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2. LATEST NEOGENE PLANKTONIC FORAMINIFERAL BIOSTRATIGRAPHY OF THE CALIFORNIA MARGIN[1]

J.P. Kennett,[2] G.A. Rozo-Vera,[3] and M.L. Machain Castillo[4]

ABSTRACT

Late Neogene biostratigraphy of planktonic foraminifers has been investigated from 13 sites cored during Ocean Drilling Program Leg 167 off the coast of California. The planktonic foraminiferal biostratigraphy of six of these sites is presented here at higher stratigraphic resolution for the interval that encompasses the late early Pliocene through the Quaternary (~3.5 Ma to present day). The sites form a transect along the California margin from 31°N to 41°N within the California Current system. A new planktonic foraminiferal zonation has been established largely on evolutionary changes within the *Neogloboquadrina* plexus, supported by other taxa. A total of eight zones are recognized, most of which are broadly applicable throughout the region, thus providing a biostratigraphic zonation of the sequence at ~0.5-m.y. intervals. The new zonation appears to be unique to the California Current system.

The diversity of planktonic foraminiferal assemblages during the late Neogene appears to have remained relatively constant despite large-scale paleoclimatic change. The assemblages are consistently dominated by few taxa that almost always include the neogloboquadrinids and *Globigerina bulloides.* Low diversity and high dominance of the assemblages favored these and other taxa well adapted to upwelling systems exhibiting high seasonal surface ocean variability. Apparently the oceanographic conditions that favor such assemblages have persisted at least for the duration of the late Neogene (~3.5 Ma to present day). The biostratigraphically important forms have been illustrated with scanning electron micrographs.

INTRODUCTION

The California Current system is one of the most biologically productive modern water masses in the world's ocean. The geologic record indicates that high biogenic productivity along the California margin was established during the early Neogene and has since persisted (Ingle, 1973b; Barron, 1975). An understanding of the geological history of the California Current system has required progressive development—at sufficiently high resolution—of a stratigraphic and chronologic framework. Part of this framework has continued to be based on the biostratigraphy of planktonic foraminifers. During the Neogene, planktonic foraminifers have been an important biotic element of the plankton of the California Current system. Planktonic foraminifers are sensitive to changes in the near-surface marine environment, are important contributors to the hemipelagic sediments deposited on the California margin, and represent the primary group used in stable isotopic investigations. Nevertheless, the history of development of Neogene planktonic foraminifer faunas of the California margin is known only in broad outline.

The late Neogene planktonic foraminiferal sequences of the California margin have been the subject of investigation since the pioneering investigations of Ingle (1967, 1973a, 1973b). His studies initially focused on marine sequences exposed on land and later were extended into off-shore drilled (Deep Sea Drilling Project [DSDP]) sequences. These investigations were fundamental in establishing a basis for the Neogene biochronology of the California margin and represented a major advance toward understanding of the Neogene paleoclimatic and paleoceanographic evolution of the California Current. Because paleoceanographic changes in the California Current system have been highly sensitive to global climate change, the investigations of Ingle (1967, 1973a) represent major contributions toward understanding the history of Neogene global climate change. Changes in planktonic foraminiferal assemblages throughout the Neogene have reflected the changing relative strengths of the cool California Current from the north and warm, subtropical waters from the south.

Later investigators extended and modified the biochronology of Ingle (1973b). In particular, Keller (1978a, 1978b, 1978c, 1979a, 1980) and Keller and Ingle (1981) documented the late Neogene planktonic foraminiferal biostratigraphy for a number of deep-sea sites drilled in the North Pacific, which has helped to correlate the California sequences with those elsewhere in the North Pacific, including Japan. During these investigations, Keller (1978c) observed a greater range of taxonomic diversity in the *Neogloboquadrina* plexus than discovered in the previous work and began to exploit changes in the ranges of these forms for biostratigraphic subdivision of the late Neogene of the North Pacific. This followed pioneering investigations of Maiya et al. (1976), who had identified and named a suite of *Neogloboquadrina* species in late Neogene marine sequences exposed on land in Japan. These taxa have since been found in relatively cool waters of the entire North Pacific. Further contributions toward understanding the late Neogene planktonic foraminiferal sequence of western North America were made by other investigators studying sequences drilled by the DSDP and the Ocean Drilling Program (ODP). These have included the work of Poore (1981), who examined sequences along the western margin (including California) and Zellers (1995), who investigated sequences in the far northwest Pacific, north of California.

A further major advance was made by Lagoe and Thompson (1988) who compiled a late Neogene chronostratigraphic framework based on planktonic foraminiferal datums and coiling shifts in *Neogloboquadrina pachyderma* observed in marine sequences exposed on land that were calibrated with magnetostratigraphy. Several of the late Neogene datums recognized by Lagoe and Thompson (1988) have also been observed in offshore sequences drilled on the California margin.

Until now the late Neogene planktonic foraminiferal sequences of the California margin have been largely correlated with the standard

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[2]Department of Geological Sciences and Marine Science Institute, University of California, Santa Barbara CA 93106, USA. kennett@magic.geol.ucsb.edu
[3]CICTUS/Universidad de Sonora, Rosales y Niños Heroes S/N, A.P. 1819, C.P. 83000, Hermosillo, Sonora, Mexico.
[4]Instituto de Ciencias del Mar y Limnologia, Universidad Nacional Autonóma de Mexico, Apdo Postal 70-310, Mexico 04510, D.F., Mexico.

Neogene zonation (N zones) of Banner and Blow (1965). This has never been satisfactory because the N zonation is based on a change in stratigraphic range of subtropical to tropical planktonic foraminifers that are absent to rare along the California margin. Thus, this zonal scheme is not directly applicable to sequences drilled off California, and correlations with these zones have been indirectly determined using other stratigraphic criteria. The only previous late Neogene foraminiferal zonation established for the California margin is that of Keller (1979a), who established this on a single drilled site (DSDP Leg 18, Site 173) off Southern California. Development of a zonal sequence that might be broadly applicable to the region has been difficult because of a combination of poor preservation and relatively low abundances of planktonic foraminifers in the margin sequences and, until now, inadequate material to develop such a zonation. Earlier drilled sites on the margin provided insufficiently continuous records and were often cored at locations that were not optimal for foraminiferal preservation.

Drilling during ODP Leg 167 provided, for the first time, a high-quality suite of late Neogene sections along the entire length of the California margin (Fig. 1; Table 1). These sequences contain a relatively continuous record of abundant planktonic foraminifers suitable for determining, at relatively high stratigraphic resolution, a biostratigraphic zonation for the California Current system. Our contribution documents the stratigraphic ranges of key planktonic foraminiferal taxa in six of these sites and establishes a new planktonic foraminiferal zonation from the late early Pliocene through the Quaternary (~3.5 Ma to present day) that is applicable to a broad sector of the California margin. A general outline of the biostratigraphy presented here began to be established at sea during Leg 167 and was based on core-catcher samples (Lyle, Koizumi, Richter, et al., 1997). Following Leg 167, we selected six of the sites from locations throughout the length of California to conduct a higher resolution biostratigraphic analysis (Fig. 1; Table 1). Biostratigraphic data on the remaining sites (Lyle, Koizumi, Richter, et al., 1997) support those presented here, although these earlier investigations were made at lower resolution; also, several of the taxa that have since been used to construct the new zonation were not employed during Leg 167.

MATERIAL AND METHODS

The sediment sequences cored during Leg 167 are made up primarily of hemipelagic sediments containing a relatively continuous succession of planktonic and benthic foraminifers. These occur in sufficiently high abundances since 3.5 Ma to provide a strong base for the development of a regional late Neogene planktonic foraminiferal zonation. Sedimentation rates are relatively high in the six sites documented in this study, ranging from ~8 to ~20 cm/k.y. Samples (10 cm^3) were taken at 1.5- to 3-m intervals down the length of the cores. Samples were gently washed over a 63-µm sieve and the residues dried at 50°C. Semiquantitative estimates were made of the relative abundance (abundant, common, few, and rare) of stratigraphically important taxa in the >150-µm fraction for each sample. Samples were strewn over a picking tray divided into 45 quadrants. Taxa that occurred once per quadrant were considered common, and those that occurred, on average, in every several quadrants were considered few. If a taxon was observed only once or twice per tray, it was considered rare (Tables 2–7).

Earlier shipboard investigations on core-catcher samples and the recognition of a biostratigraphic succession (Lyle, Koizumi, Richter, et al., 1997) enabled us to identify planktonic foraminifers of potential biostratigraphic importance. During our later, shore-based investigations we estimated the relative abundance of these forms (Tables 2–7). Changes in the relative abundance of other taxa were not recorded.

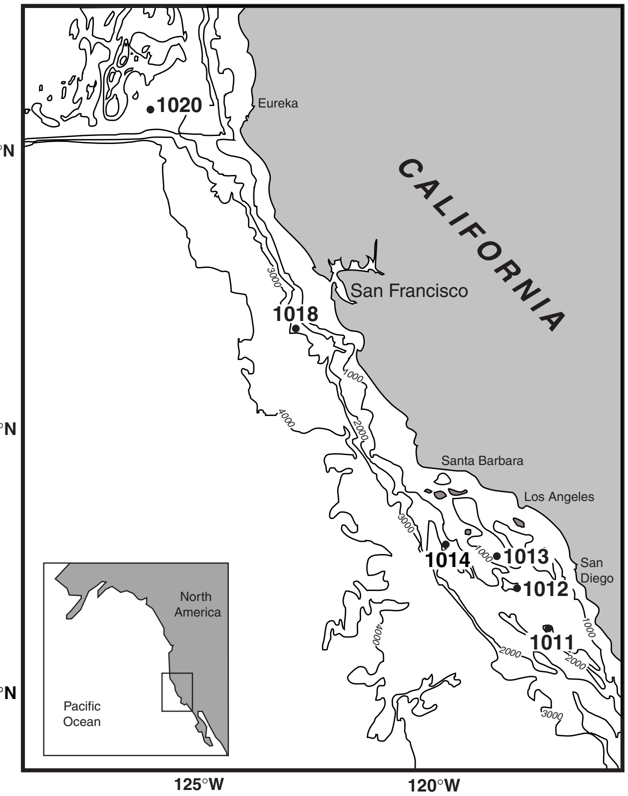

Figure 1. Location of the six sites drilled along the California margin during Leg 167 used to develop planktonic foraminiferal zonation in this investigation.

GENERAL CHARACTER OF ASSEMBLAGES

Late Neogene planktonic foraminiferal assemblages of the California margin are consistently of low diversity. Diversity remained relatively low even during warmer intervals. Assemblages are dominated throughout the interval by *Globigerina bulloides* and a number of species of *Neogloboquadrina.* Other persistent forms occurring throughout in varying frequencies are *Globigerina quinqueloba, Globigerinita glutinata, Orbulina universa,* and *Globorotalia scitula. Globorotalia (Globoconella*) spp. also occurs throughout, although in relatively low frequencies. *Globigerinoides ruber* occurs fairly persistently, although in low frequencies in the southern sites of the transect. Reasons for this persistently low diversity are unclear, but it probably resulted from the relatively cool sea-surface temperatures that marked the California Current system during the late Neogene in combination with strong seasonal upwelling. High variability in the modern surface waters results in part from the strong coastal upwelling. Planktonic foraminiferal assemblages of the California margin mostly include generalist forms that must be adapted to high variability of near sea-surface conditions.

The *Neogloboquadrina* plexus exhibits a dynamically changing succession of forms, with one or two species dominating at any particular interval. This group includes relatively large forms such as *Neogloboquadrina kagaensis* and *Neogloboquadrina asanoi,* forms of intermediate size that include *Neogloboquadrina humerosa praehumerosa* and *Neogloboquadrina dutertrei,* and smaller forms that include a number of taxa that were previously considered to represent variants of *N. pachyderma* (Kennett, 1976; Keller, 1978c). These morphotypes include both sinistral- and dextral-coiled forms as well as those exhibiting differences in general shape, numbers of chambers in the final whorl, apertural characteristics, and other features. A

Table 1. Leg 167 drill sites used to construct planktonic foraminiferal zonation.

Site	Location	Latitude and longitude	Distance from shore (km)	Water depth (m)	Sediment thickness drilled (mbsf)
1011	Animal Basin	31°16.8′N; 117°38.0′W	85	2033	276
1012	East Cortes Basin	32°17.0′N; 118°23.0′W	105	1783	274
1013	San Nicolas Basin	32°48.0′N; 118°53.9′W	115	1575	146
1014	Tanner Basin	32°50.0′W; 119°58.9′W	155	1177	449
1018	Sediment drift, south of Guide Seamount	36°59.3′N; 123°16.7′W	76	2476	426
1020	Eastern flank, Gorda Ridge	41°0.1′N; 126°26.1′W	167	3050	278

Table 2. Distribution and relative abundances of stratigraphically useful planktonic foraminifers in Pliocene–Quaternary Hole 1011B.

