## 32. SUMMARY COMMENTS ON NEOGENE BIOSTRATIGRAPHY, PHYSICAL STRATIGRAPHY, AND PALEO-OCEANOGRAPHY IN THE MARGINAL NORTHEASTERN PACIFIC OCEAN

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## INTRODUCTION AND HISTORICAL PERSPECTIVE

Leg 18 sites located adjacent to the Pacific Coast of North America (Figure 1) encompass a span of 18° of latitude from 39° 57.71'N (Site 173) to 57° 52.88'N (Site 182) and represent an unusually rich source of information relating to marine geologic and biologic events at this particular ocean-continent boundary during the Neogene<sup>1</sup> interval. The stratigraphic record at each of these sites reflects in varying degrees the extremely dynamic nature of oceanographic, sedimentary, and tectonic processes characteristic of this particular area. Moreover, each site offers a relatively undisturbed link to an understanding of the much thicker, structurally complex, and in many instances conterminous deposits subaerially exposed along the adjacent continental margin. Therefore it seems appropriate to briefly review the progress of geologic and paleontologic investigation within this parallel sedimentary sequence in order to better cast the results of Leg 18 into the role of intermediary between continent and ocean basin.



Figure 1. Location of sites drilled during Leg 18 and schematic paths of the California Current and Alaskan Current in the marginal northeastern Pacific.

#### BIOSTRATIGRAPHY AND PALEOCEANOGRAPHY

Ignoring momentarily the inorganic debris on the sea floor, it is of specific interest to biostratigraphic problems in this area to focus attention on the implications derived from the high and mid-latitude positions which Leg 18 traversed in the marginal northeastern Pacific. The breadth of latitude crossed during this expedition encompasses the higher mid-portion of the pole-to-equator climatic gradient which plays a major role in generating atmospheric transport and ultimately the characteristics of surface circulation, temperature distribution, etc., in this portion of the Pacific basin. Moreover, the clockwise nature of surface circulation in the Pacific Ocean dictates that the cooler water generated at these higher latitudes will be driven south along the eastern margin of the North Pacific creating a major eastern boundary current. This latter flow, termed the California Current, has dictated the nature of the biota in the marginal eastern Pacific at least since Cretaceous time (Sliter, 1972). Any oscillations between a stable cool climatic state to a stable warm state over geologically significant intervals should be clearly sensed in this intermediate area of pole-to-equator atmospheric-oceanic gradients. Cool isotherms should be more readily moved south during periods of intense polar refrigeration, whereas warmer isotherms may take longer to move north or "upstream" during warm events. Relatively cooler conditions can be expected to have continuously prevailed at the latitudinally higher end of the Leg 18 traverse to be pierced only during the most severe warmer climatic intervals.

Significantly, even the earliest studies of variation in Tertiary molluscan faunas along the Pacific Coast were recognized as manifestations of climatic oscillations in this region (Smith, 1919), with later studies detailing these trends as a function of migrating isotherms north and south along the coast in response to major intervals of polar refrigeration or warming (Durham, 1950; Addicott, 1969). Benthonic foraminifera also display similar patterns throughout the Cenozoic in this area as exemplified by the appearance of subtropical shelf and littoral faunas during portions of the Miocene, Pliocene, and Pleistocene, with intervening intervals dominated by more boreal faunas (Kleinpell, 1938; Ingle, 1967). Stratigraphic variations of these latter benthonic microfossils have in fact been used by Kleinpell (1938), Natland (1957), and Mallory (1959) to define the well-known provincial stages of the California Tertiary and Quaternary. However, the utility of stage designations based on benthonic species is tempered by the climatically induced faunal migrations and the rather narrow ecologic tolerances of these animals leading to time-transgressive facies problems (Bandy, 1967; Ingle, 1967; Steineck and Gibson, 1971).

 $<sup>^{1}\,\</sup>mathrm{The}$  term Neogene is herein modified to include the Miocene through Recent interval.

Studies of planktonic foraminifera, calcareous nannoplankton, and Radiolaria within these same deposits have also clearly demonstrated that Neogene planktonic faunas inhabiting the proto-California Current system generally exhibit a cool to warm-temperate low-diversity character with periodic incursions of subtropical and warmer biofacies associated with migrating isotherms induced by climatic oscillations.<sup>2</sup> The effect of climatic oscillations and the attendant marching of critical isotherms north and south along the marginal eastern Pacific has played havoc with attempts at correlation of paleontologic events in this area with stages erected in lower latitude-high diversity faunal provinces (Bolli, 1966; Blow, 1969). However, the marginal to sometimes common appearances of critical tropical-subtropical index species has allowed recognition of the standard Neogene planktonic foraminiferal and calcareous nannopolanktonic zones in a broad way (Lipps, 1967a; Lipps and Kalisky, 1972; Ingle, 1967; Bandy and Ingle, 1970, Bandy, 1972). The tropical zonal schemes have in some cases been amended to include critical transitional and subarctic water mass species (Bandy and Ingle, 1970) similar to the zonations detailed by Jenkins (1967) and Kennett (1967) for the Neogene of New Zealand.

