lines are from diatom biostratigraphy. Diagonal lines = dissolution; wavy lines = hiatus.

The dominant diatom taxa in the middle and upper Miocene of these sequences include *Actinocyclus ingens*, *Coscinodiscus marginatus* Ehrenberg, the *Denticulopsis* group (*D. hustedtii*, *D. lauta*, *D. hyalina*, *D. praedimorpha*), *Rouxia* spp., and *Thalassionema nitzschioides* (tables 1–3).

Upwelling component

Thalassionema nitzschioides is a nearly cosmopolitan living marine diatom (Kanaya and Koizumi, 1966; Jousé et al., 1971). In equatorial regions, it is associated with nutrient rich waters in upwelling regions (Burckle, 1978b; Sancetta, in press). Kanaya and Koizumi (1966)

grouped *T. nitzschioides* with the tropical to subtropical diatom assemblage but also noted that the species is an important constituent of mixed middle-latitude assemblages in areas off Japan and California. Similarly, Sancetta (1979) found *T. nitzschioides* to be associated with the subtropical gyre, south of the subarctic front, in her study of latest Quaternary diatoms from the northwest Pacific.

Thalassionema nitzschioides and its relatives (*T. hiro-sakiensis* and *T. sp. 1*) are common components of the Middle and Late Miocene assemblages of Site 173, Newport Beach and Site 470 (tables 1–3). *Thalassiothrix longissima* Cleve and Grunow, a diatom also as-

sociated with upwelling in equatorial regions (Sancetta, in press; Burckle, oral communication), is also a consistent, though less common constituent, of these assemblages. Following Sancetta (in press) and Bukry and Foster (1973), *Thalassionema* spp. and *Thalassiothrix longissima* have been tabulated together in text-figure 9 for the Site 173, Newport Beach, and Site 470 sections to reflect an upwelling component. Correlation lines drawn from diatom biostratigraphy allow the three curves to be compared. Throughout most of the Middle Miocene below 12.5 Ma the three curves show generally low values (ca. 20–30%). Slightly higher values (ca. 40%) are, however, expressed in the Site 173 and Newport Beach curves around 14.7 Ma. In contrast to the Middle Miocene, the Late Miocene *Thalassionema-Thalassiothrix* values average around 50–60% with many sharp fluctuations to values greater than 80%. The transition from the lower values of the Middle Miocene to the higher values of the Late Miocene occurs between 12.5 and 11.1 Ma, an interval which is complete at Site 470 but is interrupted by hiatuses at Site 173 and Newport Beach. At Newport Beach, Weaver et al. (1981) have previously noted the rapid increase in *Thalassionema* and *Thalassiothrix* near the Middle Miocene/Late Miocene boundary. An equivalent increase in *Thalassionema* and *Thalassiothrix* occurs during the same interval of time in the equatorial Pacific at Sites 77B (Barron, unpublished data) and 158 (Bukry and Foster, 1973). Keigwin (1979) recorded a +1‰ enrichment in the $\delta^{18}\text{O}$ of benthic foraminiferal carbonate within this interval at Site 158, which he attributed to growth of the Antarctic ice sheet. Increased *Thalassionema* and *Thalassiothrix* between 12.5 and 11.1 Ma in the California Current region and in the equatorial Pacific most likely reflect increased upwelling that results from intensification of latitudinal thermal gradients and enhanced circulation. During this same interval of time, provincialism between middle and low latitudes is greatly enhanced in all planktic groups (Keller and Barron, in press).

Diatom paleotemperature curve

In the modern ocean, *Coscinodiscus marginatus* and *Denticulopsis seminae* (Simonsen and Kanaya) Simonsen are considered "cold"-water diatoms (Kanaya and Koizumi, 1966; Jousé et al., 1971). Qualitative studies in the North Pacific (Koizumi, 1973; Barron, 1980, 1981) and comparison of the present studies with quantitative data at equatorial Pacific Site 77B (Barron, unpublished) suggest that *C. marginatus* and the ancestral *Denticulopsis* species excluding *D. nicobarica* (Grunow) Simonsen and *D. punctata* var. *hustedtii* (Schrad.) Simonsen may also be considered "cold"-water diatoms for the Miocene. Similarly, these Miocene studies identify *Rhizosolenia barboi* Brun and its

ancestor *R. praebarboi* Schrader, *Rouxia* spp., *Thalassiosira antiqua*, *T. nativa* Sheshukova-Poretzkaya and *T. sp. 1* as having "cold"-water affinities. Certainly, other taxa recorded at Site 173, Newport Beach, and Site 470 have "cold"-water affinities; however, only those taxa which constitute 5% or more of the assemblage in a given sample are considered significant for paleotemperature studies.

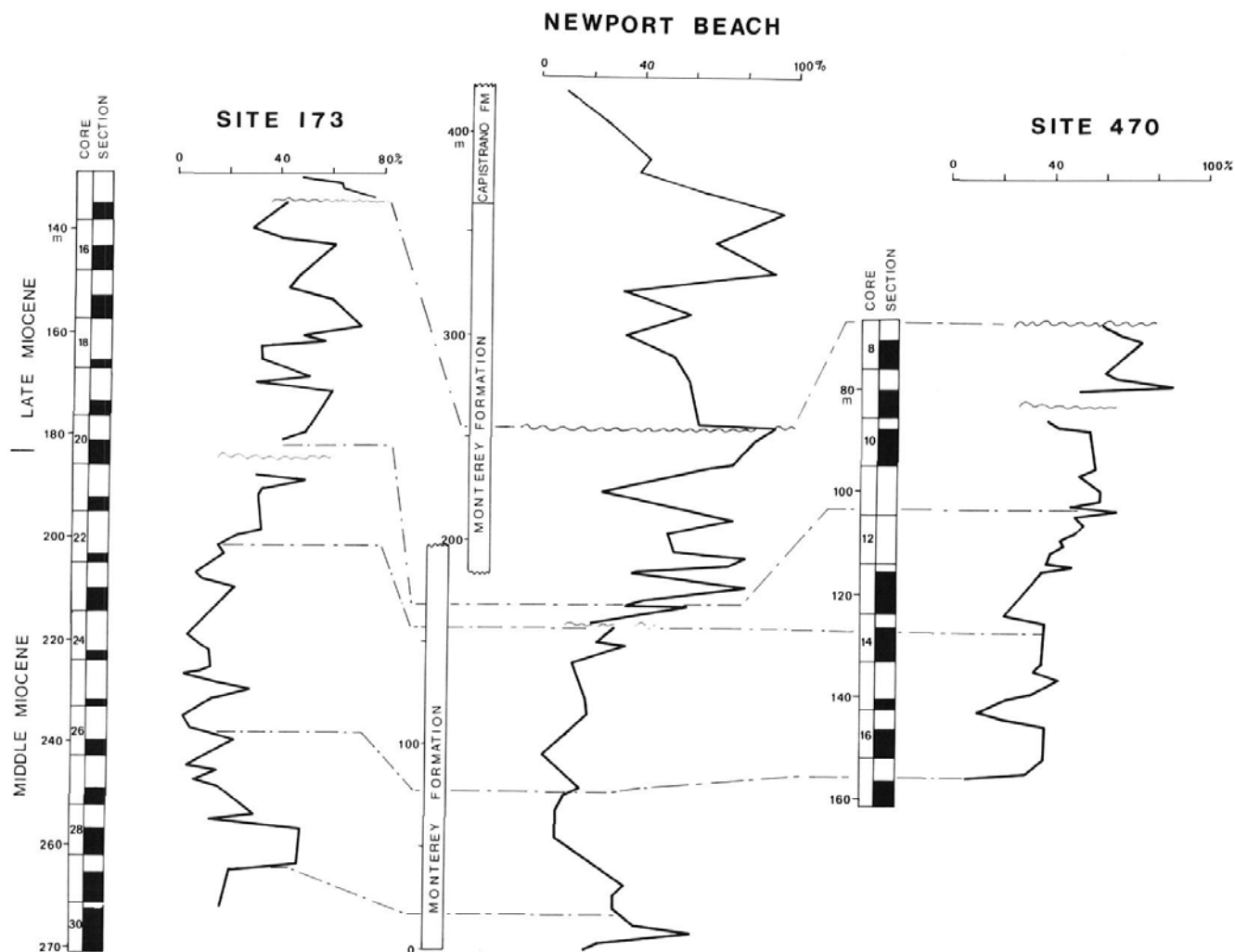
Actinocyclus ingens is a common diatom in the early Middle Miocene assemblages of the middle- to high-latitude North Pacific (Koizumi, 1973; Barron, 1980); but it is not included with the "cold"-water taxa, because quantitative studies at equatorial Site 77B show it to be as common in the lower Middle Miocene there as it is off California.