Core, section, interval (cm)	Depth (mbsf)	*Neogloboquadrina pachyderma* B	*Neogloboquadrina pachyderma* A	*Globorotalia inflata*	*Neogloboquadrina dutertrei*	*Neogloboquadrina humerosa praehumerosa*	*Neogloboquadrina pachyderma* C	*Neogloboquadrina kagaensis*	*Neogloboquadrina asanoi*	*Globorotalia puncticulata*	Zone	Age
167-1011B-												
1H-1, 50-55	0.50	F		R	F							
1H-2, 50-55	2.00	C										
1H-3, 50-55	3.55	C		R								
1H-4, 50-55	5.00	F		R								
1H-5, 50-55	6.50				A	F						
1H-6, 50-55	8.00	A		C								
2H-1, 50-55	8.90	F		F		F						
2H-2, 50-55	10.40	C									CM1	
2H-3, 50-55	11.90	A										
2H-4, 50-55	13.40	F										
2H-5, 50-55	14.90	C										
2H-6, 50-55	16.40	R				R						
2H-7, 50-55	17.90	A		C								
3H-1, 50-55	18.40	C		R								
3H-2, 50-55	19.90	A		F								
3H-3, 50-55	21.40	A		F		R						
3H-4, 50-55	22.90	A	A	C	C	A						
3H-5, 50-55	24.40	A	C	R								
3H-6, 50-55	25.90	A	A		F	C						
3H-7, 50-55	27.40	A	A			C						Quaternary
4H-1, 48-53	27.88	F		R								
4H-2, 48-53	29.38	C		C								
4H-3, 48-53	30.88	A	A	A	C	A						
4H-4, 48-53	32.38	A	F	R							CM2	
4H-5, 48-53	33.88											
4H-6, 48-53	35.38	A	A	F		R						
4H-7, 48-53	36.88	C	A			C						
5H-1, 50-55	37.40	F	F									
5H-2, 50-55	38.90	A	C	C		C						
5H-3, 50-55	40.40	A	A	C								
5H-5, 50-55	43.40											
5H-6, 50-55	44.90											
5H-7, 50-55	46.40											
6H-1, 51-56	46.91											
6H-2, 50-55	48.40											
6H-4, 55-60	51.45					R						
6H-5, 50-55	52.90											
6H-6, 50-55	54.40										CM3 to CM4	
6H-7, 50-55	55.90											
7H-1, 50-55	56.40			R								
7H-2, 50-55	57.90			R				R				
7H-3, 50-55	59.40			R								
7H-4, 50-55	60.90			R		F						
7H-5, 64-69	62.54					R						
7H-6, 50-55	63.90					C						
7H-7, 50-55	65.40					C						
8H-1, 50-55	65.90					R	A	C				
8H-2, 50-55	67.40					R	A	C				
8H-3, 50-55	68.90					F	A	A				
8H-4, 50-55	70.40						A	A				late Pliocene
8H-5, 50-55	71.90						C	R			CM5	
8H-6, 50-55	73.40					F	F	R				
9H-2, 49-53	76.89					C	A	A				
9H-3, 49-53	78.39					R	A	A		F		
9H-4, 49-53	79.89					R	A	C				
9H-5, 49-53	81.39			R		R	C	F	R	R		
9H-6, 53-57	82.93			R		R	A	A	C			
9H-7, 49-53	84.39						F	F		R	CM6	
10H-1, 45-54	84.85					R	C	C	R			

Table 2 (continued).

Core, section, interval (cm)	Depth (mbsf)	*Neogloboquadrina pachyderma* B	*Neogloboquadrina pachyderma* A	*Globorotalia inflata*	*Neogloboquadrina dutertrei*	*Neogloboquadrina humerosa praehumerosa*	*Neogloboquadrina pachyderma* C	*Neogloboquadrina kagaensis*	*Neogloboquadrina asanoi*	*Globorotalia puncticulata*	Zone	Age
10H-2, 45-54	86.35					F		C	C	C	CM6	late Pliocene
10H-3, 45-54	87.85			R		F		C	A			
10H-4, 45-54	89.35							R	F	F		
10H-5, 45-54	90.85					R		C	A	C		
10H-6, 45-54	92.35							F	C	R		
11H-1, 50-55	94.40					F		C	A	R		
11H-2, 50-55	95.90							C	A			
11H-3, 50-55	97.40					R		C	C			
11H-4, 50-55	98.90			A				A	A			
11H-5, 50-55	100.40					R		F	F	R		
11H-6, 50-55	101.90					C		A	F			
12H-1, 50-55	103.90			C		C		A	C	R		
12H-2, 50-55	105.40					A		A	A			
12H-3, 50-55	106.90					A		A	C			
12H-4, 50-55	108.40					A		A				
12H-5, 50-55	109.90					A		A				
12H-6, 50-55	111.40					C		A		F		
13H-1, 50-55	113.40			A		C		C		A		
13H-2, 50-55	114.90			C				F		C		
13H-3, 50-55	116.40					R		C	F	R		
13H-4, 50-55	117.90			R				F	R	R		
13H-5, 50-55	119.40			R				R				
13H-6, 50-55	120.90			F				R		F		
14H-1, 50-55	122.90			R		F		C		A		
14H-2, 50-55	124.40					R		R				
14H-3, 50-55	125.90					F		C	R			
14H-4, 50-55	127.40					C		C	R			
14H-5, 50-55	128.90					C		C				
14H-6, 50-55	130.40					F		C	R			
14H-7, 50-53	131.90					C		C			CM7	early Pliocene
15H-1, 50-55	132.40					R		F				
15H-2, 50-55	133.90					C		C				
15H-3, 50-55	135.40					F		C				
15H-4, 50-55	136.90					F		C				
16H-1, 49-54	138.39					F		F				

Notes: California margin (CM) zones indicated. A = abundant, C = common, F = few, R = rare.

long-standing question has been whether the different forms of *N. pachyderma* represent distinct species or ecophenotypic varieties of the same species (Bandy, 1959; Kennett, 1976; Keller, 1978c). However, recent molecular biological studies (DNA) of modern forms (Darling et al., 1998; Stewart et al., 1998) have demonstrated that at least some of these morphotypes, including sinistral- and dextral-coiled forms, are distinct species.

We have discovered that several morphotypes of *N. pachyderma* have distinct biostratigraphic ranges in the late Neogene sequences of the California margin. Furthermore, their appearance and disappearance in the sequence appear to represent unique events. This suggests that several of the morphotypes are distinct and separate forms within the phylogeny of the neogloboquadrinid plexus. From an evolutionary perspective, these forms act as distinct species, an interpretation that supports the general results of the molecular biological investigations (Darling et al. 1998; Stewart et al., 1998). Nevertheless, in this investigation we continue to classify them as forms of *N. pachyderma*—but in doing so, we recognize that their future classification will need to refer to them as separate species. The taxonomy of each of the stratigraphically important forms is discussed below.

PLANKTONIC FORAMINIFERAL ZONES

The relative abundances of stratigraphically important planktonic foraminiferal species are shown for each of the six sites in Tables 2 through 7. Their stratigraphic ranges are plotted in Figures 2 through 7, and the ranges of specific taxa have been employed to construct the new zonation. A sequence of eight zones has been established for the late early Pliocene through the Quaternary (~3.5 Ma to present day; Figs. 2–8). Thus the planktonic foraminiferal sequence is subdivided into a series of zones, each representing ~0.5 m.y. The average duration of the well-recognized succession of subtropical to tropical Neogene planktonic foraminiferal zones (Banner and Blow, 1965; Berggren et al., 1985) is approximately double this.

Biostratigraphic data generated during Leg 167 indicated the need and potential to construct a relatively high-resolution late Neogene planktonic foraminiferal zonation that is broadly applicable to the California margin. This zonation, constructed after the expedition, appears to be broadly applicable to the California margin despite the relatively large meridional range of the sequences (31°N to 41°N). In constructing the new zonation, we tried to use species that are easily

Table 3. Distribution and relative abundances of stratigraphically useful planktonic foraminifers in Pliocene–Quaternary Hole 1012A.

Core, section, interval (cm)	Depth (mbsf)	*Neogloboquadrina pachyderma* B	*Neogloboquadrina pachyderma* A	*Globorotalia inflata*	*Neogloboquadrina dutertrei*	*Neogloboquadrina humerosa praehumerosa*	*Neogloboquadrina kagaensis*	*Neogloboquadrina asanoi*	*Globorotalia puncticulata*	Zone	Age
167-1012A-											
1H-1, 50-55	0.50	F			R					CM1	Quaternary
1H-2, 50-55	2.00	A						C			
1H-3, 50-55	3.50	A									
2H-1, 50-55	5.20	A									
2H-2, 50-55	6.70	R									
2H-3, 50-55	8.20	R									
2H-4, 50-55	9.70	F									
2H-5, 50-55	11.20	A		F	A						
2H-6, 50-55	12.70	A		A	R						
3H-1, 46-50	14.66	A									
3H-2, 50-55	16.20	R									
3H-3, 50-55	17.70	C									
3H-4, 50-55	19.20	R									
3H-5, 50-55	20.70	A		F							
3H-6, 50-55	22.20	A			R						
3H-7, 50-55	23.70	C									
4H-1, 50-55	24.20	F			R						
4H-2, 50-55	25.70	A		F	R			F			
4H-3, 50-55	27.20	C									
4H-4, 50-55	28.70	F									
4H-5, 50-55	30.20	F									
4H-6, 50-55	31.70	A		F	A						
4H-7, 50-55	33.20	A		A	R						
5H-1, 50-55	33.70	F									
5H-2, 50-55	35.20	C		R	R						
5H-3, 50-55	36.70	C									
5H-4, 50-55	38.20	A		F	R						
5H-5, 49-55	39.69	F		R							
5H-6, 50-55	41.20	A									
5H-7, 50-55	42.70	R									
6H-1, 50-55	43.20	A		C							
6H-2, 50-55	44.74	A		R							
6H-3, 50-55	46.27	A		C							
6H-4, 50-55	47.77	A									
6H-5, 50-55	49.32	A									
6H-6, 50-55	50.87	A		F				C			
6H-7, 50-55	52.40	A	A	F						CM2	
7H-1, 50-55	52.70	R									
7H-2, 50-55	54.20	F									
7H-3, 50-55	55.70	A		F							
7H-4, 50-55	57.20	A		R	R						
7H-5, 50-55	58.70	A									
7H-6, 50-55	60.20	A									
7H-7, 50-55	61.70	A	C	A	R						
8H-1, 50-55	62.20	A	F	F							
8H-2, 50-55	63.70	A	C								
8H-3, 50-55	65.20	F	C								
8H-4, 50-55	66.70	R									
8H-5, 50-55	68.20	C	C	A		C					
8H-6, 50-55	69.70	C	C	R							
8H-7, 50-55	71.20	A	F			R					
9H-1, 55-60	71.75	A	C	A		A					
9H-2, 50-55	73.20	A	C	R							
9H-3, 50-55	74.70	A	C	C		C					
9H-4, 55-60	76.20	A	F	F		A					
9H-5, 55-60	77.70	A	R	A	A	A					
9H-6, 50-55	79.20	C	C								
9H-7, 50-55	80.70	C		F							
10H-1, 50-55	81.20	A	R	C							
10H-2, 50-52	82.70	A	C								
10H-3, 50-55	84.20	C		R		F					
10H-4, 50-55	85.70	A	C	C		C					
10H-5, 50-55	87.20	F									
10H-6, 50-55	88.70		A							CM3 to CM4	
11H-1, 50-55	90.70										
11H-2, 50-55	92.20			F							
11H-3, 50-55	93.70										
11H-4, 50-55	95.20			F							
11H-5, 50-55	96.70					R					
11H-6, 50-55	98.20			A		R					
11H-7, 50-55	99.70			R		R					

Table 3 (continued).

Core, section, interval (cm)	Depth (mbsf)	*Neogloboquadrina pachyderma* B	*Neogloboquadrina pachyderma* A	*Globorotalia inflata*	*Neogloboquadrina dutertrei*	*Neogloboquadrina humerosa praehumerosa*	*Neogloboquadrina kagaensis*	*Neogloboquadrina asanoi*	*Globorotalia puncticulata*	Zone	Age
12H-1, 50-55	100.20									CM3 to CM4	late Pliocene
12H-2, 58-63	101.95			F							
12H-3, 50-55	103.37			R							
12H-4, 50-55	104.87			F							
12H-5, 50-55	106.37										
12H-6, 50-55	107.87										
12H-7, 50-55	109.37		C	R							
13H-1, 50-55	109.70										
13H-2, 50-55	111.20			A		A	A				
13H-3, 50-55	112.70			R		R					
13H-4, 50-55	114.20										
13H-5, 50-55	115.70										
13H-6, 50-55	117.20			F							
13H-7, 50-55	118.70		C	C		C					
14H-1, 50-54	119.20						C			CM5	
14H-2, 50-54	120.70			R		R	F				
14H-3, 50-54	122.20			A		F	F				
14H-4, 50-54	123.70										
14H-5, 50-54	125.20						F				
14H-6, 50-54	126.70			F		C	A				
15X-1, 50-54	128.90					F	C				
15X-2, 50-54	130.40			R			R				
15X-3, 50-54	131.90			F		F	C				
15X-4, 50-54	133.40					R	A				
15X-5, 50-54	134.90					F	C	C		CM6	
15X-6, 50-54	136.40			R		R	F	F			
16X-1, 50-55	138.50			R		F	A				
16X-2, 50-55	140.00						R				
16X-4, 50-55	143.00			R							
16X-5, 50-55	144.50						F				
16X-6, 50-55	146.00					R	R				
17X-1, 50-55	148.10			R							
17X-2, 50-55	149.60			R		R					
17X-3, 50-55	151.10			R			C	C			
17X-4, 50-55	152.60						C	C			
17X-5, 50-55	154.10			R		R	C	C			
17X-6, 50-55	155.60						F				
18X-1, 50-55	157.70										
18X-2, 50-55	159.20					R					
18X-3, 50-55	160.70										
18X-4, 50-55	162.20			R		R	C	C			
18X-5, 50-55	163.70					F	C	C			
18X-6, 50-55	165.20						R				
19X-1, 50-55	167.30			R		F	C	A	F		
19X-2, 50-55	168.80					F	C	A			
20X-1, 50-55	170.40			R		R	A	A	C		
20X-2, 50-55	171.90						C	C			
20X-3, 50-55	173.40					F	A	A	R		
20X-4, 50-55	174.90					R	C	A			
20X-5, 50-55	176.40			R		R	A	A	R		
20X-6, 50-55	177.90						F				
21X-1, 50-55	179.00					R	F	F			
21X-2, 50-55	180.50						C	F			
21X-3, 50-55	182.00					R	A	A			
21X-4, 50-55	183.50					R	C	F			
21X-5, 50-55	185.00					F	C	C	R		
22X-1, 50-55	188.50					F	C				
22X-2, 50-55	190.00					F	A	F			
22X-3, 50-55	191.50			R		F	C				
22X-4, 50-55	193.00					R	C	R			
22X-5, 50-55	194.50					C	A	C			
23X-1, 50-55	198.10			R		C	A	C	R		
23X-2, 50-55	199.60					R					
23X-3, 50-55	201.10						F				
23X-4, 50-55	202.45					R	C				
23X-5, 50-55	203.95					R	F				
23X-6, 50-55	205.45					C	C				
24X-1, 50-55	207.80			R		F	F				
24X-2, 50-55	209.30					R	F	R			
24X-3, 50-55	210.80										
24X-4, 50-55	212.30			C							
24X-5, 50-55	213.80			A					F		
24X-6, 50-55	215.30			C			C	C	A		
25X-1, 50-55	217.20			C			C		C		

Table 3 (continued).