The fact that climatic oscillations are sensed most sharply at mid-latitude locations and most especially within areas of eastern boundary currents provides an immediate and uniquely valuable tool for correlation transcending the biostratigraphic problems induced by generally lowdiversity faunas in the zoogeographic province defined by the limits of the California Current system and the related Alaskan Current gyre (Figure 1). Expressions of major paleoclimatic-paleo-oceanographic events within lowdiversity planktonic foraminiferal faunas proved especially useful in Leg 18 biostratigraphic analysis as discussed below. Moreover, not all groups exhibit extremely low diversity. The North Pacific diatom zones proposed and defined in this volume by Schrader (Chapter 17) allow biostratigraphic correlations to be made within horizons and areas where the utility of calcareous nannoplankton and planktonic foraminifera are drastically reduced due to marginally diverse or monospecific faunas. Radiolarian zonation offers similar assistance, and both diatoms and radiolarians are useful in sediments devoid of calcareous material just as they are in similar deposits exposed on the adjacent continental margin.

### PHYSICAL STRATIGRAPHY AND TECTONISM

Terrigenous sediments have poured off the Pacific edge of the North American continent into a variety of reservoirs including trenches during the Mesozoic-early Tertiary (Bailey, et al., 1964) and the mid-Tertiary (Atwater, 1970), as well as into discrete marginal basins throughout the Cenozoic (Reed, 1933). Evidence obtained on Leg 18 and from earlier reports (Menard, 1964) demonstrates that terrigenous sediments have been splayed far out onto the adjacent abyssal plains where basins or trenches were filled or a simple continental slope existed - a pattern not unlike the present. In addition, biogenous sediment has predominated within certain intervals of the Cenozoic in this area as a product of vigorous upwelling and appropriate sites for preservation. Miocene diatomaceous deposits assigned to the Monterey Shale are regional in extent (Bramlette, 1946), and this same lithologic event is prominently present at Sites 173 and 178 drilled during Leg 18. A glance at any geologic map of this portion of the continental edge reveals that many of these former bathyal marine deposite are now complexly interwoven into the Coast Ranges along this margin and are available for study without ship or sea surely a marine geologic resource of the first order. Unfortunately, early studies of these rocks and the associated paleontologic record treated the edge of California as a major unconformity between known and unknown, a philosophy fostering rather exotic and unrealistic explanations of things observed. As research on modern depositional processes and associated biologic patterns along this margin has progressed (Emery, 1960; Van Andel and Shor, 1964), so has the understanding of the record of Cenozoic events preserved in the thousands of meters of marine sediment contained within the Coast Range province of the Pacific margin. Trench, slope, fan, shelf, and littoral deposits have all been readily identified within the Cenozoic sedimentary sequences of the Coast Ranges by direct analogy with modern depositional environments in this same area.

Evidence of major Cenozoic structural episodes is also held within the Coast Ranges of North America, and the record is decidedly nonlinear. There have been at least two periods of marginal basin formation. An early Tertiary cycle of basin subsidence and in-filling was followed by another similar cycle in the later Tertiary, with an intervening Oligocene interval characterized by thick continental deposits and marginal marine deposition. Both of these major tectonic episodes may be related to significant changes in rate and/or vector of plate motion in the Pacific area. Given the Pliocene and Pleistocene age of many of these bathyal sequences now exposed in large structures within the Coast Range province, it seems clear that the present structure and topography of this belt is a product of major Pleistocene tectonic events. This scenario is reinforced by information obtained from the majority of sites drilled on Leg 18 where seismic evidence illustrated the presence of deformed and faulted wedges of sediments at the continental margin ultimately determined to be Pliocene, Pleistocene, and in some instances Holocene in age. Thus evidence both onshore and offshore demonstrates that the thick wedges and basins of sediment currently being deposited along the continental margin are being systematically deformed, uplifted, and incorporated into the margin where in many instances they are now displayed via erosion within the coastal belt.

### EXPANSION AND PRESERVATION OF THE BIOSTRATIGRAPHIC-PALEO-OCEANOGRAPHIC RECORD

Given the Neogene record of major excursions of surface isotherms and associated migrations of planktonic biofacies within the California Current system and the deposition of

<sup>&</sup>lt;sup>2</sup>See a recent symposium volume edited by J.H. Lipps (1972) for a current review of eastern Pacific plankton biostratigraphy.