Taken as a group, the "cold"-water taxa constitute a major component of the Middle and Late Miocene assemblages of Site 173, the Newport Beach section and Site 470. Therefore, fluctuations in the percentage abundance of "cold"-water taxa in these sections should reflect fluctuations in the intensity of the California Current and hence, paleotemperature.

The abundance of "cold"-water diatoms in the Site 173, Newport Beach, and Site 470 sections is also a measure of the similarity of the assemblage with that of the cold-water regions off the North Pacific (north of 40°N). It was argued earlier that the *Thalassionema-Thalassiothrix* group (text-fig. 9) primarily responds to the level of upwelling in these temperate sections. In an absolute sense, both the upwelling and "cold"-water groups should increase in abundance when the high latitudes are cooled and the California Current is strengthened. The former would increase, because increased latitudinal thermal gradients increase wind stress and cause increased upwelling, and the latter should increase as "cold"-water floras displace "warm"-water floras as a function of southward penetration of subarctic water.

In order to measure paleotemperature effects independent from upwelling effects, it is necessary to remove the upwelling component (*Thalassionema-Thalassiothrix* group) and compare the percentage of the "cold"-water group with the remainder of the planktic assemblage. This is done for the middle and upper Miocene of Site 173, Newport Beach, and Site 470 on text-figure 10. Because text-figure 10 incorporates numerous species through 10 m.y. of time and because the temperature tolerances of individual species and their descendants do not necessarily remain constant, the curves in text-figure 10 are somewhat relative, in that Middle Miocene "cold" intervals are not necessarily as cold as Late Miocene "cold" intervals of comparable amplitude. Nevertheless, relative paleotemperature values may be compared for the three

THALASSIONEMA and THALASSIOTHRIX



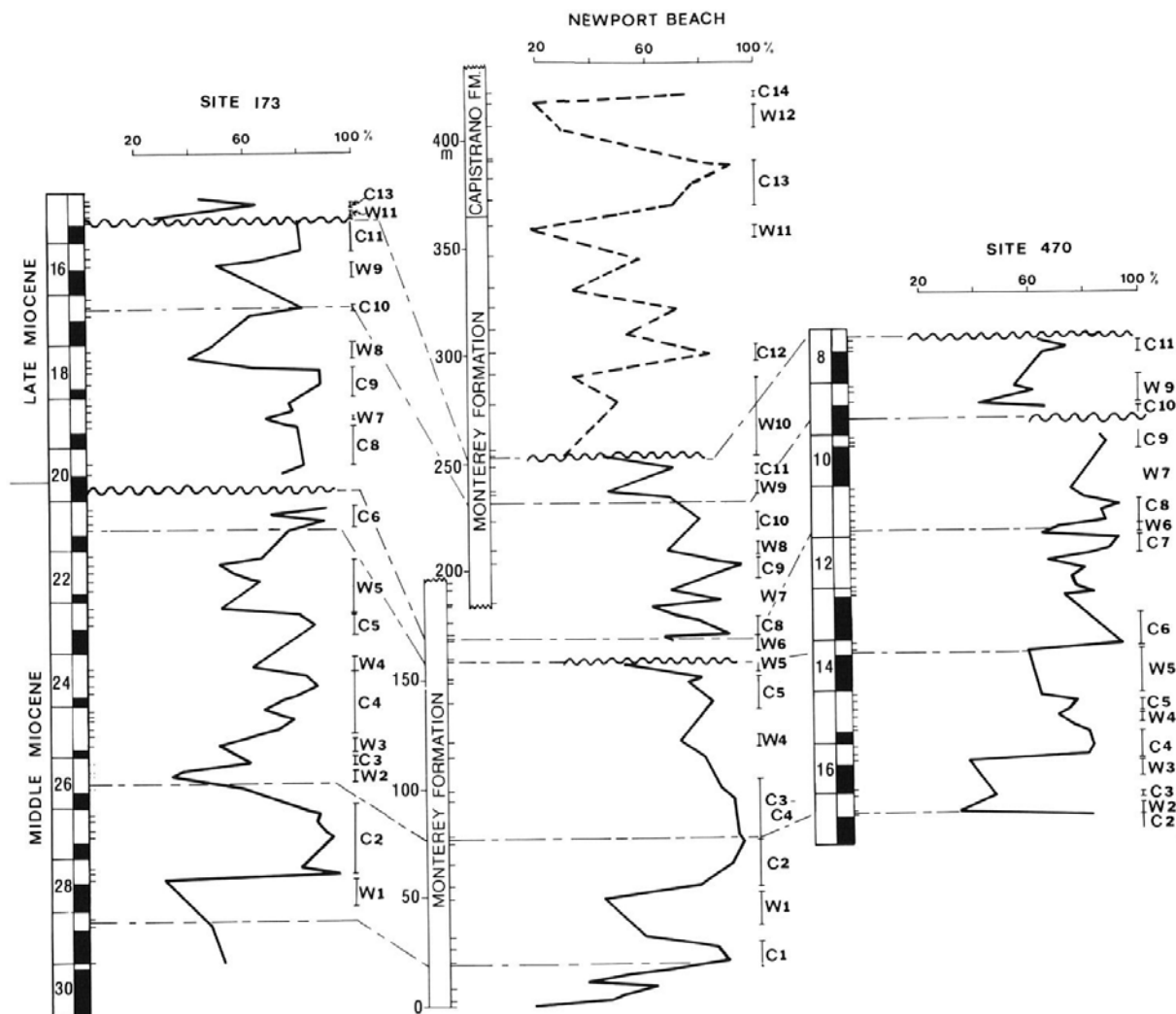
TEXT-FIGURE 9

Percentage of upwelling component (*Thalassionema nitzschioides*, *T. hiroakiensis*, *T. sp. 1*, and *Thalassiothrix longissima*) in diatom assemblages in middle and upper Miocene of Sites 173 and 470 and Newport Beach section. Correlation lines are from diatom biostratigraphy. Wavy lines = hiatus.

sections—by use of diatom biostratigraphy (correlation lines on text-fig. 10) and more precisely, by the sediment accumulation rate diagrams (text-figs. 2–4). Above the hiatus at 255 m, the curve at Newport Beach is dashed to reflect greater ambiguity. Benthic foraminiferal studies (K. McDougall, oral communication, 1981) reveal a marked shallowing of the Newport Beach section above the hiatus, therefore the transport of diatoms and the presence of localized nearshore ecologic irregularities are apt to be significant.