Core, section, interval (cm)	Depth (mbsf)	*Neogloboquadrina pachyderma* B	*Neogloboquadrina pachyderma* A	*Globorotalia inflata*	*Neogloboquadrina dutertrei*	*Neogloboquadrina humerosa praehumerosa*	*Neogloboquadrina kagaensis*	*Neogloboquadrina asanoi*	*Globorotalia puncticulata*	Zone	Age
25X-2, 50-55	218.70						F			CM6	late Pliocene
25X-3, 50-55	220.20			R			F				
25X-4, 50-55	221.70			F		R	R				
25X-5, 50-55	223.20			F		R	C	F	R		
25X-6, 50-55	224.61			R		R	F	R			
26X-1, 50-55	226.90			A			F		C		
26X-2, 50-55	228.40			F							
26X-3, 50-55	229.90										
26X-4, 41-46	231.31			R		R	F				
26X-5, 50-55	232.90					R	F				
27X-1, 50-55	236.50			F			R	R			
27X-2, 50-55	238.00						R				
27X-3, 50-55	239.50					F	F				
27X-4, 50-55	241.00					R	F	R			
27X-5, 50-55	242.50						R	R			
28X-1, 50-55	245.10					R	F				
28X-2, 50-55	246.60					F	F				
28X-3, 50-55	248.10						R				
28X-4, 50-55	249.60					R	C	R			
28X-5, 50-55	251.10						F	R			
28X-6, 50-55	252.60					F	C	R			
29X-2, 50-55	255.93					C	A	A			
29X-3, 50-55	257.43					C	C	C			
29X-4, 50-55	258.93					R	R				
29X-5, 67-72	260.60					F	F	F			
29X-6, 50-55	261.93					R	F	F			
30X-2, 50-55	264.68						R				
30X-3, 50-55	266.18					C	C	A			
30X-4, 50-55	267.68					R	R			CM7	e. Plio.
30X-5, 50-55	269.18					R	R				
30X-6, 50-55	270.68										l. Mio.
30X-7, 49-54	272.17										

Notes: California margin (CM) zones indicated. A = abundant, C = common, F = few, R = rare.

identified, exhibit consistent ranges throughout the region, sequentially appear and disappear in the same order, and are plentiful enough to recognize zonal boundaries with confidence. The zonation is based primarily on changes in the neogloboquadrinid complex, a dominant and rapidly evolving group within the California Current system (Figs. 2–7). A number of other groups exhibiting evolution and biostratigraphic change within the sequences were not employed for the zonation because they occur in insufficient abundances and because of the difficulty this poses in plotting with confidence their first and last appearances. Such taxa include *Globorotalia truncatulinoides, Globorotalia inflata, N. dutertrei,* and *N. humerosa praehumerosa.* These forms are shown to have discontinuous ranges throughout (Tables 2–7), probably because of their migration into these waters only during relatively brief warm episodes.

The zonal sequence is made up of a series of range zones, overlap zones, and gap zones (Figs. 2–7). To simplify utilization, the zones have been assigned a number code with numbers increasing with age. Each numerical zone has a prefix—for example, CM = California margin. We recognize that convention in biostratigraphy employs numerical zones increasing with decreasing age, in accord with the natural evolutionary development of assemblages. This is not practicable in the present study because the late Neogene planktonic foraminiferal sequence in Leg 167 sites is not complete, extending downward only to the late early Pliocene. Older, biosiliceous-rich sediments in the sequences generally lack planktonic foraminifers. Thus, the number code, as established, can be continued back earlier in the Neogene as a result of future work. This numerical code, increasing with age, is thus similar to that employed in magnetostratigraphy and oxygen isotope stratigraphy.

Our planktonic foraminiferal zonation provides a higher resolution biostratigraphic subdivision than that of Keller (1979a) for DSDP Leg 18, Site 173, drilled off the coast of Southern California. The late Neogene zonal scheme of Keller (1979a) is made up of one zone representing the Quaternary and based on the first appearance of *G. truncatulinoides.* We found this species to be stratigraphically unreliable as a zonal marker in the California margin sequences because of its rarity and highly discontinuous stratigraphic range. We recognize three zones in the Quaternary. Keller (1979a) established three zones for the Pliocene based on changes in stratigraphic range of species of *Globorotalia (Globoconella*) (*Globoconella puncticulata; Globoconella inflata*, transitional variety; and *G. inflata*, modern variety). We did not use these forms to construct the zonation because their insufficient stratigraphic continuity did not allow us to confidently plot their ranges over the broader region of the margin. We established five zones ranging from the late-early Pliocene through the late Pliocene. These zones remain to be correlated with biostratigraphic zones based on other microfossil groups in these sequences and placed within a chronological framework by integration with pa-

Table 4. Distribution and relative abundances of stratigraphically useful planktonic foraminifers in Pliocene–Quaternary Holes 1013A and 1013B.

Core, section, interval (cm)	Depth (mbsf)	Abundance	*Neogloboquadrina pachyderma pachyderma*	*Neogloboquadrina pachyderma* B	*Neogloboquadrina pachyderma* A	*Globorotalia inflata*	*Neogloboquadrina dutertrei*	*Neogloboquadrina humerosa praehumerosa*	*Neogloboquadrina pachyderma* C	*Neogloboquadrina kagaensis*	*Neogloboquadrina asanoi*	*Globorotalia puncticulata*	Zone	Age
167-1013B-														
1H-2, 10-12	1.60	A	A	A		R	R							
1H-3, 20-22	3.20	A	A	A		R								
1H-4, 30-32	4.80	A	C	A			R							
1H-5, 0-2	6.00	A	C	A		R	R							
167-1013A-														
2H-2, 100-102	7.60	C	F	C										
2H-3, 70-72	8.80	C		C			R							
167-1013B-														
2H-2, 10-12	10.20	A	F	A										
2H-2, 120-122	11.30	R		R										
2H-3, 20-22	11.80	B												
2H-3, 100-102	12.60	A	A	F		R	C							
2H-4, 110-112	14.20	A	R	C		F	R							
2H-5, 120-122	15.80	A	R	A		R								
2H-6, 50-52	16.60	C	R	C			R							
167-1013A-														
3H-2, 130-132	17.40	A		A			F							
3H-3, 120-122	18.20	F		F										
167-1013B-														
3H-2, 10-12	19.70	C	F	C		R	R							
3H-3, 20-22	21.30	C	C	F			C							
3H-4, 30-32	22.90	A	A	A		R	F						CM1	
3H-5, 40-42	24.50	B												
3H-6, 60-62	26.20	B												
4H-1, 130-132	28.90	B												
4H-2, 140-142	30.50	B												
4H-3, 110-112	31.70	A	A	R		R	R							
4H-4, 120-122	33.30	A	F	A										
4H-5, 130-132	34.90	F	R	F										
4H-6, 140-142	36.50	C		C										
167-1013A-														
5H-3, 118-120	37.80	C	F	A										Quaternary
167-1013B-														
5H-2, 80-82	39.40	B												
5H-3, 90-92	41.00	B												
5H-4, 100-102	42.60	A	F	A		R	C							
5H-5, 110-112	44.20	A	C	A		F	C							
5H-6, 120-122	45.80	A	F	A			F							
167-1013A-														
6H-3, 130-132	47.80	A	F	C										
167-1013B-														
6H-2, 80-82	48.90	A	C	A		C	C							
6H-3, 80-82	50.40	A	C	A		R								
6H-4, 53-55	51.60	R	R	R										
6H-5, 60-62	53.20	A	F	A	A	R								
6H-6, 70-72	54.80	A	C	A										
167-1013A-														
8H-1, 82-84	62.90	F	F	A		R		F						
8H-2, 28-30	63.80	A		A	C	F	F	F						
8H-3, 0-2	65.10	A	R	C									CM2	
167-1013B-														
8H-1, 90-92	66.50	A	A	A		A								
8H-2, 110-112	68.20	A	C	A		A	A	A						
8H-3, 60-62	69.20	A		A	A	C								
8H-4, 90-92	71.00	C	R	C		R								
8H-5, 100-102	72.60	A	C	A	C									
8H-6, 10-12	73.20	B												
167-1013A-														
9H-2, 48-50	73.50	F				R	R	R						
9H-3, 118-120	75.80	B											CM3	
167-1013B-														
9H-1, 100-102	76.10	C	C		C	R								
167-1013A-														
9H-4, 30-32	76.40	B												

Table 4 (continued).

Core, section, interval (cm)	Depth (mbsf)	Abundance	*Neogloboquadrina pachyderma pachyderma*	*Neogloboquadrina pachyderma* B	*Neogloboquadrina pachyderma* A	*Globorotalia inflata*	*Neogloboquadrina dutertrei*	*Neogloboquadrina humerosa praehumerosa*	*Neogloboquadrina pachyderma* C	*Neogloboquadrina kagaensis*	*Neogloboquadrina asanoi*	*Globorotalia puncticulata*	Zone	Age
167-1013B-														
9H-2, 100-102	77.60	B											CM3	Quaternary
9H-3, 50-52	78.60		F			R								
9H-4, 0-2	79.60	C	F		F									
9H-5, 0-2	81.10	R	F		F				R					
167-1013A-														
10H-1, 100-102	82.10	R	R			F								
10H-2, 48-50	83.00	C	R			C								
10H-3, 0-2	84.10	C	C			F		F						
167-1013B-														
10H-1, 100-102	85.60	C	C		C									
10H-2, 100-102	87.10	B											CM4	late Pliocene
10H-3, 0-2	87.60	B												
10H-4, 100-102	90.10	B												
10H-6, 50-52	92.60	B												
10H-7, 0-2	93.60	B												
11X-1, 100-102	95.10	F	F					R						
11X-2, 0-2	95.60	F	F											
11X-3, 0-2	97.10	B												
167-1013A-														
12X-1, 100-102	99.10		R			F		F	A	C			CM5	
12X-2, 0-2	99.60	C	C					F	C	C				
12X-3, 50-52	101.60	A	C					F	C	C				
12X-4, 0-2	102.60	A							A	A				
13X-1, 100-102	108.70	A				F		F	C	A				
13X-2, 0-2	109.20	A	C						C	A				
13X-3, 50-52	111.20	C	C			F			C	C				
13X-4, 50-52	112.70	A							C	C				
13X-5, 100-102	114.70	R				F				R	R		CM6	
13X-6, 50-52	115.70	A				F			C	A	C			
14X-1, 0-2	117.30	F							F	F	F	R		
14X-2, 100-102	119.80	C							C	C	F	R		
14X-3, 0-2	120.30	A	C					F	A	C	F	R		
14X-4, 50-52	122.30	A	F						A	C	C	R		
14X-5, 0-2	123.30	A	A					F		A	C	R		
14X-6, 99-101	125.80	A	A					R		C	A	R		
14X-7, 0-2	126.30	B												
15X-1, 50-52	127.40		C					F		A	A			
15X-2, 100-102	129.40	A	A					R		A	A			
15X-3, 100-102	130.90	A	A					R		A	A			
15X-4, 0-2	131.40	A	C					R		C	A			
15X-5, 48-50	133.40	R	R											
15X-6, 100-102	135.40	R	R								R			
16X-1, 100-102	137.50	A	A					R		C	A			
16X-2, 50-52	138.50	B												
16X-3, 0-2	139.50	A	A		R	R		F		C	A	R		
16X-4, 50-52	141.50	C	F					F			C			
16X-5, 100-102	143.50	C				C		F				C		
16X-6, 0-2	144.00	R				R					R	F		

Notes: California margin (CM) zones indicated. A = abundant, C = common, F = few, R = rare, B = barren.

leomagnetic stratigraphy. This will enable the biostratigraphic events of the California Current system to be placed within a global framework.

ZONE DEFINITIONS

CM1: *Neogloboquadrina pachyderma* B partial range zone

Top: Not defined, but the zone includes all faunas above the last appearance of *Neogloboquadrina pachyderma* A
Base: Last appearance of *Neogloboquadrina pachyderma* A
Age: Late Quaternary
Taxa: Marked by the last occurrence of *N. humerosa praehumerosa* and the first occurrence of *N. dutertrei* in several sites
Reference section: Hole 1014A

CM2: *Neogloboquadrina pachyderma* B–*Neogloboquadrina pachyderma* A Overlap zone

Top: Last appearance of *Neogloboquadrina pachyderma* A
Base: First appearance of *Neogloboquadrina pachyderma* B
Age: Early Quaternary
Reference section: Hole 1014A

CM3: *Neogloboquadrina pachyderma* A partial range zone

Table 5. Distribution and relative abundances of stratigraphically useful planktonic foraminifers in Pliocene–Quaternary Hole 1014A.