these planktonic elements into the rapidly deposited wedges of sediment at the continental margin, the stage is set for preservation of an expanded stratigraphic record along the Pacific margin. Pieces of this record have already been analyzed from structurally complex settings within the Coast Ranges where portions of this wedge have been uplifted and subaerially exposed (Bandy and Kolpack, 1963; Lipps, 1964, 1967b, 1968; Ingle, 1963, 1967, 1972; Lipps and Kalisky, 1972; Bandy et al., 1969; Bandy and Ingle, 1970; Bandy and Wilcoxon, 1970; Bandy, 1972, Wilcoxon, 1969; Casey, 1972; and others), as well as in the Mohole cores drilled at the distal end of the California Current (Parker, 1964; Martini and Bramlette, 1963; Bandy and Ingle, 1970) and in cores representing the Pleistocene interval (Kheradpir, 1970). All of these studies along with others not cited have added to our knowledge of both the planktonic biostratigraphy and paleo-oceanography of the eastern Pacific margin. However, all have been plagued by the relatively discontinuous nature of the record available within surface sections of the structurally complex coastal zone with the exception of deep-sea Pleistocene cores. In contrast, the apparently continuous late Oligocene-late Pleistocene stratigraphic record available at Site 173 off northern California represents a premier example of the convergence of factors favorable to nearly continuous deposition in an area directly beneath the California Current and only lightly disturbed by subsequent structural adjustments. It is apparent that the planktonic record preserved at this site presents an ideal control section for this area of the Pacific basin. The multiple zonations delimited within this particular sequence, as well as attendant paleoecologic and paleo-oceanographic implications are briefly analyzed in the following sections. Many of the Neogene planktonic events delimited within the thick but discontinuous Coast Range stratigraphic column are readily recognizable in the continuous, if relatively thin record, preserved at Site 173, providing major assistance in ordering these events within the larger context of physical process and biologic response in the California Current province and geological context of the Pacific margin. Further and more detailed study of this particular site should provide an unparalelled standard for the subarcticcool temperate region of the North Pacific and a means for correlation with lower latitude.

## MULTIPLE BIOSTRATIGRAPHY OF SITE 173 AND RELATIONSHIP TO THE RADIOMETRIC TIME SCALE, CALIFORNIA NEOGENE STAGES, AND PALEOCLIMATIC EVENTS

#### General

Drilling, coring, and sampling at Site 173 revealed that skeletal planktonic debris has rained down on this particular area from the late Oligocene through the late Pleistocene in response to the prolific productivity of the surface waters overlying this location, which continues today. Physical stratigraphy and continuity of microfaunas and floras within this sequence indicate that essentially continuous deposition has occurred at this site since the late Oligocene. Thus, this sequence does indeed represent an excellent biostratigraphic reference section for the eastern North Pacific and provides a record of major planktonic and sedimentary events spanning a 23 m.y. interval within a cool-temperate to subarctic zoogeographic province dominated by the California Current system. Moreover, biostratigraphic, lithostratigraphic, and paleooceanographic events delineated at Site 173 can be correlated directly with similar and related events known in surface sections exposed along the Pacific margin (Figure 2).

Benthonic foraminifera are common throughout this sequence and confirm that deposition during the Oliocene-Pleistocene interval took place at lower bathyal<sup>3</sup>



Figure 2. Location of Neogene marine surface sections and deep sea drilling sites mentioned in text.

<sup>&</sup>lt;sup>3</sup>See Ingle (Chapter 14) for depth classification used in this report.

depths similar to the depth of the sediment/water interface today (2927 m). However, the uniformity of bathymetric setting is not matched by uniformity of sediment composition and process. A quick perusal of the dominant lithologies present within this sequence (Figure 3) illustrates that major variations have occurred both in terms of composition and dominant mode of sediment transport during the interval represented. Thirty-five meters of glauconitic calcareous nannofossil oozes were initially deposited on top of a volcanic basement during the late Oligocene-early Miocene with an abrupt change to dominantly diatomaceous sediments within the early Miocene-late Miocene interval. These latter deposits represent 147 meters of distinctive biogenic siliceous sediment undoubtedly related to similar but in some cases much thicker deposits of diatomaceous shales distributed around the rim of the North Pacific during the same interval. These deposits are discussed in more detail in a later section of this report. The pattern of biogenic sedimentation prevailing during the Miocene interval is abruptly ended near the Miocene-Pliocene boundary where terrigenous muds, silts, and fine sands appear in abundance, representing gravity driven transport from the continental margin. Subsequent rapid deposition during the Plio-Pleistocene interval supplied 138 meters of sediment to this area via nepheloid layer and infrequent turbidite deposition.

## Multiple Biostratigraphic Zones and Datum Planes

Figure 3 depicts an encouragingly large number of biostratigraphic zones delineated within the 320 meters of prolifically fossiliferous late Oligocene-late Pleistocene sediment encountered at Site 173. These zones are a product of both evolution and ecologically induced migration of species representing members of the planktonic microbiota of the California Current system at this latitude, along with infrequent incursions of species from neighboring water masses. The resulting biostratigraphic and ecologic picture is far more complex than normally encountered within relatively stable low-latitude areas. The relatively long duration of zones based on high-latitude species and the somewhat obscure and imprecise boundaries attached to the identifications of zones developed at lower latitudes are symptomatic of problems encountered in developing viable biostratigraphic zonal schemes in higher latitude areas.