The curves of Site 173, Newport Beach, and Site 470 show remarkable similarity. As expected, the percentage of cold-water oceanic diatoms at the northern Site 173 is consistently greater than, or equal to, that

at southern Site 470. Detailed correlation between the three sections using the sediment accumulation rate diagrams (text-figs. 2–4) allows identification of distinctive warm and cold intervals which appear in two or more of the curves at the same interval of geologic time. Fourteen distinctive cold intervals (labelled C1–C14) and 12 distinctive warm intervals (labelled W1–W12) have been identified in the curves for the Middle and Late Miocene. As will be discussed below, 11 of these same cold and 10 of these same warm events have also been identified in the paleotemperature curves of planktic foraminifers (text-fig. 8), and identical notation has been used. As with the planktic foraminifer curve, the magnitude of the cold and warm events identified varies, and recognition of the events



TEXT-FIGURE 10

Diatom paleotemperature curves for middle and upper Miocene of Sites 173 and 470 and Newport Beach section. Percentage of cold-water, oceanic diatoms excludes upwelling (*Thalassionema* and *Thalassiothrix*) component. Cold-water diatoms include *Coscinodiscus marginatus*, *Denticulopsis dimorpha*, *D. hustedii*, *D. hyalina*, *D. lauta*, *D. praedimorpha*, *Rhizosolenia barboi*, *R. praebarboi*, *Rouxia* spp., *Thalassiosira antiqua*, *T. nativa*, and *T. sp. 1*. Correlation lines from diatom biostratigraphy. Wavy lines = hiatus. Dashed curve for Newport Beach signifies absence of corroboration at other two sites.

is dependent on sample spacing. Unlike planktic foraminifers, however, all samples studied (identified with tick marks, text-fig. 10) contain diatoms, therefore the diatom curve is more detailed than the planktic foraminiferal curve.

Integrated paleotemperature curve

Most of the 14 cold and 12 warm events identified in the middle and upper Miocene of Site 173, Newport Beach, and Site 470 are recognizable in both the planktic foraminiferal (text-fig. 8) and the diatom (text-fig. 10) relative paleotemperature curves. Four of the events, namely W10, C12, W12, and C14, however, are present only in the Newport Beach section within sediments barren of foraminifers. Table 8 summarizes

the extrapolated age of the 14 cold and 12 warm events and the number of curves (planktic foraminifer and diatom) in which they have been recognized. The latter factor is a measure of the confidence that we place in each event.

In text-figure 11, composite diatom and planktic foraminifer relative paleotemperature curves have been constructed by averaging the diatom and planktic foraminifer paleotemperature values for each of the cold and warm events identified on text-figures 8 and 10. As stated above, three cold events (C6, C12, C14) and two warm events (W10, W12) are recognized by diatoms in sediments devoid of planktic foraminifers, so that the diatom paleotemperature curve is more complete than the planktic foraminifer paleotemperature

TABLE 8

Age of relative paleotemperature events and curves (see text-figs. 7, 9) in which they are recognized. NP. = Newport Beach.

Event	Age (Ma)	Curves in which Recognized	
		Diatom	Planktic Foram.
C14	4.9	NP.	—
W12	5.0	NP.	—
C13	5.4–5.2	173, NP.	173
W11	5.6–5.5	173, NP.	470
C12	6.2–6.1	NP.	—
W10	6.5–6.3	NP.	—
C11	7.8–7.5	173, NP., 470	NP., 470
W9	8.2–7.9	173, NP., 470	NP., 470
C10	8.5	173, NP., 470	173, NP.
W8	9.2–9.0	173, NP.	173
C9	9.7–9.3	173, NP., 470	173, NP.
W7	10.0	173, NP.	173, NP.
C8	11.0–10.7	173, NP., 470	173, NP., 470
W6	11.1	NP., 470	NP., 470
C7	11.3–11.2	470	470
C6	12.4–11.9	173, 470	—
W5	12.7–12.5	173, NP., 470	173, NP.
C5	12.9–12.8	173, NP., 470	173, 470
W4	13.0	173, NP., 470	173
C4	13.4–13.1	173, NP., 470	173, 470
W3	13.5	173, 470	470
C3	13.6	173, 470	470
W2	13.8–13.7	173, 470	NP., 470
C2	14.3–14.0	173, NP., 470	NP., 470
W1	14.5–14.4	173, NP.	NP., 470
C1	14.7–14.6	NP.	NP.

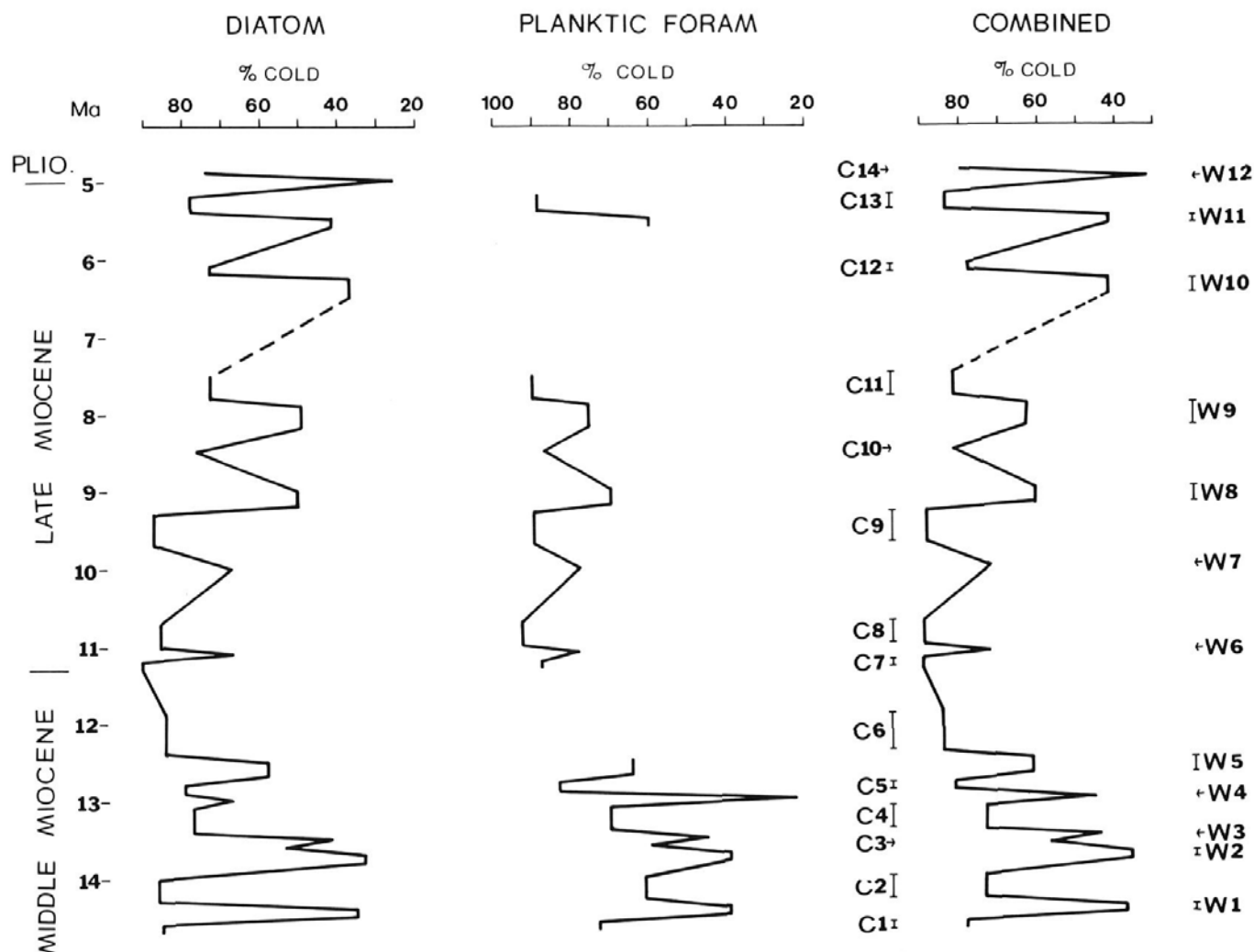
curve. Nevertheless, the overall trend and amplitudes of the two curves for the Middle and Late Miocene are remarkably similar. Differences are most apparent in the early Middle Miocene (14.7 to 13.4 Ma), where the diatom curve is generally colder than the planktic foraminifer curve. On the right side of text-figure 11 the two curves have been averaged to synthesize a combined paleotemperature curve for the Middle and Late Miocene. Diatom paleotemperature values (% cold water taxa) are typically 10% greater than planktic foraminifer values for the same horizon; therefore, the combined values for the three cold events (C6, C12, C14) and two warm events (W10, W12) that are not recognized by planktic foraminifers have been estimated accordingly.

