Cenozoic Benthic Foraminifera
Case Histories of Paleoceanographic
and Sea-Level Changes

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"The reports of my death have been greatly exaggerated." (Twain, 1897)

INTRODUCTION

Since the inception of their use in commercial micropaleontology, benthic foraminifera have proven to be eminently useful in the solution of geological problems. The utilitarian credentials of benthic foraminifera in estimating paleodepths from marsh through neritic environments with a reasonable degree of accuracy and to indicate approximate ages (viz. subdivision of series/epochs) have been established in both commercial and academic applications. Benthic foraminifera are generally more resistant to dissolution than planktonic foraminifera, and have wide distributions; many taxa have restricted stratigraphic ranges, making them suitable for correlation and paleoenvironmental studies. Yet, three problems have tended to limit the utility of benthic foraminifera: 1) there is a lack of uniformity in taxonomy (Boltovskoy, 1980; Douglas & Woodruff, 1982); 2) attempts to erect zonal schemes using benthic foraminifera have resulted in boundaries which are later proven to be diachronous relative to planktonic zonations (e.g. the California provincial stages, Poore, 1976); and 3) attempts to interpret paleodepths from deep-sea benthic foraminifera have produced widely-varying results. One could perhaps conclude, as Boltovskoy (1965a) did over a decade ago, that these problems indicate "...the near future of this science is rather bleak."

Such obstacles can be overcome by: 1) revising taxonomic and biostratigraphic assignments; and 2) evaluating paleoenvironmental interpretations of benthic foraminifera in view of other paleoenvironmental indicators (isotopic, seismic, lithologic, independent estimates of paleodepth, etc.), for interpretations of faunal changes are often equivocal without such corroborative data. Two examples illustrate the success of this procedure. The paleobathymetric interpretations of Cretaceous-Early Tertiary flysch-type agglutinated benthic foraminiferal faunas have ranged from paralic to abyssal (Gradstein & Berggren, 1981), and their biostratigraphic and paleoecologic utility was doubted.
Although largely depth-independent, flysch-type foraminifera have been shown to be predominantly deep-sea forms (bathyal-abyssal; Gradstein & Berggren, 1981; Gradstein et al., 1981). Despite diachrony of certain taxa, flysch-type foraminifera have been correlated to planktonic biostratigraphic zonations, and have proven useful in zonations in the Canadian margin, North Sea, and deep sea. Comparisons of distribution of this group with other paleoenvironmental indicators (see below) have shown that they can be useful in indicating restricted circulation (Gradstein & Berggren, 1981; Miller et al., 1982).

The paleobathymetric and stratigraphic utility of deep-sea (bathyal-abyssal) calcareous benthic foraminifera similarly have been doubted. Bolotovsky (1980) found that deep-sea "...benthonic foraminifera are poor stratigraphic index fossils...". In addition, it has been shown that the distributions of some Recent and Pleistocene deep-sea foraminifera are not consistently depth stratified. The abundances of deep-sea benthic foraminifera are correlated with water masses (T, S, O_2) and properties that covary with water masses independent of depth (see discussion below). Nevertheless, due to the regional depth stratification of water masses, deep-sea benthic foraminiferal biofacies are often regionally depth consistent (e.g. Streeter & Lavery, 1982; Miller & Lohmann, 1982). Ranges of deep-sea benthic foraminifera can be calibrated to planktonic biostratigraphic zonations and independent estimates of paleodepth obtained from subsidence models of oceanic crust. Once so calibrated, deep-sea benthic foraminifera can be useful in age and paleobathymetric control (Tjalsma & Lohmann, 1982).

I will outline several examples where Cenozoic benthic foraminifera have figured in the interpretation of paleoceanographic and sea-level changes. Both shallow- (neritic) and deep-water (bathyal-abyssal) applications will be presented, although I will stress the relationships among deep-sea benthic foraminifera, other indicators of paleoenvironment, and abyssal circulation changes. Ecologic, paleoecologic, and biogeographical controls on benthic foraminiferal distribution are dealt with elsewhere in this volume. Historical background, sampling methods, preservation, and studies of larger foraminifera are omitted; for these the reader is referred to other reviews (Bolotovsky & Wright, 1976; Douglas, 1979; Douglas & Woodruff, 1982; Adams, 1967).