There are exceptions to these general problems. For example, the North Pacific Diatom Zones defined by Schrader (Chapter 17) allow a good scale of biostratigraphic resolution within the Pleistocene-Miocene interval in contrast to the lengthy intervals delineated by silicoflagellates and radiolarian zones. It is tempting here to speculate about possible differences in rates of evolution of diatoms in this cooler province as opposed to other groups. Zones based on planktonic foraminifera and calcareous nannoplankton are variable in length due in part to ecologic regulation of some of the stratigraphically important species which only allow precise zonal boundaries to be defined during warmer intervals, with attendent incursions of critical index species with imprecise control in terms of tropical zones prevalent in the intervening intervals. Wise (Chapter 15) overcame this problem in part by combining ranges of both calcareous nannofossils and silicoflagellates (Figure 3), allowing a finer biostratigraphic resolution within some intervals than could have been achieved with either group alone. In addition, both calcareous nannofossils and planktonic foraminiferal zonations make use of lineages best developed at higher latitudes such as the *Globigerina pachyderma* datum in the later Miocene and the newly identified *Discoaster mendomobensis* (Figure 3).

Ultimately, when all zonal schemes depicted on Figure 3 are combined, they present over 50 readily identifiable horizons within the 22.5 m.y. interval represented at Site 173, not including datum planes occurring within various zones. This multiplicity of useful horizons results in a scale of biostratigraphic resolution oscillating between 1 and 0.5 m.y., certainly a finer scale than could be achieved by any single group. The combination zonal scheme also overcomes problems stemming from the low-diversity nature of several of the groups utilized.

Selected datum planes, or more properly datum surfaces, are given on Figure 3 in conjunction with correlation with the paleomagnetic time-scale. These surfaces represent additional stratigraphic sign posts leading to an even finer biostratigraphic resolution of the interval represented. However, caution must be exercised in the use of these surfaces at high latitudes where absolute ranges or a given taxon may be restricted due to variations in oceanographic conditions.

## Definition of Boundaries at Site 173

The low diversity and paucity of some microfossil groups within certain intervals at Site 173 and their increase in diversity within other intervals dictates that placement of epoch boundaries and correlations of the various zonal schemes will involve some arbitrary decisions in terms of which zonal schemes will prevail for purposes of definition. In addition, differences exist in placement of epoch boundaries between groups, despite the fact that there may be general agreement in correlation of zones between various groups. An example of this latter problem involves placement of the Miocene-Pliocene boundary. Diatom specialists (Burckle, 1970; Schrader, Chapter 17, this volume) place this boundary at a horizon correlative with the base of planktonic foraminiferal zone N. 18 based on correlations with the type lower Pliocene of northern Italy, whereas foraminiferal specialists more commonly place this boundary at the top or within the upper portion of zone N. 18 (Berggren, 1972).

The Pleistocene/Pliocene boundary at Site 173 and at other more northern sites on Leg 18 is placed at the base of the *Eucyrtidium matuyami* radiolarian zone of Hays (1970). This zone is currently correlated with the base of the Olduvai geomagnetic event, in turn equated with a radiometric age of 1.85 m.y. (Opdyke, 1972). The base of North Pacific Diatom Zone V<sup>4</sup> is thought to fall within or near the base of the Olduvai event, providing some continuity of definition. Recognition of a definitive

<sup>&</sup>lt;sup>4</sup>North Pacific Diatom Zones are proposed and defined by Schrader (Chapter 17, this volume).

### NORTHEASTERN PACIFIC NEOGENE BIOSTRATIGRAPHY



Figure 3. Comparison and correlation of zonations based on planktonic foraminifera, calcareous nannofossils, silicoflagellates, diatoms, and radiolarians at Site 173 off northern California. Authors responsible for definition of zonal boundaries and zone assignments are noted above. Correlation of California (Pacific Coast) benthonic foraminiferal stages with this sequence is based upon planktonic foraminiferal zonation; Hallian through Mohnian Stage boundaries are tilted to depict the time-transgressive and facies-controlled character of these units. A discrepancy in the alignment of radiolarian and diatom zonal markers with an estimated 5.0 m.y. age of zone N. 18 by Berggren (1969; 1972) is shown by a line spanning the questionable interval. The correlation of foraminiferal (F), diatom (D), radiolarian (R), and calcareous nannofossil (N) datums with the paleomagnetic-radiometric time scale is explained in the text.

Pleistocene/Pliocene boundary on the basis of calcareous nannoplankton and planktonic foraminifera is hampered by the general absence of *Discoaster* and *Globorotalia truncatulinoides* at Site 173 and other sites on Leg 18. However, these zonal markers are present at more southern latitudes within the California Current province (Bandy and Wilcoxon, 1970; Ingle, 1967). Recognition of this boundary is also aided within this province by a major interval of increased surface temperature perhaps reaching  $20^{\circ}$ C at Site 173. This warmer interval is marked by the incursion of a subtropical-warm temperate biota easily recognized throughout the province and allowing recognition of this horizon despite the absence of critical zonal markers.