The relative paleotemperature curve in text-figure 11 corroborates published benthic foraminiferal oxygen isotope curves for the Middle and Late Miocene of the Pacific (Keigwin, 1979; Woodruff et al., 1981; Savin et al., 1981). A cooling trend begins in the middle part of the Middle Miocene and is intensified toward the end of the Middle Miocene. The Late Miocene is characterized by generally cool conditions but contains numerous fluctuations due to somewhat warmer conditions. Woodruff et al. (1981) have shown that the Middle Miocene cooling trend begins in the lower part of planktic foraminiferal zone N 11 and extends to the top of zone N 12. Using correlations at DSDP Site 77B (Keller, 1981b; Barron, in press), this cooling interval corresponds to about 14.0 to 12.7 Ma on our time-

scale. Thus, cold events C3 (13.6 Ma), C4 (13.4–13.1 Ma), and C5 (12.9–12.8 Ma) correlate with the Middle Miocene cooling trend of Woodruff et al. (1981). Subsequent warming reported by these authors probably corresponds with warm event W5 (12.7–12.5 Ma). Warm events W2 (13.8–13.7 Ma) and W3 (13.5 Ma) are not immediately apparent in the curve of Woodruff et al., although their detailed measurements in planktic foraminifer zone N 11 show considerable fluctuation. Keigwin (1979) reported that at DSDP Site 158 in the Panama Basin the major cooling at the end of the Middle Miocene began in planktic foraminiferal zone N 14 at about 12 Ma and was completed in zone N 15 by about 11 Ma. Keigwin's major cooling seems to correspond with cold events C6 (12.4–11.9 Ma) and C7 (11.3–11.2 Ma), both of which are significant cold events according to the diatom and planktic foraminiferal curves. Woodruff et al. (1981) also reported significant cooling in upper zone N 14 and zone N 15; however, they identified an even more substantial cooling in the middle of zone N 16. Correlations suggest that this major cooling most likely corresponds with cold event C9 (9.7–9.3 Ma).

In our earlier papers (Keller and Barron, 1981, in press) we have argued that Miocene deep-sea hiatuses are caused by enhanced bottom water activity (erosion and/or dissolution) during periods of high-latitude cooling or polar refrigeration. We have also pointed out that Miocene deep-sea hiatuses correspond with intervals of eustatic lowering of sea level, intervals of cooling or global ice volume increase as indicated by oxygen isotope studies, and intervals where faunas and floras indicate cooling. In text-figure 12 we compare the intervals of hiatus at Site 173, Newport Beach, and Site 470 as revealed by diatom and planktic foraminiferal biostratigraphy with the combined relative paleotemperature curve. Each of the hiatuses occurs during an interval in which we (Keller and Barron, in press) have identified widespread deep-sea hiatuses, and we have applied the terminology of Keller and Barron (in press). It is immediately apparent that each of the hiatuses corresponds closely with our cold events. Hiatus NH 4 (ca. 12–11 Ma) at Site 173 and Newport Beach correlates with cold events C6 and C7 at Site 470 (see also text-figs. 1–3). Hiatus NH 5 at Site 470 (ca. 9.8–8.5 Ma) corresponds with cold events C9 and C10 at Site 173 and Newport Beach. Hiatus NH 6 (ca. 7.2–6.5 Ma) is present in all three sections, and an unlabelled cool event has been inferred in text-figure 10. Hiatus NH 7 at about the Miocene/Pliocene boundary of Site 173 and Site 470 correlates with cold event C14 and possibly C13 at Newport Beach. Although it is not expressed in any of the three sections, hiatus NH 3 (13.5–12.5 Ma) of Keller and Barron (in press) also is coincident with cold intervals C4 and C5 in our sections.