Core, section, interval (cm)	Depth (mbsf)	Abundance	*Neogloboquadrina pachyderma pachyderma*	*Neogloboquadrina pachyderma* B	*Neogloboquadrina pachyderma* A	*Globorotalia inflata*	*Neogloboquadrina dutertrei*	*Neogloboquadrina humerosa praehumerosa*	*Neogloboquadrina pachyderma* C	*Neogloboquadrina kagaensis*	*Neogloboquadrina asanoi*	*Globorotalia puncticulata*	Zone	Age
167-1014A-														
1H-1, 120-122	1.20	A	A			F	A							
1H-2, 120-122	2.70	A	A	A										
1H-CC	3.00	A		A			C							
2H-2, 120-122	5.80	A	C	A										
2H-6, 120-122	11.80	C					C							
2H-CC	13.00	A	A			A	A							
3H-1, 120-122	13.80	A	F	A		A	A							
3H-2, 120-122	15.30	A		A		C								
3H-6, 120-122	21.30	A		A		F								
3H-CC	22.00	A	C	A		R								
4H-2, 120-122	24.80	A	F	A		F								
4H-6, 120-122	30.80	A	A	C		R		R					CM1	
4H-CC	32.00	A	F	A		R								
5H-3, 120-122	35.80	C		C										
5H-5, 120-122	38.84	C		C		F								
5H-CC	41.00	A		A		F	C							
6H-2, 120-122	43.80	A		A		F								
6H-4, 120-122	45.87	C		C										
6H-CC	49.15	A	R	A		F		R						
7X-2, 118-120	53.28	A		A		F								
7X-CC	54.00	A	F	A		R								Quaternary
8X-2, 120-122	57.00	A	F	A										
8X-5, 120-122	61.50	A	A			R		F						
8X-CC	64.00	A	A	A	A									
9X-2, 120-122	66.70	A	A	A	F			R						
9X-5, 120-122	71.20	A		A		R								
9X-CC	74.00	A		F										
10X-3, 120-122	78.00	C		F									CM2	
10X-5, 120-122	81.00	A	C		A	R		F						
10X-CC	84.00	A	A	C	A	C		A						
11X-2, 120-122	86.20	A		A		C		F						
11X-5, 120-122	90.70	A		A										
11X-CC	93.00	C		A	C									
12X-2, 120-122	95.32	A	C	C	A			R						
12X-5, 120-122	99.72	A	F		A			F						
12X-CC	102.80	A	A		A	C							CM3	
13X-2, 120-122	105.50	A	F		A									
13X-5, 122-124	110.02	C	C		F									
13X-CC	112.40	A	F		A									
14X-1, 120-122	113.60	F			F									
14X-5, 120-122	119.46	B												
14X-CC	122.00	B												
15X-2, 120-122	123.40	B												
15X-5, 120-122	127.90	A	A			R								
15X-CC	132.00	C											CM4	
16X-2, 120-122	133.38	R	R			R								
16X-5, 120-122	137.88	C	C			F								
16X-CC	141.00	B												
17X-2, 120-122	143.90	R							R					
17X-5, 120-122	148.40	C	F			R		R	C	C				
17X-CC	151.00	F								C				
18X-2, 120-122	152.61	A	R					R	A	C				
18X-5, 120-122	157.11	A	C					F	A	C				
18X-CC	160.00	A	C					F	A	A				
19X-2, 121-123	163.11	A						F		A				
19X-5, 120-122	167.60	R	R											
19X-CC	170.00	C				R			A				CM5	
20X-1, 120-122	171.20	C	C						F					late Pliocene
20X-5, 120-122	176.61	F	F						R					
20X-CC	179.60	C	F					R	C	C				
21X-2, 120-122	181.32	C	R						C	C				
21X-5, 120-122	185.82	A	C			F				A				
21X-CC	189.20	B												
22X-2, 120-122	191.90	F	F							R	R			
22X-5, 120-122	195.24	C	R						A	F	C			
22X-CC	198.80	A	A							A	F			
23X-2, 120-122	200.41	C	R							F	C			
23X-5, 105-107	204.53	A	C			R				C	A			
23X-CC	208.40	A	A			A		C		A	A	A	CM6	
24X-2, 122-124	209.91	A								R	A			
24X-4, 119-121	212.88	A									A			
24X-5, 83-85	214.02	A									A			
24X-CC	218.00	F								F	F			
25X-2, 122-124	220.72	F	F							R	R			

Table 5 (continued).

Core, section, interval (cm)	Depth (mbsf)	Abundance	*Neogloboquadrina pachyderma pachyderma*	*Neogloboquadrina pachyderma* B	*Neogloboquadrina pachyderma* A	*Globorotalia inflata*	*Neogloboquadrina dutertrei*	*Neogloboquadrina humerosa praehumerosa*	*Neogloboquadrina pachyderma* C	*Neogloboquadrina kagaensis*	*Neogloboquadrina asanoi*	*Globorotalia puncticulata*	Zone	Age
25X-4, 102-104	223.52	C	C								F		CM6	late Pliocene
25X-CC	223.50	A	C							A	A			
26X-1, 120-122	224.70	A								F	A			
26X-4, 120-122	229.20	A								F	A			
26X-CC	227.70	E								C	C			
27X-2, 120-122	229.66	B												
27X-5, 120-122	233.66	C						F		C	F			
27X-CC	237.30	C	C							C				
28X-2, 120-122	240.00	A	C							A	A			
28X-4, 105-107	242.05	C								C	R			
28X-CC	246.90	A	F							A	C			
29X-2, 120-122	249.60	A						F		A	A			
29X-CC	250.10	A	A							A	A			
30X-2, 120-122	252.80	A	A					F		A	R			
30X-4, 120-122	255.80	R	R									R		
30X-CC	256.60	A						F		A				
31X-2, 120-122	258.16	R	R			R								
31X-5, 120-122	262.66	C	C			R		R		R				
31X-CC	266.00	A	A			R				A		R		
32X-2, 120-122	268.18	C	C					R		R	R			
32X-4, 120-122	271.18	R										R		
32X-CC	275.80	A				A					R	F		
33X-2, 120-122	278.50	C				C		R		C	R	F		
33X-5, 120-122	281.94	B												
33X-CC	285.50	C								C	F	C		
34X-2, 120-122	288.20	R									R			
34X-5, 120-122	292.70	F									F			
34X-CC	295.10	A				A				F		C		
35X-2, 120-122	297.10	B												
35X-5, 120-122	301.60	A								A	R	R		
35X-CC	304.80	A	F			R				A		F		
36X-2, 120-122	306.45	C	F									C		
36X-5, 120-122	310.68	R								R	R			
36X-CC	314.40	A								A				
37X-2, 121-123	316.01	C								C	R			
37X-5, 121-123	320.51	R								R				
37X-CC	324.10	C								C	C			
38X-2, 121-123	326.81	R	R							R			CM7	early Pliocene
38X-5, 120-122	331.30	R	R							R				
38X-CC	333.70	R	R							R				
39X-2, 120-122	335.76	B												
39X-5, 120-122	339.43	B												
39X-CC	343.40	R								R				
40X-2, 121-123	344.98	B												
40X-5, 122-124	349.49	R	R							R				
40X-CC	353.00	R								R				

Notes: California margin (CM) zones indicated. A = abundant, C = common, F = few, R = rare, B = barren.

Top: First appearance of *Neogloboquadrina pachyderma* B
Base: First appearance of *Neogloboquadrina pachyderma* A
Age: Early Quaternary
Occurrence: In northernmost Hole 1020B, Zone CM3 is not recognized and is included within an undifferentiated zone: CM3 to CM5. In the southernmost sites (Holes 1011B and 1012A), the zone is also unrecognized, being included in an undifferentiated zone: CM3 and CM4.
Reference section: Hole 1014A

CM4: Gap zone between last appearance of *Neogloboquadrina kagaensis* and first appearance of *Neogloboquadrina pachyderma* A

Top: First appearance of *Neogloboquadrina pachyderma* A
Base: Last appearance of *Neogloboquadrina kagaensis*
Age: Latest Pliocene
Occurrence: In northernmost Hole 1020B, Zone CM4 is not recognized and is included within an undifferentiated zone: CM3 to CM5. In the southernmost sites (Holes 1011B and 1012A), the zone is also unrecognized, being included in an undifferentiated zone: CM3 and CM4.
Reference section: Hole 1014A

CM5: *Neogloboquadrina kagaensis* partial range zone

Top: Last appearance of *Neogloboquadrina kagaensis*
Base: Last appearance of *Neogloboquadrina asanoi*
Age: Late Pliocene
Occurrence: In northernmost Hole 1020B, Zone CM5 is included within an undifferentiated zone: CM3 to CM5.
Taxa: Includes the partial range of *Neogloboquadrina pachyderma* C, which disappears at the end or within this zone
Reference section: Hole 1014A

CM6: *Neogloboquadrina asanoi* range zone

Top: Last appearance of *Neogloboquadrina asanoi*

Table 6. Distribution and relative abundances of stratigraphically useful planktonic foraminifers in Pliocene–Quaternary Hole 1018A.

Core, section, interval (cm)	Depth (mbsf)	Abundance	*Neogloboquadrina pachyderma pachyderma*	*Neogloboquadrina pachyderma* B	*Neogloboquadrina pachyderma* A	*Globorotalia inflata*	*Neogloboquadrina dutertrei*	*Neogloboquadrina humerosa praehumerosa*	*Neogloboquadrina pachyderma* C	*Neogloboquadrina kagaensis*	*Neogloboquadrina asanoi*	*Globorotalia puncticulata*	Zone	Age
167-1018A-														
1H-2, 120-122	2.70	A	F	A		R	F						CM1	Quaternary
1H-CC	5.00	A		A										
2H-2, 120-122	7.60	F	R	F										
2H-5, 120-122	12.10	C	F	C										
2H-CC	14.00	A		A										
3H-2, 120-122	17.10	F		F										
3H-5, 120-122	21.60	C		C										
3H-CC	24.00	A		A										
4H-2, 120-122	26.60	A		A										
4H-5, 120-122	31.10	C		C										
4H-CC	33.00	A		A										
5H-2, 120-122	36.10	C		C										
5H-5, 120-122	40.66	F		F										
5H-CC	43.00	F		F										
6H-2, 120-122	45.60	F		F										
6H-5, 120-122	50.10	A	F	A										
6H-CC	52.00	C	R	C										
7H-2, 120-122	55.10	B												
7H-5, 120-122	59.60	R		R										
7H-CC	62.00	A	A	F			A							
8H-2, 120-122	64.60	F		F										
8H-5, 120-122	69.10	C		C										
8H-CC	71.00	A		A										
9H-2, 120-125	74.10	C	F	C										
9H-5, 120-125	78.60	C		C										
9H-CC	80.00	A	F	A		C								
10H-2, 120-125	83.60	C		C										
10H-5, 120-125	88.10	A		A										
10H-CC	90.00	A		A		C								
11X-2, 120-125	92.90	A		A										
11X-5, 120-125	97.40	F		F										
11X-CC	99.00	A	A	C		R	C	C						
12X-2, 120-125	101.80	B												
12X-CC	109.00	C	C	C	F			F					CM2	
13X-2, 120-125	111.40	C		C										
13X-5, 120-125	115.90	B												
13X-CC	118.00	R		R										
14X-2, 120-125	121.00	A	C	A	C									
14X-5, 120-125	125.50	B												
14X-CC	128.00	A		A		R								
15X-2, 120-125	129.72	C		C	R									
15X-5, 120-125	134.19	B												
15X-CC	138.00	C	C	F										
16X-2, 120-125	140.40	R		R	R									
16X-CC	148.00	A		A	A									
17X-2, 120-125	150.00	A		A	A									
17X-5, 120-125	154.50	B												
17X-CC	157.00	A		A	A	R								
18X-2, 120-122	158.42	B											CM3	
18X-5, 120-122	162.92	F			F									
18X-CC	167.00	B												
19X-2, 120-125	169.20	F			F	R								
19X-5, 120-125	173.70	F		C	F									
19X-CC	176.00	C	F	F	F									
20X-2, 120-125	178.80	A	F		A									
20X-5, 120-125	183.30	B												
20X-CC	186.00	A	A		C									
21X-2, 123-128	187.43	B												
21X-5, 119-124	192.89	F			F									
21X-CC	195.00	C			R									
22X-2, 122-127	198.02	C			C									
22X-5, 121-126	202.51	B												
22X-CC	205.00	C	F		C									
23X-2, 120-125	207.60	B											CM4	late Pliocene
23X-5, 120-125	212.10	F	F					R						
23X-CC	215.00	B												
24X-2, 120-125	217.20	B												
24X-5, 120-125	221.70	B												
24X-CC	224.00	B												
25X-2, 121-126	226.91	B												
25X-5, 120-128	231.40	F	R						F					
25X-CC	234.00	C	C					F	R					
26X-2, 120-125	236.50	F	F						F					
26X-5, 120-125	241.00	B												

Table 6 (continued).

Core, section, interval (cm)	Depth (mbsf)	Abundance	*Neogloboquadrina pachyderma pachyderma*	*Neogloboquadrina pachyderma* B	*Neogloboquadrina pachyderma* A	*Globorotalia inflata*	*Neogloboquadrina dutertrei*	*Neogloboquadrina humerosa praehumerosa*	*Neogloboquadrina pachyderma* C	*Neogloboquadrina kagaensis*	*Neogloboquadrina asanoi*	*Globorotalia puncticulata*	Zone	Age
26X-CC	244.00	C	C										CM5	late Pliocene
27X-CC	253.00	C							A	C				
28X-2, 120-125	255.70	F	R						F	R				
28X-5, 122-127	260.22	B												
28X-CC	263.00	R								R				
29X-2, 120-125	265.20	B												
29X-5, 120-125	269.70	R							R	R				
29X-CC	272.00	F	R						R	F				
30X-2, 120-125	274.90	F												
30X-5, 120-125	279.40	B							F	R				
30X-CC	281.00	R								R				
31X-5, 121-126	289.01	B												
31X-CC	292.00	F	R							F				
32X-2, 120-125	294.20	B												
32X-5, 120-125	298.70	B												
32X-CC	301.00	B												
33X-2, 120-125	303.80	F	R								F		CM6	
33X-5, 120-125	308.30	R									R			
33X-CC	311.00	B												
34X-2, 120-125	313.40	R	R								R			
34X-5, 120-125	317.90	F	R							R	F			
34X-CC	320.00	C	C			F				C	C			
35X-2, 120-125	323.00	B												
35X-5, 119-124	327.49	B												
35X-CC	330.00	C								C	C			
36X-2, 120-125	332.70	B												
36X-5, 120-125	337.20	R									R			
36X-CC	340.00	F								F				
37X-2, 120-125	342.40	R								R	R			
37X-5, 119-124	346.89	R								R	R			
37X-CC	349.00	F				R				F				
38X-2, 119-124	352.09	B												
38X-5, 119-124	356.59	R	R							R				
38X-CC	359.00	B												
39X-2, 127-131	361.77	R	R							R	R			
39X-5, 125-130	366.25	A								A	A			
39X-CC	369.00	C	C							C	F			
40X-2, 124-128	371.44	A								A	A			
40X-5, 120-124	375.90	C								C			CM7	early Pliocene
40X-CC	378.00	F								F				
41X-2, 119-122	380.99	F								F		F		
41X-5, 119-122	385.49	C								R				
41X-CC	388.00	B												
42X-2, 117-120	390.57	C				R				C				
42X-5, 120-123	395.10	F								F				
42X-CC	397.00	R								R				
43X-2, 120-123	400.20	B												
43X-5, 122-125	404.72	F				C				R		R		
43X-CC	407.00	C	R			C				C				
44X-2, 120-123	409.70	B												
44X-5, 122-125	414.22	R	R											
44X-CC	417.00	B												
45X-2, 118-120	419.38	B												
45X-5, 121-123	423.91	B												
45X-CC	426.00	R						R				R		

Notes: California margin (CM) zones indicated. A = abundant, C = common, F = few, R = rare, B = barren.