The Miocene/Pliocene boundary is arbitrarily placed at the earliest appearance of Pliocene planktonic foraminifera including *Globorotalia puncticulata* (Core 14) and equated with the base of zone N. 19. As noted above this arbitrary boundary is in conflict with that currently used by many foraminiferal specialists who place this horizon within zone N. 18 or diatom specialists who currently place the boundary at the base of zone N. 18. The base of North Pacific Diatom zone XI is correlated with this latter boundary.

The middle Miocene/late Miocene boundary is placed at 186 meters (Core 20) at Site 173 at the base of the Dictyocha asper-Reticulofenestra pseudoumbilicata silicoflagellate-calcareous nannofossil combination range zone. The approximate base of the Late Miocene Dictyocha pseudofibula silicoflagellate zone occurs within Cores 19 or 20, and the approximate base of the late Miocene Ommatartus anteperultimus radiolarian zone occurs within the Core 20 to 21 interval compatible with the arbitrary epoch boundary cited above. The earliest occurrence of a dominantly sinistral population of Globigerina pachyderma currently correlated with planktonic foraminiferal zone N. 15 (Bandy and Ingle, 1970; Bandy, 1972) takes place in Core 20 and marks a horizon approximately equivalent to the middle Miocene/late boundary as defined by Blow (1969), Berggren (1969, 1972), and others. Berggren (1972) correlates this latter horizon with an estimated radiometric age of 10.5 m.y. It should be noted, however, that Bandy and Ingle (1970), Bandy et al. (1971), and Bandy (1972) place this same boundary between zones N. 12 and N. 13 as marked by the earliest appearance of Globigerina pachyderma in temperate and boreal latitudes. This latter horizon occurs at the base of Core 21 at Site 173. The base of North Pacific Diatom Zone XIX is correlated with the middle Miocene/late Miocene boundary based on correlations by Burckle (1972).

The middle Miocene/early Miocene boundary is placed at the base of Core 27 at Site 173 at the earliest occurrence of Orbulina suturalis, commonly used to mark the base of planktonic zone N. 9 (Blow, 1969). The base of the Sphenolithus heteromorphous calcareous nannofossil zone of tropical latitudes is correlated with the first appearance of Discoaster exilis in Core 28 at Site 173, in turn marking the base of the newly defined (Wise, this volume) Cyclicargolithus floridanus Range-zone. The base of the Sphenolithus heteromorphous Zone is currently correlated with an interval falling midway between the final

appearance of the planktonic foraminifer Catapsydrax stainforthi and the initial appearance of Orbulina suturalis, essentially compatible with the sequence observed at Site 173. However, portions of Cores 28, 29, and 30 are barren or contain only sparse planktonic foraminiferal assemblages. Consequently, it is conveivable that the Orbulina datum (base of zone N. 9) may occur below Core 27 but no lower than Core 30 where abundant assemblages reappear. Moreover, the base of North Pacific Diatom Zone XXIV, equated with the early Miocene/middle Miocene boundary, occurs at the base of Core 30, and the base of the Dorcadospyris alata radiolarian zone, also equated with this boundary, occurs within the Cores 28 to 31 interval. Thus, an alternate conservative case can be made for placing the early Miocene/middle Miocene boundary as low as the base of Core 30 at Site 173.

The early Miocene/late Oligocene boundary is arbitrarily placed at the base of Core 34 at the top of the *Reticulofenestra bisecta* - *Triquetrorhabulus carinatus* calcareous nannofossil range zone. Poor to moderately preserved planktonic foraminifera in Cores 34 and 35 include *Globigerina angulisuturalis*, *Globorotalia opima nana*, and *Catapsydrax dissimilis* suggesting assignment to the lowermost Miocene or latest Oligocene (zone N. 3/4).

# Correlation with the Radiometric Time Scale

A number of critical diatom, radiolarian, nannofossil, and foraminiferal datum surfaces at Site 173 allow correlation with sequences directly dated by paleomagnetic signature (Hays et al., 1969) or by multiple correlations and estimated alignment of the paleomagnetic-radiometric time scale (Berggren, 1969; 1972). A series of estimated radiometric ages based on correlation of various microfossil datum planes are presented on Figure 3.

The voungest potential datum surface with a known radiometric age at Site 173 is represented by the base of a warm interval delimited by populations of dextral-coiling Globigerina pachyderma in Core 1 and thought to represent the Holocene/Pleistocene boundary of 11,000 to 12,000 years. This same event has been noted in Pleistocene cores obtained both north and south of Site 173 (Bandy, 1967; Duncan et al., 1970). Diatom correlations (Schrader, Chapter 17, this volume) allow definition of horizons thought to be equivalent to 0.26 m.y., 1.30 m.y., 2.20 m.y., 2.50 m.y., and 4.3 m.y. based on paleomagnetic alignment of Plio-Pleistocene diatom datums by Burckle (1972) and Donahue (1970).<sup>5</sup> Similarly, Plio-Pleistocene radiolarian datums present at Site 173 allow correlation with horizons paleomagnetically dated as 0.9 m.y., 1.82 m.y., 2.80 m.y., 4.2 m.y., and 5.0 m.y. by Hays (1970) and Hays et al. (1969).6

It is important to note that there is a discrepancy in the estimated radiometric ages of the Miocene/Pliocene interval at Site 173. Radiolarian and diatom correlations with paleomagnetically dated sequences suggest that an interval encompassing the base of Core 14 through the top of Core 17 represents an age of 4.2 to 5.0 m.y., whereas

<sup>&</sup>lt;sup>5</sup>See Chapter 17 by Schrader for details of correlation.