RELATIVE PALEOTEMPERATURE CURVES



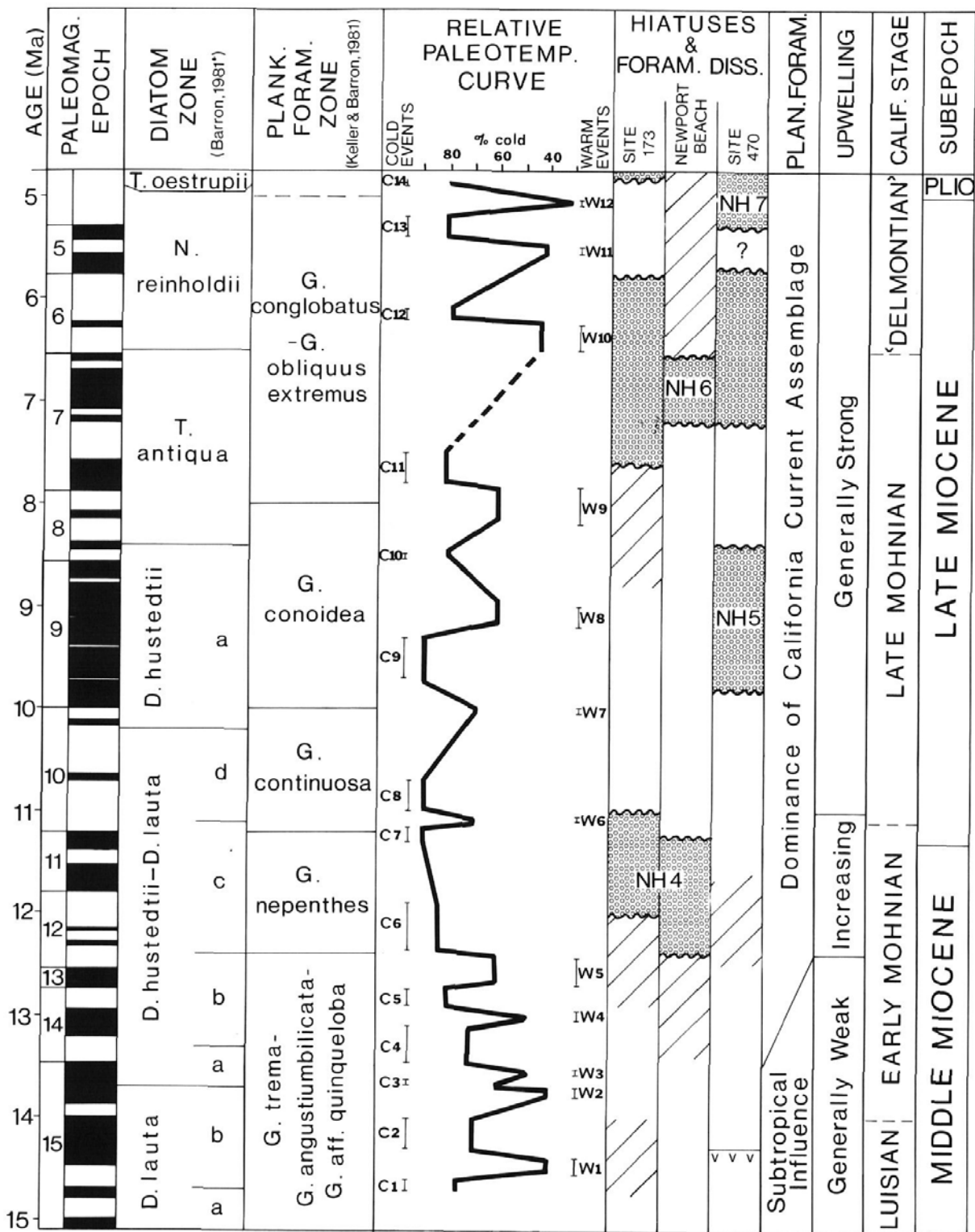
TEXT-FIGURE 11

Diatom and planktic foraminifer relative paleotemperature curves for Middle and Late Miocene of middle-latitude eastern North Pacific and a combined curve constructed by averaging both curves.

Text-figure 12 also shows that intervals of increased dissolution of foraminifers are associated with the hiatuses. Dissolution of biogenic sediment is one of the major causes of hiatuses, and Keller (1980a, 1980b, 1981a, 1981b) has noted that dissolved foraminifers are characteristic of cooler intervals during the Miocene at low and middle latitudes of the North Pacific.

Cold events C4 (13.4–13.1 Ma), C6 (12.4–11.9 Ma) and C7 (11.3–11.2 Ma) are responsible for major changes in the planktic foraminiferal and diatom assemblages. Prior to cold event C4, subtropical elements are consistently present at Site 470 as evidenced by the presence of numerous subtropical

planktic foraminifers including *Globoquadrina altispira* (Cushman and Jarvis), *G. dehiscens* (Chapman, Parr and Collins), *Globorotalia bauerensis* Quilty, *G. fohsi fohsi* Cushman and Banner, *G. minutissima* Bolli, *G. peripheroronda* Blow and Banner, and *G. praemenardii*. After cold event C6, virtually all these subtropical species are absent from the Site 470 faunas, and the cool water California Current assemblage is totally dominant. In diatom assemblages, a dramatic change occurs in the interval including cold events C6 and C7, where the upwelling diatoms *Thalassionema* spp. and *Thalassiothrix longissima* increase dramatically in all three sections (text-fig. 9). As was pointed out earlier, this increase in the upwelling component is probably as-



TEXT-FIGURE 12

Summary diagram comparing synthesized relative paleotemperature curve for northeastern Pacific with hiatuses (circle pattern), foraminifer dissolution (diagonal line pattern), faunal and floral assemblage changes and California Benthic Foraminiferal Stages. Note that base of the *D. hustedtii-D. lauta* Zone has been modified in this study (see Appendix). Upwelling based on abundance of *Thalassionema* and *Thalassiothrix* spp. (this study). Correlation of California Benthic Foraminiferal Stages based on Barron (1976) and Baldauf and Barron (1982). vvv = basalt.

sociated with an increasing latitudinal thermal gradient and enhanced circulation at the end of the Middle Miocene.

The California benthic foraminiferal stages of Kleinpell (1938) are placed in text-figure 12 following the correlations of Keller and Barron (1981). Each of these stages contains a characteristic benthic foraminiferal fauna; and despite some inherent problems of diachroneity, they have been the traditional means of correlation in California on shore sections. Text-figure 12 shows that the boundaries of the Middle and Late Miocene California benthic stages are all closely coincident with major cold events. The Luisian/Mohnian boundary is associated with cold event C2, and in fact, Baldauf and Barron (1982) noted strong cooling in the diatom assemblages at the top of the type Luisian Stage in central California, and Kleinpell (1938) associated cooling with his Luisian/Mohnian boundary. The early Mohnian/late Mohnian boundary coincides with cold event C7 (11.3–11.2 Ma) and hiatus NH 4 at the end of the Middle Miocene. This hiatus is common in sections from the California Continental Borderland (J. K. Crouch, oral communication, 1978; Barron, 1981), so it is likely that the early Mohnian/late Mohnian boundary is typically observed at an unconformity in onshore southern California sections. Similarly, the Mohnian/"Delmontian" boundary as correlated by Barron (1976) is correlative with a hiatus NH 6 in all three sections studied. As stated earlier, this interval (ca. 7 Ma) typically corresponds with the top of the Monterey Formation in California and the base of the more terrigenous overlying units including the Sisquoc, Pancho Rico, and Purisima formations. Sediment accumulation rates are significantly higher in the overlying units, and major regional changes in benthic foraminiferal assemblages might be expected. Available evidence (Keller and Barron, in press) also indicates a major cold event of global extent associated with hiatus NH 6.

Comparison with other paleoclimatic studies

The paleotemperature curve of text-figure 11 may be compared with the results of other paleoclimatic studies both in the California area and elsewhere. Most previous studies, however, lack detailed time control and have recognized fairly long (1 m.y. or more) climatic events. Consequently, the paleotemperature interpretations of other workers at Site 173, the Newport Beach section, and Site 470 are easiest to compare with our paleotemperature curve.

At Site 173, earlier paleotemperature studies include those of Ingle (1973) and Keller (1978, 1980a) on planktic foraminifers and Bukry (1973, 1981) on silicoflagellates. Ingle (1973) reported major cooling in Cores 20-18 (= cold events C8 and C9), a brief sub-

tropical interval in Core 16 (= warm event W9), and a major cooling in Core 15 (= cold event C13). Keller (1978) noted major cooling near the Miocene/Pliocene boundary in Core 15 (= C13), and in a later paper, Keller (1980a) reported major cooling in Core 21 (= C6) and Core 17 (= C10). Bukry (1981) reinterpreted his earlier (1973) silicoflagellate data at Site 173, and his results show good agreement with our paleotemperature curve (text-fig. 11). Bukry observed a general cooling trend with minor cooling in Core 28 (= C2), Core 25 (= C4) and Core 23 (= C5) and major cooling beginning in Core 20 (= C8), reaching its peak in Core 18 (= C9), and interrupted by a warm event in Core 16 (= W9). Bukry's data also show cooling at the top of Core 16 (= C11).