Base: First appearance of *Neogloboquadrina asanoi*

Age: Early late Pliocene

Taxa: The last occurrence of *Globorotalia puncticulata* is within the middle to upper part of CM6 in all sections except in Holes 1018A and 1011B. The first appearance of *Globorotalia inflata* is in the lower part of CM6 except in Hole 1018A, where it appears in CM7. Populations of *G. inflata* throughout CM6 represent early evolutionary forms of this taxon and are likely equivalent to the "transitional" variety identified by Keller (1979a).

Reference section: Hole 1014A

CM7: *Globorotalia puncticulata* partial range zone

Top: First appearance of *Neogloboquadrina asanoi*

Base: Last appearance of *Globorotalia (Globoconella) ikebei* and *Globigerina decoraperta*

Age: Late early Pliocene

Taxa: CM7 represents a gap zone for the interval between the first occurrence of *Neogloboquadrina asanoi* and the last occurrence of *Globorotalia (Globoconella) ikebei* and *Globigerina decoraperta.* This zone takes its name from *Globorotalia puncticulata,* which consistently occurs through this interval. *G. puncticulata* was not observed in CM7 in Hole 1014A, probably because of significant carbonate dissolution over this interval.

Reference section: Hole 1020B

Table 7. Distribution and relative abundances of stratigraphically useful planktonic foraminifers in Pliocene–Quaternary Hole 1020B.

Core, section, interval (cm)	Depth (mbsf)	Abundance	*Neogloboquadrina pachyderma pachyderma*	*Neogloboquadrina pachyderma* B	*Neogloboquadrina pachyderma* A	*Globorotalia inflata*	*Neogloboquadrina humerosa praehumerosa*	*Neogloboquadrina pachyderma* C	*Neogloboquadrina kagaensis*	*Neogloboquadrina asanoi*	*Globorotalia puncticulata*	*Globorotalia decoraperta*	*Globorotalia ikebei*	Zone	Age
167-1020B-															
1H-2, 120-125	2.70	A		A											
1H-5, 120-125	7.20	A		A											
1H-CC	8.00	A		A											
2H-2, 120-125	10.50	A		A											
2H-5, 120-125	15.00	F	F		F										
2H-CC	17.00	A		A											
3H-2, 120-125	20.00	A		A											
3H-5, 120-125	24.50	C		C											
3H-CC	27.00	A	A	A											
4H-2, 120-125	29.50	R		R											
4H-5, 120-125	34.00	C		C											
4H-CC	36.00	A		A										CM1	
5H-2, 120-125	39.00	B													
5H-5, 120-125	43.50	A		A											
5H-CC	46.00	A		A											
6H-2, 120-125	48.50	A		A		C									
6H-5, 120-125	53.00	A		A											
6H-CC	55.00	A	A	A		R									
7H-2, 120-125	58.00	R	R												
7H-5, 120-125	62.50	A	R	A											
7H-CC	65.00	R		R											
8H-2, 120-125	67.50	A		A											
8H-5, 120-125	72.00	F		F	F										
8H-CC	74.00	A		A	A										Quaternary
9H-2, 120-125	77.00	A		A	A										
9H-5, 120-125	81.50	A		A	A										
9H-CC	84.00	A		A	A										
10H-2, 120-125	86.50	A	A	A	A	C								CM2	
10H-5, 120-125	91.00	A		A	A	R									
10H-CC	93.00	A		A	A										
11H-CC	102.00	R	R	R	R										
12H-2, 120-125	105.50	A	A	A	C										
12H-5, 120-125	110.00	C		R	C	R									
12H-CC	112.00	R	R		R										
13H-2, 120-125	115.00	F			F										
13H-5, 120-125	119.50	R	R												
13H-CC	122.00	B													
14H-2, 120-125	124.50	F	F		F										
14H-5, 120-125	129.00	C	C		C										
14H-CC	131.00	C	C		C	R									
15H-2, 120-125	134.00	F	F		R	R									
15H-5, 120-125	138.50	A	A		A	R	R								
15H-CC	141.00	F	F		F		R							CM3 to CM5	
16H-2, 120-125	143.50	C	C												
16H-5, 5-125	146.85	R	R												
16H-CC	150.00	A	A		C	F	A								
17H-2, 120-125	153.00	R						R							
17H-5, 120-125	157.10	R			R										
17H-CC	160.00	C	C		C										
18H-2, 120-125	162.50	B													
18H-6, 120-125	168.50	C	C					C							
18H-CC	170.00	A	C		C		R	A							
19X-2, 118-122	171.98	F	F						F						
19X-5, 120-123	176.50	A	A						A	A					
19X-CC	179.00	C	R				F		C						
20X-CC	189.00	A	A				C		A						
21X-4, 130-133	194.30	A	A				R		A						late Pliocene
21X-CC	198.00	A	A				F		A						
22X-4, 121-124	203.81	A				A		A	C	F					
22X-CC	208.00	R							R		R			CM6	
23X-4, 117-120	213.37	B													
23X-CC	217.00	B													
25X-4, 118-122	232.68	A	A			R			A	R	R				
25X-CC	237.00	C				C	F		C	C	C				
26X-4, 126-130	242.36	A	C				R		F	R	A				
26X-CC	246.00	A							C	A					
27X-4, 120-125	252.00	F	R								F				
27X-CC	256.00	B												CM7	
28X-4, 120-125	261.60	R	R												
28X-CC	265.00	A	A				C				A	F	A		early Pliocene
29X-2, 126-129	268.06												C	CM8	
29X-CC	275.00	A									A	A	A		
30X-1, 112-115	275.82	B													

Notes: California margin (CM) zones indicated. A = abundant, C = common, F = few, R = rare, B = barren.

CM8: *Globigerina decoraperta* partial range zone

Top: Last appearance of *Globorotalia (Globoconella) ikebei* and *Globigerina decoraperta*

Base: As yet undefined because the sequences below the zone largely lack planktonic foraminifers in association with biosiliceous-rich sediments

Age: late early Pliocene

Occurrence: The zone is observed in Hole 1020B.

Reference section: Hole 1020B

TAXONOMIC NOTES

Although diversity of late Neogene foraminiferal assemblages is relatively low in California margin sedimentary sequences cored during ODP Leg 167, sufficient change in assemblages occurred through evolution and migration to provide a base for a relatively high-resolution biostratigraphic subdivision. The zonation is based on changes in the vertical distribution of seven taxa. This is supported by range changes in five other forms. Taxonomic discussion is limited to this total of 12 taxa. General taxonomy follows that of Kennett and Srinivasan (1983). All are illustrated by scanning electron micrographs (Plates 1, 2). Our intent is not to make detailed taxonomic descriptions for each taxon but to briefly summarize principal morphologic characteristics and primary differences between closely related forms.

Neogloboquadrina asanoi (Maiya, Saito, and Sato) = *Globoquadrina asanoi* Maiya, Saito, and Sato, 1976
(Plate 1, figs. 19–22; Plate 2, figs. 1–3)

This is a large, distinct form, marked by four globular chambers in the final whorl, rounded outline, and high conical arrangement of early whorls. The distinct aperture is interiomarginal; a distinctly open moderately high arch with rim but lacking a lip. Aperture is umbilical to extraumbilical; in some forms, the aperture is distinctly umbilical in position. A detailed description of this form is provided by Saito et al. (1981; but the captions for the plates are reversed between *N. asanoi* and *N. kagaensis*). Lagoe and Thompson (1988) provided a synonymy list for *N. asanoi* resulting from earlier work in the California region. Keller (1978a, 1978b, 1978c) and Keller and Ingle (1981) included specimens assignable to *N. asanoi* within a taxon referred to as *Neogloboquadrina pachyderma* form 3. Keller (1979a, 1980) later assigned this form to *N. asanoi*. *N. asanoi* is a useful zonal marker for California margin sequences where it forms a distinct range zone (CM6). Our initial biostratigraphic studies (Lyle, Koizumi, Richter, et al., 1997) referred this form to *Neogloboquadrina* sp. (rounded). Poore (1981), during studies of California margin–drilled Neogene sequences (DSDP Leg 63), included forms we assign as *N. asanoi* in *Neogloboquadrina atlantica.*

N. asanoi is phylogenetically closely related to *N. kagaensis.* Maiya et al. (1976) considered that *N. asanoi* evolved into *N. kagaensis.* However, in the California margin sequences described here, *N. kagaensis* appears first and evolves in an apparently gradational bioseries into *N. asanoi.* Early populations of *N. asanoi* exhibit morphological gradation with the ancestral form—*N. kagaensis.* It seems that Maiya et al. (1976) suggested an opposite phylogenetic relationship between the two taxa because the sections in Japan in which these forms were first described were not of sufficient age to reveal their biostratigraphic and phylogenetic relations. For California, Lagoe and Thompson (1988) clearly demonstrated that *N. asanoi* is preceded by an illustrated form they referred to as *Neogloboquadrina* sp., which we assign to *N. kagaensis.* This supports our hypothesis of the evolution of *N. asanoi* from *N. kagaensis.*

Near the top of its range, *N. asanoi* became an even more rounded, highly trochospiral form with a high-arched aperture restricted to the umbilical region (Plate 2, figs. 1–3).

Neogloboquadrina kagaensis (Maiya, Saito, and Sato) = *Globoquadrina asanoi* Maiya, Saito, and Sato, 1976
(Plate 1, figs. 15–18)

This is a large, distinct form with 4.0–4.5 chambers in the final whorl and moderately quadrate equatorial periphery. The aperture is umbilical to extraumbilical, with a low arch and no distinct lip. This species is distinguished from *N. asanoi* by its more extraumbilical aperture, more quadrate equatorial periphery, and by 4.0–4.5 chambers in the final whorl instead of four (as in *N. asanoi).* A detailed description of this form is provided by Saito et al. (1981; plate captions are reversed between *N. asanoi* and *N. kagaensis*). Our early studies of Leg 167 materials (Lyle, Koizumi, Richter et al., 1997) referred this species to *N. asanoi.*

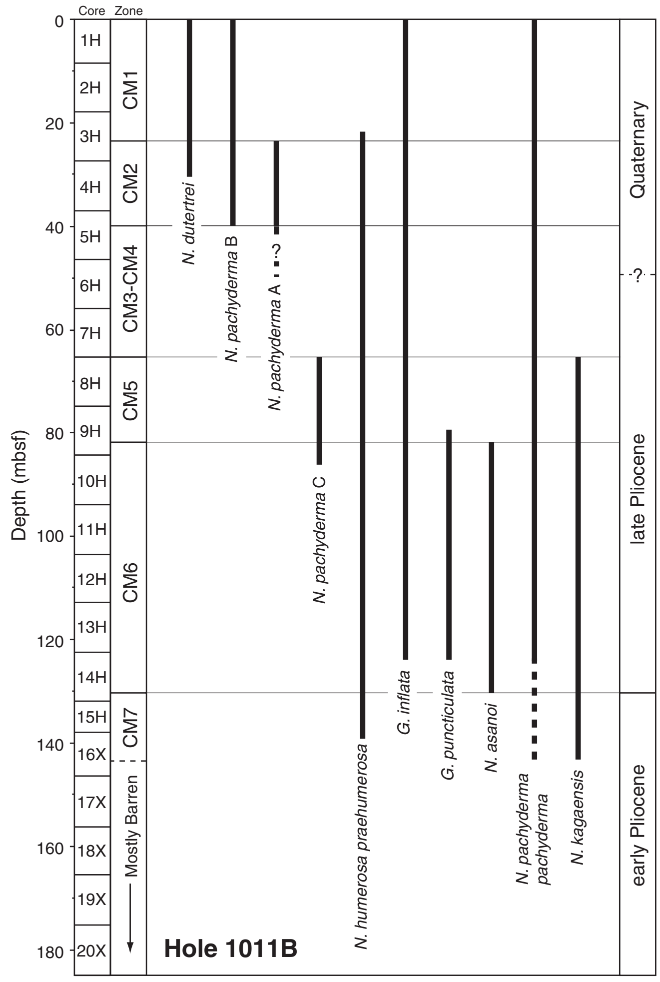

Figure 2. Depth ranges of key Pliocene–Quaternary planktonic foraminiferal zonal species and other stratigraphically useful taxa in Hole 1011B, California margin. California margin (CM) planktonic foraminiferal zones shown at left. Question mark and dashed lines represent range extensions that are questionable or based on rare specimens.

This species appears before and is considered to be the ancestor of *N. asanoi* (see discussion on *N. asanoi*). It seems likely that Keller (1979a, 1980) included both *N. kagaensis* and *N. asanoi* within a form assigned to *N. asanoi.* Lagoe and Thompson (1988) assigned forms that we consider to be *N. kagaensis* to *Neogloboquadrina* sp. They thus recognized the distinction between these two forms in the California Pliocene, demonstrated that *N. kagaensis* appeared first, and suggested that *N. kagaensis* may be ancestral to *N. asanoi.* Poore (1981) appears to have included this form in *Neogloboquadrina atlantica* in Pliocene sequences drilled on the California margin during DSDP Leg 63.

N. kagaensis is useful in biostratigraphically subdividing the Pliocene of the California margin. This form has a longer stratigraphic range than *N. asanoi,* having evolved earlier and survived longer—thus forming additional useful datum levels.

Neogloboquadrina dutertrei (d'Orbigny) = *Globigerina dutertrei* d'Orbigny, 1839
(Plate 2, figs. 4, 5)

This is a familiar species with five to six chambers in the final whorl and deep umbilical region. In the California margin sequences studied here, the taxa has an umbilical aperture and lacks umbilical plates.