<sup>&</sup>lt;sup>6</sup>See Chapter 16 by Kling for details of correlation.

correlations by planktonic foraminifera and calcareous nannofossils suggest that zone N. 18, equated with the 5.0 m.y. horizon, occurs slightly above this within the Cores 14 to 15 interval as noted on Figure 3.

Estimated radiometric ages below the 5.0 m.y. horizon are based on correlations of planktonic foraminiferal events and calcareous nannoplankton horizons with the radiometric-paleomagnetic time scale of Berggren (1969; 1972). These estimated ages are augmented by potassium-argon dates reported by Turner (1970) and Dymond (1966) from the Miocene of California and presented on Figure 3 along with the California benthonic foraminiferal stages.

Globorotalia acostaensis initially appears in Core 18, and this datum is equated to 9.0 m.y. by Berggren (1969; 1972), forcing a rather telescoped section of time within the Cores 16 to 18 interval at Site 173. However, paleo-oceanographic events at this site may have prevented the earlier appearance of this species at this latitude and the correlation is thus tentative. The earliest appearance of a sinistral-coiling population of Globigerina pachyderma within the California Miocene is thought to be equivalent to about zone N.15 and the middle Miocene/late Miocene boundary of Berggren (1972), in turn correlated with an estimated radiometric age of 10.5 m.y. The initial appearance of Globigerina pachyderma s.1. in the California Miocene and at Site 173 is correlated with the zone N. 12/13 boundary, in turn dated by Berggren (1972) as 12.5 m.y. Significantly, these latter two dates are corroborated by radiometric dates performed on rocks within the Miocene portion of the Mohole cores (Dymond, 1966) where these two biostratigraphic datums also occur (Bandy and Ingle, 1970).

The first appearance of Orbulina suturalis is equated by Blow (1969) and others with the Orbulina datum. This critical biostratigraphic horizon has in turn been dated between 16 and 15 m.y. (Berggren, 1972). However, a K/Ar date within the Relizian Stage of California of 15.3 m.y. (Turner, 1970) and dates available within the Japanese Miocene (Ikebe et al., 1972) suggest the age of this horizon is closer to 15 m.y. The Catapsydrax stainforthi extinction datum is dated by Berggren (1972) as 17.0 m.y., and a date of 22.5 m.y. at the base of the Saucesian Stage of California (Turner, 1970) is equated with the base of the Miocene and the Globigerinoides datum (Berggren, 1972; Bandy and Ingle, 1970; Lipps, 1967a).

### Paleo-oceanographic Events and Noegene Paleooceanography of the California Current System

The planktonic foraminiferal sequence delimited at Site 173 contains a series of major biofacies changes (see Chapter 14, this volume) corresponding to a series of major oceanographic events within the California Current system. These biofacies variations, along with the attendant appearance of critical planktonic index species, have been detected within various portions of bathyal Pleistocene, Pliocene, and Miocene marine sections exposed within the coastal area of California, representing uplifted portions of major marine basins in this area (Bandy and Kolpack, 1963; Lipps, 1964, 1967a; Ingle, 1967; Bandy and Ingle, 1970). These same basinal sediments contain benthonic foraminiferal biofacies which have been analyzed in terms of the benthonic foraminiferal stages erected by Kleinpell (1938) and Natland (1952), in turn allowing correlation of these well-known biostratigraphic units with the lower bathyal sequence at Site 173, despite the fact that only meager benthonic evidence of correlation with these stages was available at this deep-water site. It should also be emphasized that the benthonic stages appear timetransgressive in part when placed against the framework of major planktonic datums and oceanographic events sensed ubiquitously within the California Current province as demonstrated by Bandy (1967) and Ingle (1967).

Variations in planktonic foraminiferal biofacies detailed throughout the late Oligocene-late Pleistocene interval at Site 173 are used as the primary basis in estimating variations in surface temperature within this sequence, although corroborating evidence is provided in some instances by paleotemperature estimates based on variation in silicoflagellate assemblages (Bukry, Chapter 19, this volume) and diatom Td values (Schrader, Chapter 17, this volume). Moreover Figure 4 provides a larger view of the paleo-oceanographic events sensed at Site 173 by utilizing the recognition of these major biofacies changes in surface sections along the Pacific Coast (Ingle, 1967, 1968, 1971, 1972), in the more northern DSDP Sites 177 and 178, and in the Yakataga area (Bandy et al., 1969a) to provide an overall, if somewhat schematic view, of major oscillations in temperature-sensitive planktonic biofacies within the California Current system during the later Miocene through Pleistocene interval. The more northern sections depicted on Figure 4 are representative of events within the Alaskan Current gyre.