At Newport Beach, Weaver et al. (1981) provided paleoclimatic interpretations from radiolarian data that are referenced to the diatom zonation. Weaver et al. (1981) observed temperate radiolarian assemblages in Subzone b of the *Denticulopsis lauta* Zone (compare text-fig. 12) and abrupt cooling at the *D. lauta*/*D. hustedtii*-*D. lauta* Zone boundary. Our results show planktic foraminifer dissolution beginning at this boundary (text-fig. 12), but the cooling in the diatom paleotemperature curve (text-fig. 12) begins somewhat lower in Subzone b of the *D. lauta* Zone. Weaver et al. (1981) noted generally cool conditions within the interval assigned to Subzones a, b, and c of the *D. hustedtii*-*D. lauta* Zone, but they reported brief incursions of warm-water radiolarians near the base of Subzone b (= W4?), near the top of Subzone b (= W5?), and at the base of Subzone c (= W6?) (text-fig. 12). As stated earlier, Weaver et al. (1981) observed an increase in the abundance of diatoms, especially *Thalassionema* and *Thalassiothrix*, at the base of Subzone d of the *D. hustedtii*-*D. lauta* Zone which they attributed to an intensification and broadening of the California Current system. This event is also apparent in text-figure 9, and corresponds with cold event C8, a major cold event in text-figure 11. An influx of warm-water radiolarians occurs in the lower portions of the *Nitzschia reinholdii* Zone according to Weaver et al. (1981), possibly equivalent to warm event W10 (text-fig. 12). In the middle portion of the *N. reinholdii* Zone, however, Weaver et al. reported the co-occurrence of cool-water radiolarians and common warm-water diatoms (*Hemidiscus cuneiformis* Wallich). Our results do not show common *H. cuneiformis* in this interval (table 7). The samples of Weaver et al. were probably sieved for radiolarians and may have concentrated large diatoms like *H. cuneiformis*. Both cold (C12) and warm (W11) conditions are predicted by the diatom curve (text-fig. 12) for this interval. Immediately prior to the base of the *Thalassiosira oestrupii* Zone, Weaver et al. observed the acme of the radiolarian *Lamprocyrtis heteroporos* (Hays) and related it to global warming. Although brief,

warm event W12 correlates precisely with this horizon in the diatom curve (text-fig. 12).

At Site 470 Bukry (1981) completed a detailed paleotemperature study, using silicoflagellates. Bukry's results show very good agreement with the planktic foraminifer (text-fig. 8) and diatom (text-fig. 10) results at Site 470 in that they show cooling trends in upper Core 16 (= C4), upper Core 14 (= C6), upper Core 12 (= C7), and middle Core 11 (= C8) and warming trends in lower Core 11 (= W6) and Core 9 (= W9). A warming trend in lower Core 15 and general cool values in Core 17 are at odds with our results.

The combined paleotemperature curve of text-figure 11 may be compared with detailed paleotemperature studies from sections outside the California Current area if a well-controlled correlation scheme is followed. Consequently, Bukry's (in press) detailed silicoflagellate paleotemperature curves for the latest Miocene and Pliocene of DSDP Sites 503 and 504 in the eastern equatorial Pacific may be compared directly with our curve, because they are well controlled by diatom biostratigraphy, and ties of low-latitude and middle-latitude diatom biostratigraphy have been well established for that interval (Burckle and Opdyke, 1977; Barron, 1980). Bukry's curves show a warm event at about 5.6 to 5.5 Ma (= W11), a major cold event between 5.4 and 5.2 Ma (= C13), warming at 5.0 Ma (= W12), and subsequent cooling (= C14). At Site 503 Bukry's data show a cooling between about 7.4 and 7.1 Ma which corresponds with the cooling hypothesized in text-figure 12 coincident with hiatus NH 6.

Other detailed paleotemperature studies in the Middle and Late Miocene include those of Haq (1980) on coccoliths and Poore (1981) on planktic foraminifers in the Atlantic. Correlations with these studies are less precise, but numerous similarities do exist with our results. Haq (1980) recorded warming events between 12.5 and 11.5 Ma (= W5) and between 9 and 7.5 Ma (= W8 and W9). He reported cooling at 15 Ma, general cool conditions between 14 and 12.5 Ma (= C4 and C5), a major cooling between 11 and 9 Ma (= C8 and C9), and a latest Miocene cooling peaking at 6 Ma (= C12) lasting to the end of the Miocene. Poore (1981) suggested warm events at 10 Ma (= W7), 9 Ma (= W8), 8 Ma (= W9), and 7 Ma separated by cold events at 9.5 Ma (= C9), 8.5 Ma (= C10) and 7.5 Ma (= C11).

Table 9 summarizes the microfossil studies and oxygen isotope studies which have also recognized the 14 cold and 12 warm events in the marginal northeastern Pacific and elsewhere.

DEPOSITIONAL HISTORY OF THE MONTEREY FORMATION

The predominantly siliceous Monterey Formation and similar sediments around the North Pacific margin were

TABLE 9

Recognition of paleotemperature events in previous studies (microfossil and isotope) in the California area and elsewhere. References: 1, Ingle, 1973; 2, Keller, 1978; 3, Barron, 1973; 4, Keller, 1980a; 5, Bukry, 1981; 6, Weaver et al., 1981; 7, Baldauf and Barron, 1982; 8, Bukry, in press; 9, Woodruff et al., 1981; 10, Keigwin, 1979; 11, Keller, 1981b; 12, Haq, 1980; 13, Poore, 1981.

Event	Marginal NE Pacific	N. & Eq. Pacific	N. & S. Atlantic
C14	—	8	—
W12	6	8	—
C13	1, 2	4, 8, 11	—
W11	6	8	—
C12	6	4	12
W10	6?	4	—
C11	—	4, 11	13
W9	1	4, 11	12, 13
C10	4	—	13
W8	3	—	12, 13
C9	1, 3	4, 9, 11	12, 13
W7	3	—	13
C8	1, 6	—	12
W6	6	—	—
C7	—	9, 10, 11	—
C6	4, 5	4, 10, 11	—
W5	6	9	12
C5	5	9, 11	12
W4	6	—	—
C4	5	9, 11	12
W3	—	—	—
C3	—	9	—
W2	—	—	—
C2	5, 7	—	—
W1	7	—	—
C1	—	—	—

deposited between approximately 15 and 5 Ma (Ingle, 1981). The siliceous component of Monterey sediments older than about 15 Ma is very low. The paleotemperature history based on faunal and floral analyses as well as oxygen isotope analyses of foraminifers can provide some insight into the depositional history of these siliceous deposits. Oxygen isotope data from benthic foraminifers indicate that the warmest temperatures of the Miocene occurred at about 16.5–16 Ma; thereafter temperatures steadily declined, although they rapidly fluctuated until about 13.5 Ma (Woodruff et al., 1981). The early part of the Monterey Formation, between about 15 and 13.5 Ma, contains calcareous faunas with a significant temperature component and periodic occurrence of subtropical planktic foraminifers. Diatom floras also show more subtropical influence, and upwelling, as indicated by *Thalassionema* and *Thalassiothrix* spp., is moderate, with the exception of a brief increase near the base of the Monterey Formation at about 15 Ma (text-fig. 9). These assemblages reflect the generally declining early Middle Miocene temperatures coincident with major growth of the east Antarctic ice sheet.

A definite increase in upwelling begins at about 12.5 Ma which initiated deposition of the predominantly siliceous sediments with a minor calcareous component typical of the upper Monterey Formation. This increase in upwelling appears to be due to generally enhanced Late Miocene cooling which is also noted in the in-

creased faunal and floral provincialism discussed earlier.

A survey of siliceous sediments in the World Ocean has revealed that biogenic silica is nearly absent in the Miocene prior to 16 Ma in the Indian and Pacific oceans, whereas the North Atlantic is dominated by siliceous sedimentation (Keller and Barron, in press). After about 15.5 to 15 Ma, silica-rich biogenic sediments steadily increased in the North Pacific, but declined abruptly in the North Atlantic, except in high latitudes and off equatorial Africa. One explanation proposed for this silica transfer from the Atlantic to the Pacific is the increased production of Norwegian Overflow Water which displaced the silica-rich Antarctic Bottom Water into the Pacific and Indian oceans (see also Berger, 1972; Keller and Barron, in press). This silica transfer coincides with the onset of siliceous sedimentation around the marginal North Pacific. Thereafter, declining paleotemperatures that climaxed by about 13.5 Ma were accompanied by increased upwelling in the North Pacific, further enhancing siliceous sedimentation around the marginal North Pacific.