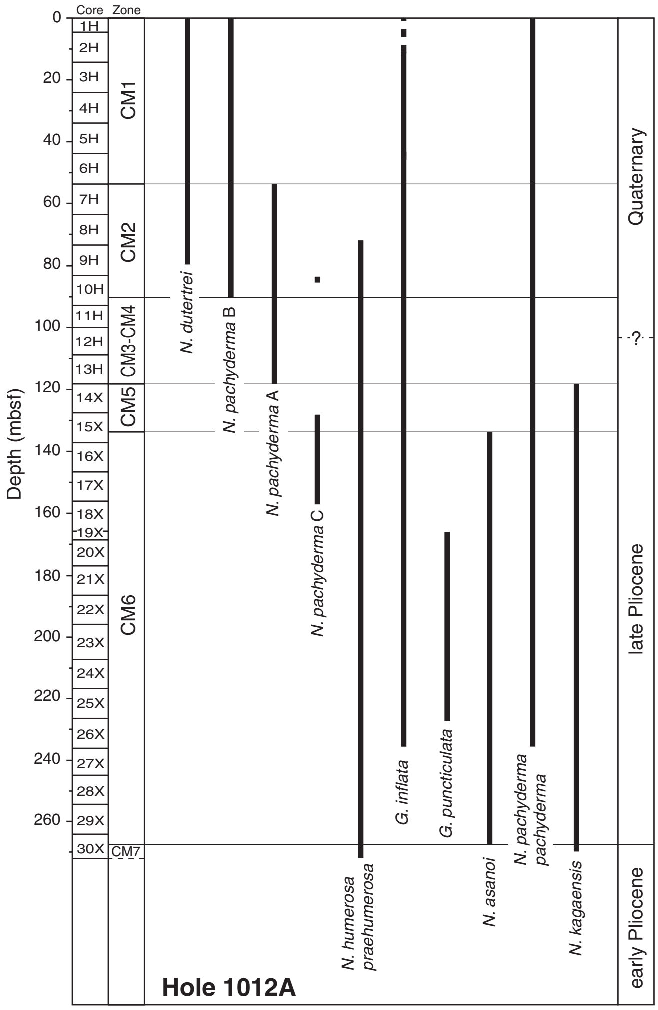

Figure 3. Depth ranges of key Pliocene–Quaternary planktonic foraminiferal zonal species and other stratigraphically useful taxa in Hole 1012A, California margin. California margin (CM) planktonic foraminiferal zones shown at left.

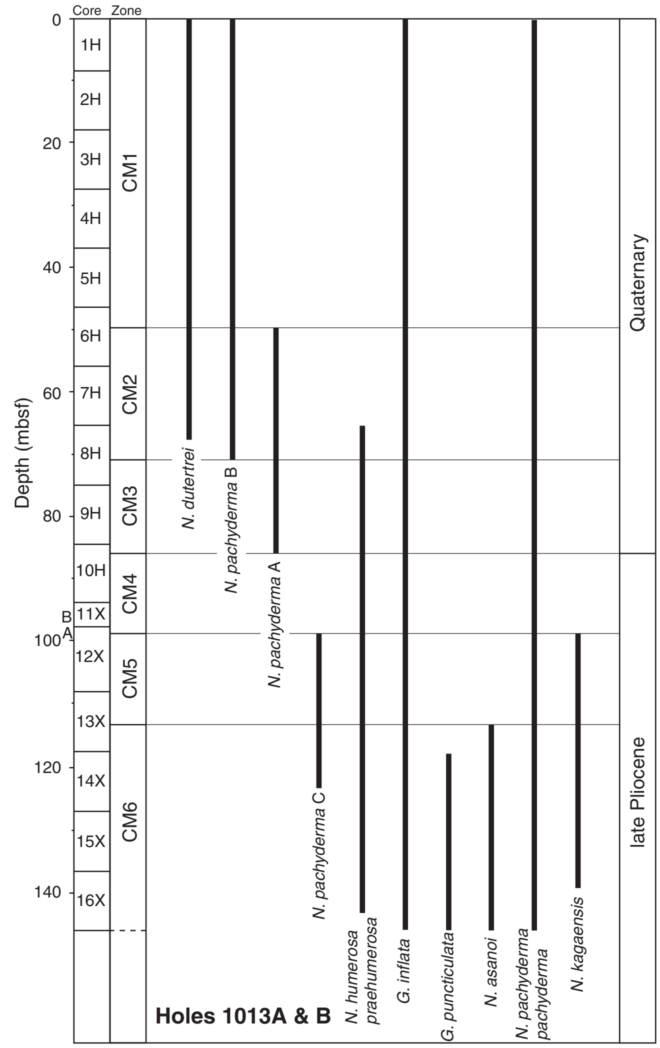

Figure 4. Depth ranges of key Pliocene–Quaternary planktonic foraminiferal zonal species and other stratigraphically useful taxa in Holes 1013A and 1013B, California margin. California margin (CM) planktonic foraminiferal zones shown at left. Cores 1H through 11X are from Hole 1013B, and Cores 12X through 16X are from Hole 1013A.

Neogloboquadrina humerosa praehumerosa Natori, 1976
(Plate 2, figs. 6, 7)

Populations of this form in the late Neogene sequences documented here are relatively large, have an open umbilical region and five chambers in the final whorl, and exhibit a narrow, distinct lip. These forms differ from *N. humerosa humerosa* in having five rather than six chambers in the final whorl and by the presence of a distinct lip (Natori, 1976).

Neogloboquadrina pachyderma pachyderma (Ehrenberg) = *Aristerospira pachyderma* Ehrenberg, 1861 (dextral, compressed form)
(Plate 1, figs. 1–3)

In this study we include forms in *N. pachyderma pachyderma* that are relatively small, dextrally coiled, with quadrate test, and have a gently compressed axial periphery. Typically, there are 4.0 to 4.5 chambers in the final whorl, and the final chamber is often reduced in size or kummerform. An apertural lip varies in strength. This species exhibits a wide range of variation and may represent more than one taxon, as has been suggested by Matoba and Oda (1982). Relationships remain unclear between this species and various forms of *N. pachyderma* identified by Keller (1978c). However, this form is similar to the dextral variety of *N. pachyderma* form 1, which is marked by a quadrate compact test. This species appears to include forms included by Matoba and Oda (1982) in both *N. pachyderma pachyderma* and *N. pachyderma* forma B. *N. pachyderma pachyderma* ranges discontinuously throughout the sequences (late early Pliocene to present day). Its spasmodic stratigraphic occurrence probably resulted from its strong affinity with warm rather than cool episodes.

Neogloboquadrina pachyderma (Ehrenberg) A. (dextral, inflated form)
(Plate 1, figs. 4, 5, 9, 10)

This is a distinct species marked by a dextral-coiled, relatively large, highly rounded, lobulate test in both axial and equatorial peripheries; four globular chambers and relatively thin lip. This form has a short range during the early Quaternary. *N. pachyderma* A appears to be equivalent to *N. pachyderma* Form 2 of Keller (1978c) and *N. pachyderma* forma A of Matoba and Oda (1982). This species primarily differs from *N. pachyderma pachyderma* by its larger, more rounded test.

Neogloboquadrina pachyderma (Ehrenberg) B. (sinistral, inflated form)
(Plate 1, figs. 11–14)

This is a sinistral-coiled form, exhibiting rounded equatorial and axial peripheries, generally with 4.0–4.5 globular chambers in the final whorl and a

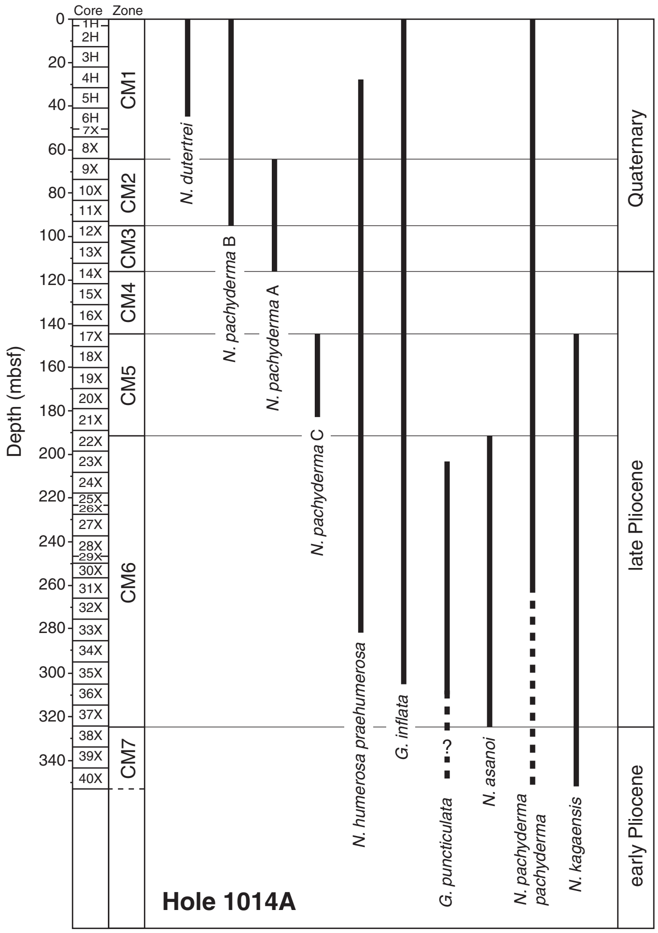

Figure 5. Depth ranges of key Pliocene–Quaternary planktonic foraminiferal zonal species and other stratigraphically useful taxa in Hole 1014A, California margin. California margin (CM) planktonic foraminiferal zones shown at left. Question mark and dashed lines represent range extensions that are questionable or based on rare specimens.

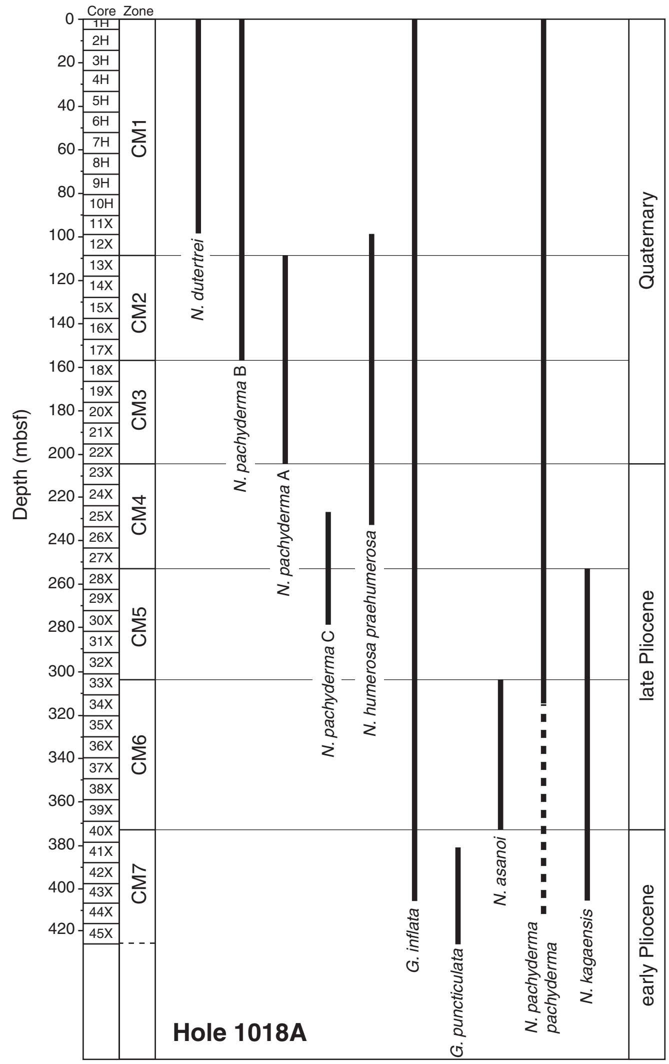

Figure 6. Depth ranges of key Pliocene–Quaternary planktonic foraminiferal zonal species and other stratigraphically useful taxa in Hole 1018A, California margin. California margin (CM) planktonic foraminiferal zones shown at left. Dashed line represents a range extension that is based on rare specimens.

distinct, strong rimlike lip. This species occurs in high abundances during the late Quaternary. *N. pachyderma* B differs from *N. pachyderma* C by exhibiting inflated chambers, rounded outline, and consistently strong lip.

Neogloboquadrina pachyderma (Ehrenberg) C. (sinistral, compressed form)
(Plate 1, figs. 6–8)

This is a relatively small, sinistral-coiled form, with quadrate test and relatively compressed axial periphery. Typically, there are 4.0–4.5 chambers in the final whorl. An apertural lip is relatively weak. Relationships are unclear between this taxon and forms of *N. pachyderma* described by Keller (1978c). This species differs from *N. pachyderma* B by its more compressed outline, greater number of chambers in the final whorl, and weaker apertural lip. This is a short-ranged latest Pliocene form.

Globorotalia (Globoconella) ikebei Maiya, Saito, and Sato = *Globorotalia ikebei* Maiya, Saito, and Sato, 1976
(Plate 2, figs. 20–23)

A distinctive Pliocene representative of *Globoconella* with five chambers in the final whorl, axial periphery broadly rounded with no keel; equatorial periphery broadly circular to elongate; relatively high-arched aperture, interiomarginal and umbilical-extraumbilical in position. This species was identified and illustrated by Keller (1980) in the early Pliocene of the central North Pacific (DSDP Leg 32, Site 310), thus showing that its geographic range extended to the North Pacific beyond Japan, where it was first described (Maiya et al., 1976).