Planktonic foraminiferal faunas within the California Current today are typically composed of Globigerina bulloides, G. pachyderma (dextral), G. quinqueloba, with lesser percentages of Globigerinita glutinata, and G. uvula. This typical fauna is termed the temperate biofacies on Figure 4. Admixtures of warmer water species appear with increasing frequency at southern latitudes, including Globorotalia inflata and Globoquadrina dutertrei. These latter two species increase dramatically within the mixing zone (subtropical biofacies) at the distal end of the California Current (Ingle, 1967) and allow the migration of this oceanic front to be traced north and south of its present latitude. The well-known coiling preferences of Globigerina pachyderma (Ericson, 1959; Bandy, 1960) are used to delineate major changes of surface temperature as far back in time as the late Miocene/middle Miocene boundary (see Chapter 14, this volume), with exclusively sinistral populations interpreted as representing minimum surface temperatures of 5°C. These same biofacies and related earlier forms such as Globigerina angustiumbilicata comprise the majority of species found in Miocene through Pleistocene sediments along the Pacific margin, indicating cool water has been swept south along this border in a manner similar to the present throughout the Neogene and in fact as long ago as the Cretaceous (Sliter, 1972). Indeed the foraminiferal biofacies changes noted at Site 173 present a particularly clear record of the oceanographic events at latitude 40°N, and the paleotemperature curve presented on Figure 3 can be used as a guide to inferred surface temperatures implied by the biofacies patterns depicted on Figure 4.

![](_page_7_Figure_1.jpeg)

Figure 4. Schematic representation of major oscillations of temperature-sensitive planktonic foraminiferal biofacies within the California Current system and re lated Alaskan Current gyre during the later Miocene through Pleistocene interval. Information on major planktonic biofacies in various surface sections is given by Ingle (1967, 1968, 1971, 1972), Ingle and Bandy (1970), and Bandy et al. (1969a). Information on planktonic biofacies variation at DSDP Sites 173, 177, and 178 is given by Ingle (Chapter 14, this volume). Sinistral-coiling populations of Globigerina Pachyderma are interpreted as evidence of surface tempera tures less than 10°C whereas dextral populations are interpreted as representing temperatures greater than 15°C. The subtropical biofacies corresponds to the 20°C isotherm.

As noted previously, the 11,000 to 12,000 year post-glacial rise in surface temperature correlated with the Holocene/Pleistocene boundary is thought to correlate with an interval in Core 1 containing a dextrally coiling population of Globigerina pachyderma. Silicoflagellates (Bukry, Chapter 19, this volume) and diatoms (Schrader, Chapter 17, this volume) also give evidence on increased surface temperatures during this interval. The glacial portion of the Pleistocene interval is characterized by a sustained interval of subarctic temperature at least as far south as latitude 30°N and probably to latitude 20°N, allowing this biofacies to move up into the Gulf of California to be trapped by the northward readjustment of isotherms in the Holocene. Correlations at Site 173 (Figure 3) indicate this interval was initiated at about 0.7 to 0.9 m.y.

The Pleistocene-Pliocene boundary interval is characterized by a sharp rise in surface temperatures and the migration of a subtropical biofacies as far north as latitude  $40^{\circ}$ N at Site 173. This same warm event is also sensed within Pleistocene marine sediments of southern California (Ingle, 1967). The Pliocene interval is marked by a series of oscillations of warm-temperate and subtropical biofacies north and south along the Pacific margin, with a pronounced subtropical interval during the early Pliocene, which saw the adjustment of the subtropical mixing zone to perhaps as far north as latitude  $40^{\circ}$ N (Ingle, 1968; Chapter 14, this volume). This event corresponds to portions of the Repettian benthonic stage and zone N. 19 as detailed at Site 173 (Figure 3).

The Pliocene-Miocene boundary at Site 173 is marked by an abrupt decrease in surface temperature to subarctic temperatures, followed by an abrupt increase to subtropical conditions, again bringing a subtropical biofacies to 40°N latitude as also expressed by diatoms, silicoflagellates, and calcareous nannofossils. This same event can be correlated within Delmontian age sediments in southern California (Ingle, 1967) and provides an easily recognized horizon along the Pacific margin.

The brief subtropical event in the latest Miocene is preceded by a lengthy interval of subarctic surface temperature during which the  $10^{\circ}$  isotherm penetrated south to  $28^{\circ}$ N latitude as detected within the Mohole cores (Parker, 1964; Bandy and Ingle, 1970) and surface sections of Mohnian age (Ingle, 1967). The initiation of this cool event is marked in the Gulf of Alaska in the Yakataga section by a change from dextral- to sinistral-coiling populations of *Globigerina pachyderma* (Bandy et al., 1969a), as well as at latitude  $28^{\circ}$ N (Figure 4), and represents a response to a major period of refrigeration in the later Miocene.