CONCLUSIONS

1) Quantitative diatom and planktic foraminiferal biostratigraphy reveals similarities in the patterns of faunal and floral abundance changes in middle and upper Miocene Sites 173, 470 and Newport Beach and greatly enhances biostratigraphic correlation.

2) Paleotemperature curves can be constructed using diatoms and planktic foraminifers with known cold-water affinities. Combining these two curves results in a detailed record of paleotemperature oscillations in the marginal northeast Pacific.

3) Fourteen cold events (C1 to C14) and 12 warm events (W1 to W12; table 8) have been recognized between 15 and 5 Ma from these faunal and floral relative paleotemperature curves, and many of these paleotemperature events have also been recognized elsewhere by other workers (table 9).

4) Cold events C4, C6, and C7 (13.4–13.1 Ma, 12.4–11.9 Ma, 11.3–11.2 Ma) appear to be responsible for major changes in diatom and planktic foraminiferal assemblages occurring between about 13.5 and 11.2 Ma. These faunal and floral changes resulted in the dominance of the cool California Current assemblages and the near absence of subtropical and temperate planktic foraminifers prevalent in the earlier Middle Miocene.

5) Increased upwelling begins in the late Middle and early Late Miocene between 12.5 and 11.1 Ma, coincident with the increased dominance of the California Current assemblages. This increased upwelling and change to cooler faunal and floral assemblages reflects an increased latitudinal thermal gradient.

6) Sediment accumulation rates increase drastically in the latest Miocene at Newport Beach and Site 173. This latest Miocene sedimentation increase occurs elsewhere in California and appears to have been caused by tectonic uplift, erosion and an increased influx of terrigenous sediment.

7) Hiatuses are present between 7 and 6.5 Ma at all three sections, between 12–11 Ma at Site 173 and Newport Beach, and between 9.8–8.5 Ma at Site 470. These hiatus intervals correspond to hiatuses widely recognized in the world oceans and suggest major paleoceanographic changes associated with increased glaciation and resulting intensified bottom current circulation and dissolution.

8) The Monterey Formation of California and similar Miocene siliceous deposits around the marginal North Pacific appear to have been the result of both a silica transfer from the North Atlantic to the Pacific and Indian oceans owing to increased production of Norwegian Overflow Water and subsequent increased siliceous productivity in the late Middle through Late Miocene associated with cooler climatic conditions and increased upwelling.

APPENDIX

Taxonomic notes

The reader is referred to Barron (1981) for the taxonomic citations and illustrations of the diatom taxa. *Coscinodiscus yabei* Kanaya has been tabulated as *C. plicatus* Grunow s. ampl. [Addendum: F. Akiba recently (1982, *Bacillaria*, 5:43–61) proposed the name *Thalassionema schraderi* Akiba for specimens classified as *T. hirosakiensis* in this report.]

Redefinition of diatom zonal boundary

The base of the *Denticulopsis hustedtii*-*D. lauta* Zone and the top of the underlying *Denticulopsis lauta* Zone has been defined by the first occurrence of *Denticulopsis hustedtii* (Koizumi, 1973; Barron, 1980, 1981). The present study (tables 1–3) and other recent studies (Rowell, 1981; Baldauf and Barron, 1982), however, cast doubt on the isochronicity of this datum level at middle latitudes. The transition from *D. hyalina* to *D. hustedtii* (or first *D. hustedtii* abundance greater than that of *D. hyalina*), on the other hand, appears to be isochronous at middle to high latitudes of the North Pacific (Barron, 1980, 1981; Keller and Barron, 1981; this study) and is proposed to replace the first appearance of *D. hustedtii* as the base of the *D. hustedtii*-*D. lauta* Zone. The resultant zonal boundary is estimated at 13.8 Ma and corresponds with the first appearance of *D. hustedtii* at low latitudes (Barron, 1981; Keller and Barron, 1981). Relatively warm conditions (W2 = 13.8 to 13.7 Ma) are hypothesized for this time (text-fig. 12), so it is unlikely that the introduction of middle-to high-latitude *D. hustedtii* into the tropics at this time was due to temperature changes in the tropics.

Denticulopsis lauta Zone

Base: First appearance of *Denticulopsis lauta* s.str. (Barron, 1980).

Top: Transition of *Denticulopsis hyalina* to *D. hustedtii* (or first *D. hustedtii* abundance greater than *D. hyalina* abundance) (redefined here).

Denticulopsis hustedtii-*D. lauta* Zone

Base: Corresponds with top of *D. lauta* Zone—transition of *D. hyalina* to *D. hustedtii* (redefined here).

Top: Last appearance of *Denticulopsis dimorpha* (Barron, 1980).

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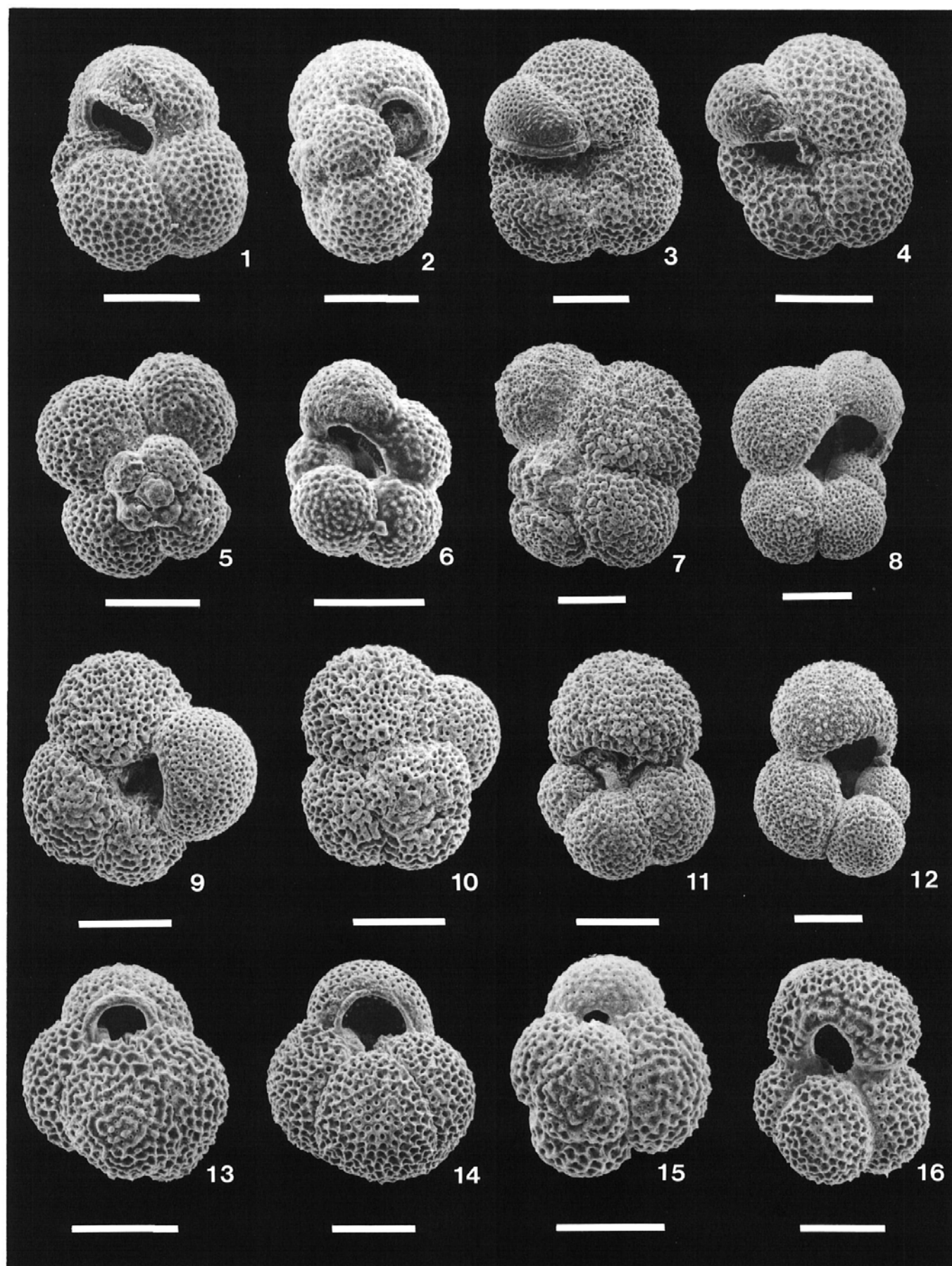
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PLATE 1

Site 470. Scale bars = 100 μ m.