Globorotalia inflata (d'Orbigny) = *Globigerina inflata* d'Orbigny, 1839
(Plate 2, figs. 10–15)

In the sequences examined, *G. inflata* is represented by early ("transitional"; Plate 2, figs. 10–12) forms and later (modern; Plate 2, figs. 13–15) forms as previously recognized by Keller (1978a, 1979a, 1979b, 1980) for North Pacific sequences. The range of *G. inflata* is often discontinuous in Leg 167 sequences and is usually represented by few specimens. As a result, we found it difficult to consistently differentiate the early and later forms, and thus have included both under *G. inflata.*

Globorotalia puncticulata (Deshayes) = *Globigerina puncticulata* Deshayes, 1832
(Plate 2, figs. 8, 9)

This is a familiar *Globoconella* with four chambers in the final whorl, equatorial periphery gently quadrilobate; axial periphery bluntly rounded, with no keel; and aperture a distinct high arch bordered by a rim. The range of *G. puncticulata* overlaps that of *Globorotalia (Globoconella) inflata* in the late Pliocene, but no morphological gradation was observed between these two forms in the assemblages. It seems likely, therefore, that in the California

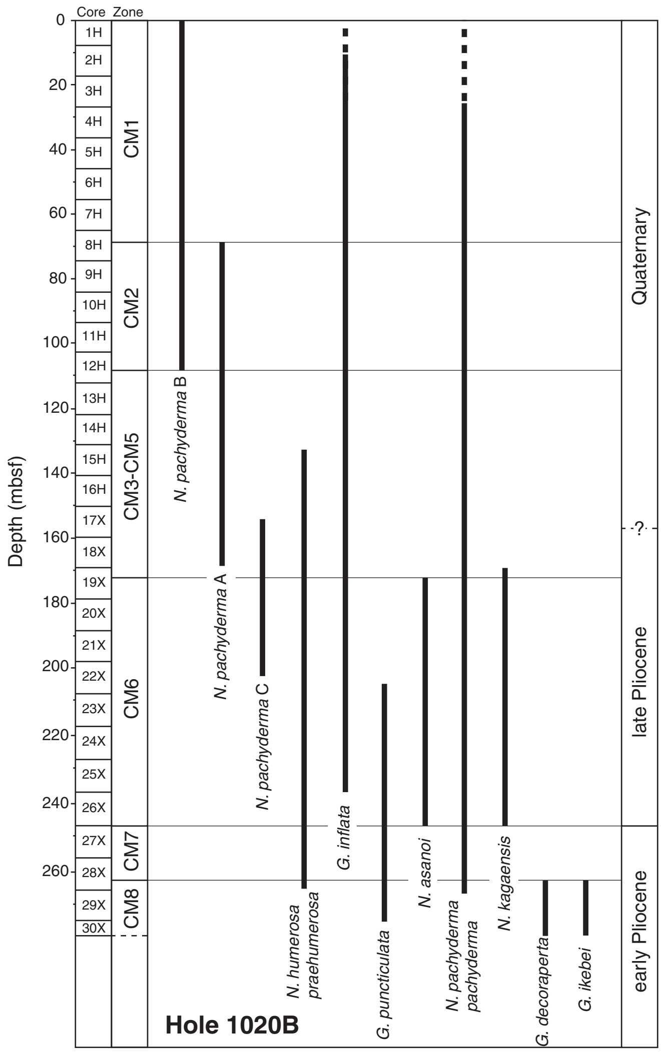

Figure 7. Depth ranges of key Pliocene–Quaternary planktonic foraminiferal zonal species and other stratigraphically useful taxa in ODP Hole 1020B, California margin. California margin (CM) planktonic foraminiferal zones shown at left. Dashed lines represent range extensions that are based on rare specimens.

region, *G. puncticulata* did not gradually evolve into *G. inflata* as has been observed in South Pacific Pliocene sequences (Kennett and Vella, 1975; Malmgren and Kennett, 1981).

Globigerina decoraperta Takayanagi and Saito = *Globigerina druryi decoraperta* Takayanagi and Saito, 1962
(Plate 2, figs. 16–19)

Distinguished by a compact test with four chambers in the final whorl, increasing uniformly in size as added; large, semicircular, high-arched aperture, bordered by distinct rim; and a coarsely cancellate surface. This is probably the same form referred to as *Globigerina woodi decoraperta* in California sequences by Bandy and Ingle (1970) and recognized as *G. decoraperta* by Poore (1981).

DISCUSSION

The late Neogene planktonic foraminiferal zonation that we have established for the California margin based on sites drilled during ODP Leg 167 consists of eight zones representing the last ~3.5 m.y. from the late early Pliocene to the present day. We have found that the zonal scheme can be consistently applied over much of the region (Figs. 1, 8), although Zones CM5 to CM3 were not individually recognized in the northernmost site; nor were Zones CM3 and CM4 individually recognized in the southernmost sites (Holes 1011B and 1012A) of the transect (Fig. 8). The interval from the late early Pliocene to the present day has been biostratigraphically subdivided at ~0.5-m.y. intervals, employing a succession of planktonic foraminiferal changes. The planktonic foraminiferal assemblages of the California Current system continued to change during the late Neogene as a result of evolutionary appearances of new taxa within California margin waters, appearances resulting from migration of taxa into the region following evolution elsewhere, and extinction. The general similarity in the succession of planktonic foraminiferal changes in the north–south transect suggests relative uniformity of response of faunas on evolutionary time scales throughout this large region. These changes were irreversible and represent evolutionary developments of the planktonic foraminiferal assemblages through time in California margin waters. The evolutionary development of the faunal sequence was superimposed on reversible changes in planktonic foraminiferal assemblages due to climatically related paleoceanographic changes in the California Current system (Ingle, 1973b). At this stage in our investigations, it is unclear if the first and last appearances of species used to define the new zones were synchronous throughout the region. This needs to be evaluated once a detailed chronological framework is established for each hole and biostratigraphic changes are integrated with paleomagnetic stratigraphy. It is clear that a few species that were not employed for the definition of the zones exhibit meridionally diachronous first or last appearances along the margin. These include the first and last appearances of *N. pachyderma* C, the last appearance of *G. puncticulata,* the last appearance of *N. humerosa praehumerosa,* the first appearance of *N. dutertrei,* and the first appearance of *G. truncatulinoides.* This diachronism almost certainly was in response to the well-known meridional paleoenvironmental gradients in surface waters in the California Current system.

Changes in the planktonic foraminiferal assemblages used to define the zones reflect important biotic events within the California Current system. Our observations suggest that the appearance of most new taxa during the late Neogene were abrupt and lack any apparent evolutionary gradation from earlier, possibly ancestral forms. A clear exception is the appearance of *N. asanoi,* which did not appear abruptly but shows evidence of gradual evolution from its ancestor *N. kagaensis* during the late Pliocene in this region. Evolutionary gradation is also apparent in the *G. inflata* lineage in the Leg 167 sites, supporting earlier interpretations of Keller (1978a, 1979a, 1979b, 1980). It remains unclear if the abrupt first appearances of other forms used to establish the zonation, especially forms of *N. pachyderma* and *N. kagaensis,* evolved within or close to the California margin through punctuated equilibrium or if the evolution occurred elsewhere with later rapid migration into these waters. A thorough study is required of the phylogeny of late Neogene neogloboquadrinids of the northeast Pacific to help resolve these issues and to assist in the resolution of paleoceanographic history of water masses along the coast of western North America.

The sequence of late Neogene (3.5 Ma to present day) planktonic foraminiferal assemblages in Leg 167 sites indicates a continued, long dominance of *G. bulloides* and neogloboquadrinids within the California Current system. Furthermore, taxonomic diversity of these assemblages remained relatively low throughout the late Neogene despite known global climate oscillations that affected the relative strength of the California Current (Ingle, 1973b; Kennett, 1982). Low diversity and high dominance of the assemblages favored these and other taxa well adapted to upwelling systems exhibiting high seasonal surface-ocean variability. *Neogloboquadrina* is a highly plastic taxon (a generalist species) well adapted to cool-water environments

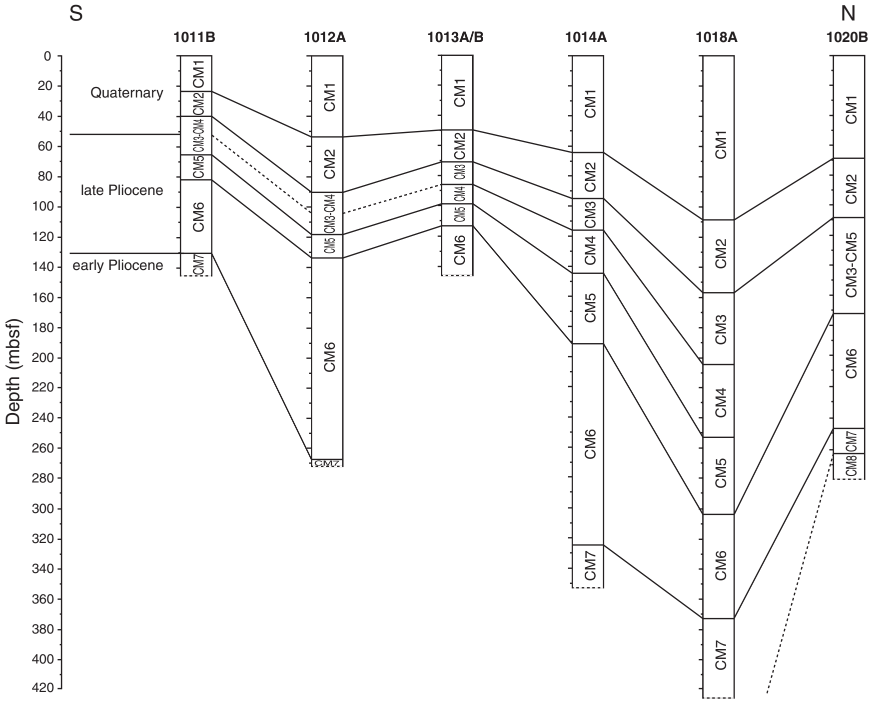

Figure 8. Intersite correlation of California margin (CM) zones in transect of Pliocene–Quaternary drilled sequences (Leg 167) used in this investigation, plotted according to depth (mbsf).

exhibiting strong seasonal changes in near-surface waters (Kennett, 1976). Apparently these oceanographic conditions, as they affect planktonic foraminiferal assemblages, have persisted in the California Current system during at least the late Neogene (3.5 Ma to present day).

CONCLUSIONS

A late early Pliocene through Quaternary planktonic foraminiferal zonation has been established for the California margin based on a north–south transect of six drilled sequences (ODP Leg 167) from 31°N to 41°N. A total of eight zones are recognized for the last ~3.5 m.y., most of which are broadly applicable in the region, thus providing a biostratigraphic zonation of the sequence at ~0.5-m.y. intervals. The zonation is largely defined by changes in the *Neogloboquadrina* complex, which underwent a dynamic evolution within the California Current system during the late Neogene. The evolution and biogeographic changes in planktonic foraminiferal assemblages that are used to define the zonation occur over a large north–south sector of the California Current system. Although elements of the faunal changes are in part also observed in the north central and northwest Pacific regions, the evolutionary succession of changes described as a whole are probably unique to the California Current system. The diversity of the assemblages during the late Neogene appear to have remained relatively constant despite large-scale paleoclimatic change. The assemblages are consistently dominated by few taxa that almost always include the neogloboquadrinids and *Globigerina bulloides.* Low diversity and high dominance of the assemblages favored these and other taxa well adapted to upwelling systems exhibiting high seasonal surface-ocean variability. Apparently the oceanographic conditions that favor such assemblages have persisted at least for the duration of the late Neogene (3.5 Ma to present day).

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REFERENCES

Bandy, O.L., 1959. Geological significance of coiling ratios in the foraminifer *Globigerina pachyderma* (Ehrenberg). *Geol. Soc. Am. Bull.,* 70:1708.

Bandy, O.L., and Ingle, J.C., Jr., 1970. Neogene planktonic events and radiometric scale, California. *Spec. Paper—Geol. Soc. Am.,* 124:131–172.

Banner, F.T., and Blow, W.H., 1965. Progress in the planktonic foraminiferal biostratigraphy of the Neogene. *Nature,* 208:1164–1166.

Barron, J.A., 1975. Late Miocene–early Pliocene marine diatoms from southern California. *Palaeontographica,* 151:97–170.

Berggren, W.A., Kent, D.V., Flynn, J.J., and van Couvering, J.A., 1985. Cenozoic geochronology. *Geol. Soc. Am. Bull.,* 96:1407–1418.

Darling, K., Kroon, D., Stewart, I., Wade, C., Dingle, R., Paramor, T., Pudsey, C., and Bijma, J., 1998. Planktic foraminiferal genotype distribution: gene flow and past ocean circulation. *6th Int. Conf. Paleoceanogr.*

Ingle, J.C., Jr., 1967. Foraminiferal biofacies variation and the Miocene-Pliocene boundary in Southern California. *Bull. Am. Paleontol.,* 52:217–394.

————, 1973a. Neogene foraminifera from the northeastern Pacific Ocean, Leg 18, Deep Sea Drilling Project. *In* Kulm, L.D., von Huene, R., et al., *Init. Repts. DSDP,* 18: Washington (U.S. Govt. Printing Office), 517–567.

————, 1973b. Summary comments on Neogene biostratigraphy, physical stratigraphy, and paleo-oceanography in the marginal northeastern Pacific Ocean. *In* Kulm, L.D., von Huene, R., et al., *Init. Repts. DSDP,* 18: Washington (U.S. Govt. Printing Office), 949–960.

Keller, G., 1978a. Late Neogene biostratigraphy and paleoceanography of DSDP Site 310 Central North Pacific and correlation with the Southwest Pacific. *Mar. Micropaleontol.,* 3:97–119.

————, 1978b. Late Neogene planktonic foraminiferal biostratigraphy and paleoceanography of the northeastern Pacific: evidence from DSDP Sites 173 and 310 at the north Pacific front. *J. Foraminiferal Res.,* 8:332–349.

————, 1978c. Morphologic variation of *Neogloboquadrina pachyderma* (Ehrenberg) in sediments of the marginal and central northeast Pacific Ocean and paleoclimatic interpretation. *J. Foraminiferal Res.,* 8:208–224.

————, 1979a. Early Pliocene to Pleistocene planktonic foraminiferal datum levels in the North Pacific: DSDP Sites 173, 310, 296. *Mar. Micropaleontol.,* 4:281–294.

————, 1979b. Late Neogene planktonic foraminiferal biostratigraphy and paleoceanography of the northwest Pacific DSDP Site 296. *Palaeogeogr., Palaeoclimatol., Palaeoecol.,* 27:129–154.

————, 1980. Planktonic foraminiferal biostratigraphy and paleoceanography of the Japan trench, Leg 57, Deep Sea Drilling Project. *In* von Huene, R., Nasu, N., et al., *Init. Repts. DSDP,* 56, 57 (Pt. 2): Washington (U.S. Govt. Printing Office), 809–833.

Keller, G., and Ingle, J.C., 1981. Planktonic foraminiferal biostratigraphy, paleoceanographic implications, and deep-sea correlation of the Pliocene-Pleistocene Centerville Beach section, northern California. *Spec. Pap.—Geol. Soc. Am.,* 184:127–135.