More temperate conditions apparently prevailed throughout most of the middle Miocene when populations dominated by *Globigerina bulloides* and variants prevailed (Figure 3), although silicoflagettes suggest surface temperatures oscillated between 3° and 8°C (Bukry, Chapter 19, this volume). This analysis is in contrast to planktonic foraminiferal biofacies within Luisian Stage sediments at Newport Bay and Bonita Canyon in southern California (Figure 2), where subtropical species occur occasionally (Lipps, 1964; Ingle, 1972).

#### NORTHEASTERN PACIFIC NEOGENE BIOSTRATIGRAPHY

Planktonic faunas within the middle Miocene through late Oligocene are typified by high abundances of *Globigerina angustiumbilicata*, *G. praebulloides*, and *Globigerinita glutinata*, all indicating cool- to warm-temperate surface conditions. This analysis is again corroborated by silicoflagellates (Bukry, this volume) which suggest a slight increase in surface temperatures at the base of the Miocene.

### ORIGIN AND CORRELATION OF MIOCENE DIATOMACEOUS SEDIMENTS ALONG THE PACIFIC MARGIN

One of the more intriguing aspects of the sedimentary column penetrated at Site 173 is the occurrence of a significant thickness of diatomaceous-rich muds and diatomites characterizing a lengthy interval spanning a portion of the early Miocene to the latest Miocene (Figure 3). These sediments represent a telescoped interval of deposition essentially identical in age and lithology to the Miocene Monterey Shale of California and other similar deposits common around the Pacific margin (Figure 5). Moreover, the diatomaceous interval is overlain by a relatively thick wedge of terrigenous clastics as duplicated in thicker fashion in other areas of the marginal North Pacific (Figure 5). Indeed, the pattern of events seen in all of the sections depicted on Figure 5 is strikingly similar: (a) a late Oligocene-early Miocene interval of volcanics, continental, or shallow marine debris gives way to (b) increasingly rapid subsidence and the appearance of middle Miocene-upper Miocene diatomaceous sediments with a finale consisting of (c) the appearance of thick, rapidly deposited Pliocene and Pleistocene terrigenous clastics capping the predominantly diatomaceous interval, with subsequent filling of the basin or deposition-on-slope.

Speculations regarding the origin of these deposits have been made by a number of individuals including Bramlette (1946) and most recently (Orr, 1972). Brameltte (1946) recognized the need for anerobic conditions for the preservation of laminated diatomites but appealed to conicident volcanism as a mechanism triggering prolific planktonic blooms. However, Calvert (1964, 1966) has clearly demonstrated that an adequate supply of silica and nutrients is available within the surface waters present in areas of prolific diatom productivity.

Given the apparently vigorous nature of oceanographic processes in the North Pacific during the early Miocene through Recent interval (Figures 3 and 4), it seems reasonable to assume upwelling and resultant availability of nutrients have continually maintained high diatom productivity along the margin of the North Pacific. Assuming a constant envelope of maximum and minimum rates of diatom productivity (tuned to climatic extremes) in this region during the early Miocene through Pleistocene interval suggests that a major tectonic and/or sedimentologic event must have occured simultaneously over a wide area at about the Miocene-Pliocene boundary, diluting the steady-state rain of biogenous sediment with a major influx of terrigenous material. It is now well established that an episode of major tectonic activity commenced around the North Pacific margin during the late Oligocene through mid-Miocene interval manifested by the formation of numerous Neogene marine basins along the Pacific Coast

![](_page_9_Figure_1.jpeg)

Figures 5. Correlation of important Neogene marine sections along the Pacific Coast of North America containing well-developed intervals of diatomaceous-rich sediments including DSSP Sites 173 and 178. Similar sections in marginal seas including the Gulf of California and the Sea of Japan provide additional evidence of the widespread nature of this event in the North Pacific region. Estimated paleobathymetry of each section is based on detailed benthonic foraminiferal biofacies analysis or information gained from the literature on critical benthonic species present. References used in compiling this figure in addition to information in this volume (Chapter 14) include Allison (1964), Smith (1970), Ingle (1967, 1971, 1972, 1973), Asano et al. (1969), and Tiffin et al. (1972). Note that absolute thicknesses are not given on this diagram.

of North America (Reed, 1933), the formation of the Sea of Japan (Minato, et al., 1965), as well as the probable formation of a proto-Gulf of California. In all likelihood this event represents a response to an adjustment of lithospheric plates within this region, creating a series of reservoirs via faulting and subsidence of the margin during the early Miocene and allowing deposition of biogenous material in essentially empty basins and slopes some distance from the newly adjusted middle Miocene strand line. The seaward advance of relatively rapidly deposited wedges of terrigenous sediments from the margins of the continent, begun in late Oligocene-early Miocene time, apparently extended across these basins and slopes to cap the underlying diatomaceous deposits at about 5 m.y., or the Miocene-Pliocene boundary, and continually dilute diatom frustules deposited after this event. The rapid influx of terrigenous material near the Miocene-Pliocene boundary may also have been aided by climatic deterioration as the Pliocene progressed. Thus, this particular view of the accumulation and preservation of these relatively unique deposits also appeals to major tectonic events as the necessary ingredient to insure their preservation as also recently suggested by Orr (1972).

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