- | | |
|---|--|
| 1-4 <i>Globorotalia continuosa</i> Blow
Sample 11 CC. | 11-12 <i>Globigerina bulloides</i> d'Orbigny
Sample 18-2 (52-62 cm). |
| 5-6 <i>Globigerina pseudociperoensis</i> Blow
Sample 16-1 (21-26 cm). | 13-14 <i>Globigerina decoraperta</i> Takayanagi and Saito
Sample 17-1 (31-36 cm). |
| 7-8 <i>Globigerina umbilicata</i> Orr and Zaitzeff
Sample 18-2 (52-62 cm). | 15-16 <i>Globigerinoides bulloideus</i> Crescenti
Sample 17-1 (31-36 cm). |
| 9-10 <i>Globigerina quadrilatera</i> d'Orbigny
Sample 18-2 (52-62 cm). | |

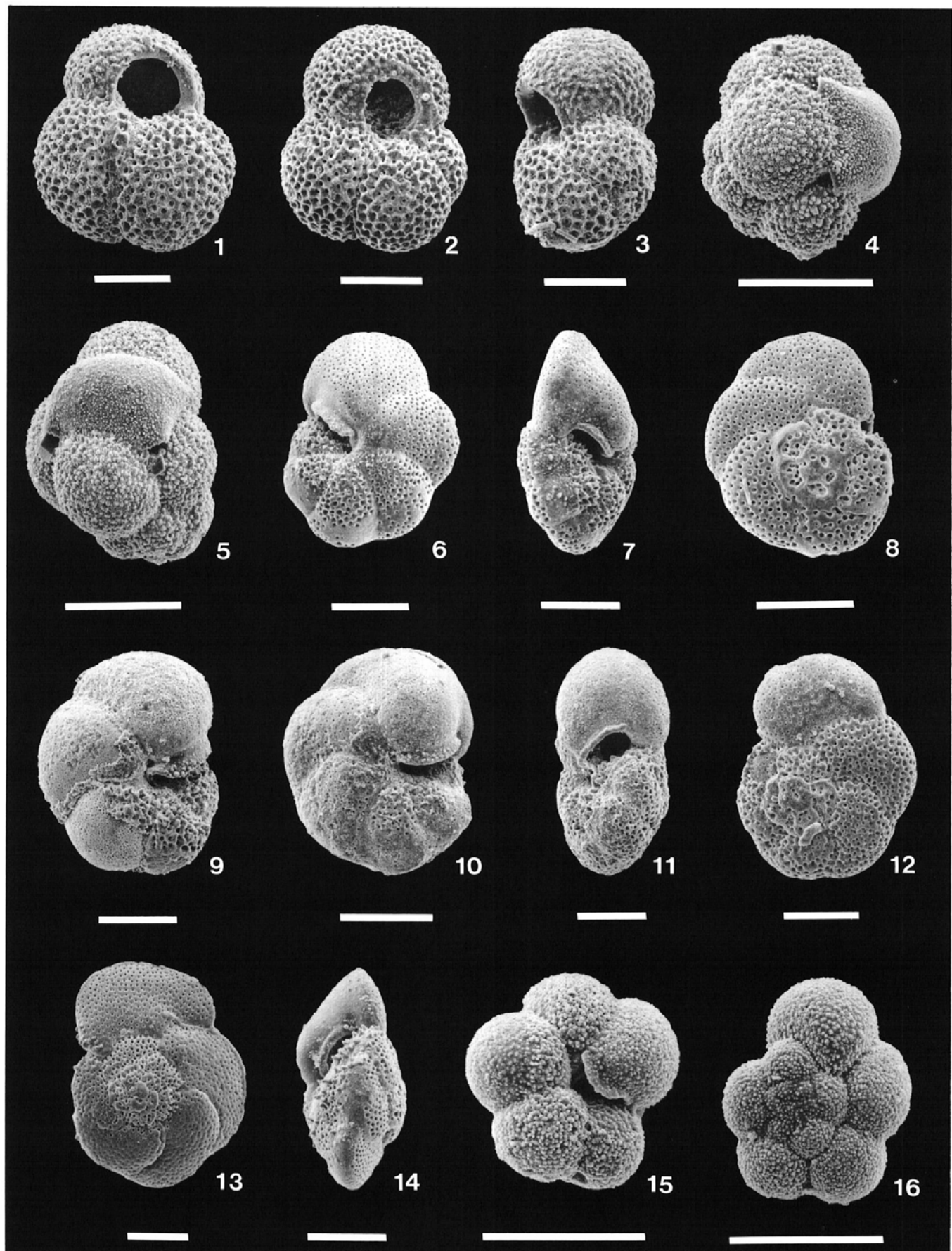


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PLATE 2

Site 470. Scale bars = 100 μ m.

- | | |
|---|---|
| 1-3 <i>Globigerina woodi</i> Jenkins
Sample 18-2 (52-60 cm). | 9-12 <i>Globorotalia peripheroronda</i> Blow and Banner
Sample 18-2 (52-60 cm). |
| 4-5 <i>Globigerinita glutinata</i> Egger
Sample 18-2 (52-60 cm). | 13-14 <i>Globorotalia praemenardii</i> Cushman and
Stainforth
Sample 17 CC. |
| 6-8 <i>Globorotalia peripheroacuta</i> Blow and Banner
Sample 17-3 (31-36 cm). | 15-16. <i>Globigerina</i> sp. aff. <i>G. quinqueloba</i> Natland
Sample 18-2 (52-60 cm). |



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PLATE 3

Site 470. Scale bars = 60 μm , except for figures 13 and 14 where scale bars = 30 μm .

- | | | |
|------|--|---|
| 1–4 | <i>Globigerina</i> sp. aff. <i>G. quinqueloba</i> Natland
Sample 18-2 (52–60 cm). | Sample 15 CC. Note, magnification is the same as for figures 15 and 16. |
| 5–7 | <i>Globorotaloides hexagona</i> (Natland)
Sample 18-1 (139–144 cm). | 13 <i>Globorotaloides trema</i> Lipps
Blow-up. Sample 15 CC. |
| 8 | <i>Globorotaloides trema</i> Lipps
Surface blow-up. Sample 15 CC. Note, magnification is the same as for figure 14. | 14 <i>Globorotaloides hexagona</i> (Natland)
Blow-up. Sample 15 CC. |
| 9–12 | <i>Globorotaloides trema</i> Lipps | 15–16 <i>Globorotaloides hexagona</i> (Natland)
Sample 15 CC. |