Kennett, J.P., 1976. Phenotypic variation in some Recent and late Cenozoic planktonic foraminifera. *In* Hedley, R.H., and Adams, C.G. (Eds.), *Foraminifera* (Vol. 2): New York (Acad. Press), 111–170.

————, 1982. *Marine Geology:* Englewood Cliffs, NJ (Prentice-Hall).

Kennett, J.P., and Srinivasan, M.S., 1983. *Neogene Planktonic Foraminifera: A Phylogenetic Atlas:* Stroudsburg, PA (Hutchinson Ross).

Kennett, J.P., and Vella, P., 1975. Late Cenozoic planktonic foraminifera and paleoceanography at DSDP Site 284 in the cool subtropical South Pacific. *In* Kennett, J.P., Houtz, R.E., et al., *Init. Repts. DSDP,* 29: Washington (U.S. Govt. Printing Office), 769–799.

Lagoe, M.B., and Thompson, P.R., 1988. Chronostratigraphic significance of late Cenozoic planktonic foraminifera from the Ventura Basin, California: potential for improving tectonic and depositional interpretation. *J. Foraminiferal Res.,* 18:250–266.

Lyle, M., Koizumi, I., Richter, C., et al., 1997. *Proc. ODP, Init. Repts.,* 167: College Station, TX (Ocean Drilling Program).

Maiya, S., Saito, T., and Sato, T., 1976. Late Cenozoic planktonic foraminiferal biostratigraphy of Northwest Pacific sedimentary sequences. *In* Takayanagi, Y., and Saito, T. (Eds.), *Progress in Micropaleontology:* New York (Micropaleontology Press), 395–422.

Malmgren, B.A., and Kennett, J.P., 1981. Phyletic gradualism in a Late Cenozoic planktonic foraminiferal lineage, DSDP Site 284: southwest Pacific. *Paleobiology,* 7:230–240.

Matoba, Y., and Oda, M., 1982. Late Pliocene to Holocene planktonic foraminifers of the Guaymas Basin, Gulf of California, Sites 477 through 481. *In* Curray, J.R., Moore, D.G., et al., *Init. Repts. DSDP,* 64: Washington (U.S. Govt. Printing Office), 1003–1026.

Natori, H., 1976. Planktonic foraminiferal biostratigraphy and datum planes in the Late Cenozoic sedimentary sequence in Okinawa-jima, Japan. In *Progress in Micropaleontology:* New York (Am. Mus. Nat. Hist., Micropaleontology Press), 214–243.

Poore, R.Z., 1981. Miocene through Quaternary planktonic foraminifers from offshore southern California and Baja California. *In* Yeats, R.S., Haq, B.U., et al., *Init. Repts. DSDP,* 63: Washington (U.S. Govt. Printing Office), 415–436.

Saito, T., Thompson, P.R., and Breger, D., 1981. *Systematic Index of Recent and Pleistocene Planktonic Foraminifera:* Tokyo (Univ. of Tokyo).

Stewart I., Darling, K., Kroon, D. Wade, C., and Troesltra, S., 1998. Morphotypic and genotypic variability in subarctic planktic foraminifera. *6th Int. Conf. Paleoceanogr.*

Zellers, S.D., 1995. Foraminiferal biofacies, paleoenvironments, and biostratigraphy of Neogene-Quaternary sediments, Cascadia Margin. *In* Carson, B., Westbrook, G.K., Musgrave, R.J. and Seuss, E. (Eds.). Proc. ODP, Sci. Results, 146 (Pt. 1): College Station, TX (Ocean Drilling Program), 79–113.

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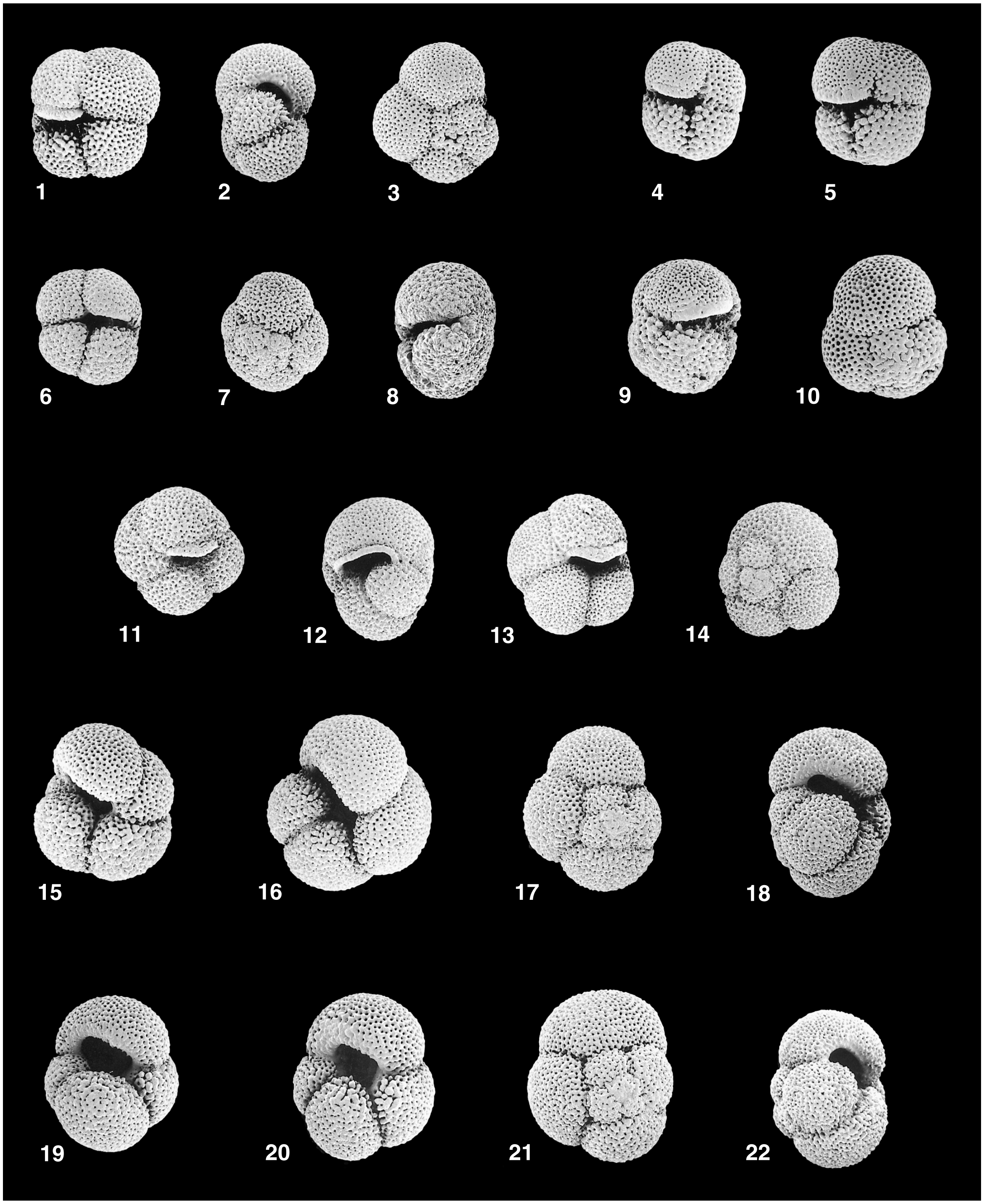

Plate 1. **1–3.** *Neogloboquadrina pachyderma pachyderma* (Ehrenberg) (dextral, flat, regular form). (1) Umbilical view, 85×; (2) side view, 79×; (3) spiral view, 79×. All from Sample 167-1014A-4H-6, 120–122 cm. **4, 5, 9, 10.** *Neogloboquadrina pachyderma* (Ehrenberg) A (dextral, inflated form). (4, 5) Umbilical view, 62×; (9) side view, 68×; (10) spiral view, 62×. All from Sample 167-1018A-17X-2, 120–125 cm. **6–8.** *N. pachyderma* (Ehrenberg) C (sinistral, flat, regular form). (6) Umbilical view, 96×; (7) spiral view, 96×; (8) side view, 130×. All from Sample 167-1014A-18X-2, 120–122 cm. **11–14.** *N. pachyderma* (Ehrenberg) B (sinistral, inflated form). (11) Umbilical view, 90×; (12) side view, 90×; (13) umbilical view, 85×; (14) spiral view, 90×. All from Sample 167-1014A-11X-5, 120–122 cm. **15–18.** *N. kagaensis* (Maiya, Saito, and Sato). (15) Umbilical view, 68×; (16) umbilical view, 62×; (17) spiral view, 62×; (18) side view, 57×. All from Sample 167-1014A-29X-2, 120–122 cm. **19–22.** *N. asanoi* (Maiya, Saito, and Sato). (19) Umbilical view, 62×; (20) umbilical view, 68×; (21) spiral view, 68×; (22) side view, 57×. All from Sample 167-1014A-29X-2, 120–122 cm.

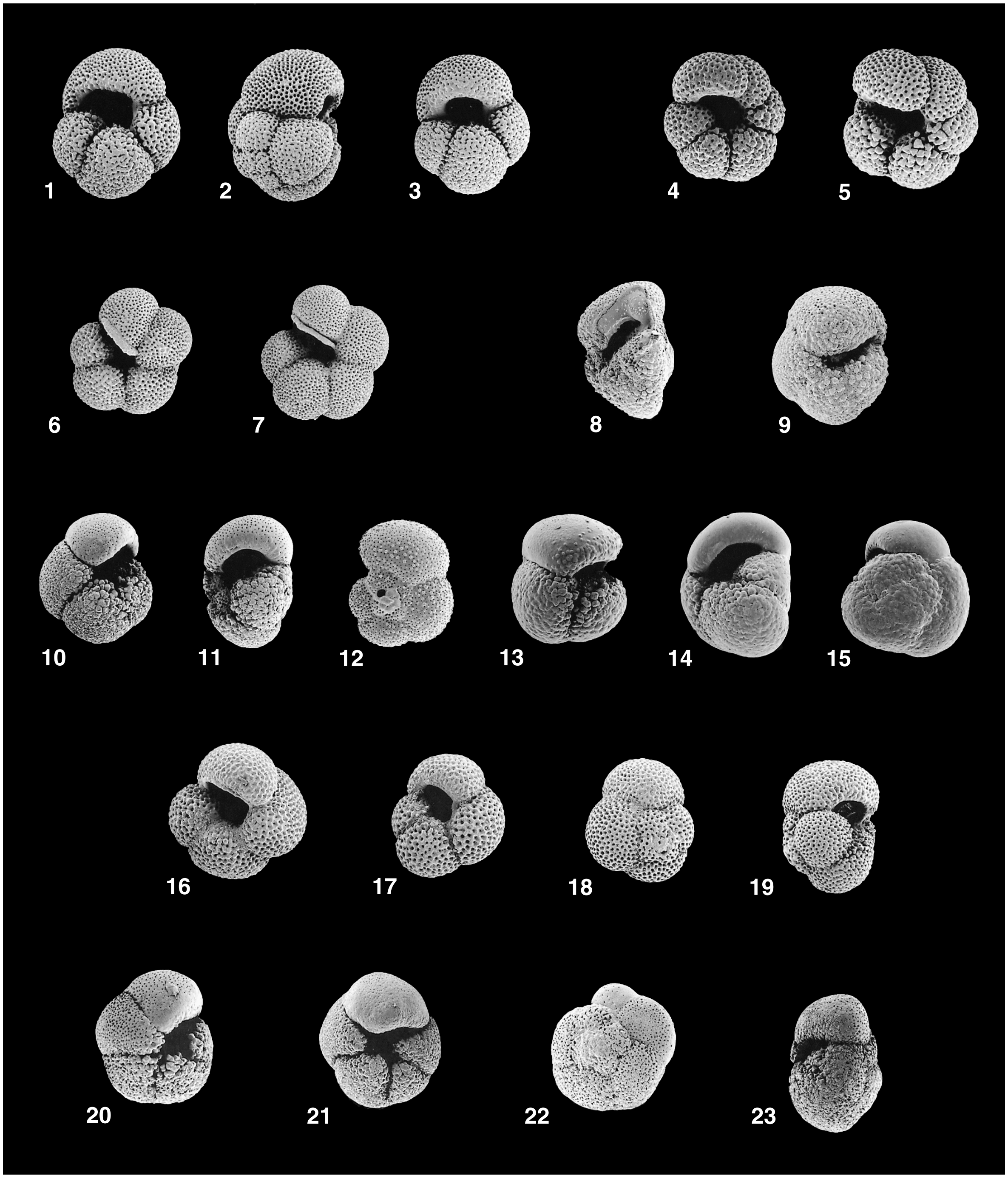

Plate 2. **1–3.** *Neogloboquadrina asanoi* (Maiya, Saito, and Sato) (highly inflated form). (1) Umbilical view, 48×; (2) side view, 48×; (3) umbilical view, 45×. All from Sample 167-1014A-23X-5, 105–107 cm. **4, 5.** *N. dutertrei* (d'Orbigny). Umbilical views, 57×. Both from Sample 167-1014A-1H-1, 120–122 cm. **6, 7.** *N. humerosa praehumerosa* (Natori). Umbilical views, 62×. Both from Sample 167-1014A-10X-CC. **8, 9.** *Globorotalia (Globoconella) puncticulata* (Deshayes). (8) Side view, 68×; (9) umbilical view, 74×. Both from Sample 167-1020B-28X-CC. **10–12.** *G.* (*Globoconella) inflata* (d'Orbigny) (transitional form). (10) Umbilical view, 57×; (11) side view, 57×; (12) spiral view, 62×. All from Sample 167-1020B-22X-4, 121–124 cm. **13–15.** *G. (Globoconella) inflata* (d'Orbigny) (modern form). (13) Umbilical view, 54×; (14) side view, 54×; (15) spiral view, 62×. All from Sample 167-1020B-10H-2, 120–125 cm. **16–19.** *Globigerina decoraperta* (Takayanagi and Saito). (16, 17) Umbilical views, 68×; (18) spiral view, 68×; (19) side view, 68×. All from Sample 167-1020B-29X-CC. **20–23.** *Globorotalia (Globoconella) ikebei* (Maiya, Saito, and Sato). (20) Umbilical view, 48×; (21) Umbilical view, 54×; (22) spiral view, 54×; (23) side view, 52×. All from Sample 167-1020B-29X-2, 126–129 cm.