MIDWAY FAUNA AND THE SUBSIDENCE HISTORY OF ROCKALL PLATEAU

Berggren and Aubert (1975) used the term "Midway fauna" for Paleocene middle-outer shelf (~ 50-200m water depth) smaller benthic foraminifera, originally described from Gulf Coast outcrops (Plummer, 1927; Cushman, 1951; Kellough, 1959, 1965). They differentiated this fauna from a shallow water (< 50m water depth), inner-middle shelf assemblage dominated by Oibicides spp., nonionids, discorbids, Elphidium spp., and larger benthic foraminifera (= Tethyan Carbonate Fauna; further subdivided and used by Berggren, 1974a)(Fig. 1). The Midway fauna is a rich, diverse fauna characterized by nodosariids, lenticulinids, dentalinids, marginulinids, vaginulinids, polymorphinids, Gavelinella,
Fig. 1. Simplified scheme of North Atlantic Paleogene benthic foraminiferal assemblages. TCF = Tethyan Carbonate Fauna. (Modified after Berggren & Schmitz, in press). Data from Tjalsma & Lohmann (1982), Miller, (in press), and Miller et al. (in press). The upper depth limits of the deep-sea faunas are poorly constrained; for example, the Barbados Oligocene fauna may be strictly abyssal.

and Cibicidoids, found primarily in clastic sediments. These faunas are distributed widely in the Gulf Coast (nominate Midway Fm., Kincaid Fm., Salt Mountain Fm., Wills Point Fm.); Atlantic Coastal Plain, and other Circum-Atlantic and Tethyan localities including Nupssuaq, West Greenland (60° paleolatitude, reconstruction of Scioter et al. (1977) (Fig. 2). In addition, they have been recorded from California, Argentina, New Zealand, Australia, Siberia, Turkmenia, Crimes, Caucasus, Ukraine, and Saudi Arabia (Fig. 2 in Berggren & Aubert, 1975).

Paleobathymetric data derived from the Midway fauna have proven useful in subsidence-history interpretations of Rockall Plateau. This foundered microcontinent lies to the west of the Irish continental shelf (Fig. 2). Berggren (1974b) and Berggren and Schmitz (in press) noted the occurrence of Midway faunas in the early Eocene of the Rockall Plateau (Sites 117, 403, 404; also see Murray, 1979). These neritic faunas are succeeded by deep-water assemblages: 1) a middle Eocene Nuttallides trigumeyi assemblage (Site 403); 2) an Oligocene Cibicidoides-Planulina assemblage (Site 117); and 3) an Oligocene Bulimina marginata-Eggerella bradyi assemblage (Site 404). The punctuated nature of the stratigraphic record recovered in the Rockall region (Miller & Tucholke, in press), prevents firm dating of the timing of these
successions. However, these data show that the subsidence of Rockall Plateau began in the late Paleocene–early Eocene and continued throughout the Eocene into the Oligocene (Berggren, 1974b; Berggren and Aubert, in press; Murray, 1979). There are significant differences in the paleobathymetric interpretations of various studies (cf. Murray, 1979 and Roberts et al., 1979 with Berggren, 1974b, Berggren & Aubert, 1976, and Berggren & Schnitker, in press). Nevertheless, these studies are in agreement that Rockall Plateau underwent differential subsidence as indicated by: 1) early Eocene deep-water benthic foraminifera noted in Sites 405 and 406 (S transform margin) suggest that this portion of the plateau subsided earlier (Murray, 1979); 2) a comparison of Sites 403 and 404 (SW margin) with Site 117 (Hatton–Rockall Basin) shows that although these sites contain the Midway fauna in the early Eocene, they are bathymetrically offset by over 1.5 km today. Thus, benthic foraminifera indicated the importance of post-rifting (Eocene–Oligocene) differential subsidence in the morphologic development of Rockall Plateau (Roberts et al., 1979).

**VELASCO FAUNA, CRETACEOUS/TERTIARY BOUNDARY, AND PALEOCENE BENTHIC CRISIS**

Berggren and Aubert (1975) applied the term "Velasco-type" fauna for deep-water Paleocene benthic foraminifera originally described from the Velasco Shale (Cushman, 1926) and the Lizard Springs Formation (Cushman & Renz, 1946) (Fig. 1). Schnitker (1979a) noted the Velasco assemblage in the deep Bay of Biscay (Site 400A and 401), while Tjalsma and Lohmann
(1982) made a detailed taxonomic comparison of Paleocene deep-water benthic foraminifera from Atlantic/Caribbean DSDP sites and the Velasco and Lizard Springs Formations. However, due to lack of material from the upper bathyal realm, the upper depth limit of the Velasco fauna (and the corresponding lower depth limit of the Midway fauna) remains poorly constrained (Fig. 1). Tjalsma and Lohmann (1982) updated the taxonomy, and reported detailed distribution data (both quantitative and qualitative) of deep-water Paleocene benthic foraminifera. Despite terming all deep-water Paleocene benthic foraminifera "Velasco-fauna," it should be noted that the Velasco-Lizard Springs samples are richer in agglutinated benthic foraminifera than the DSDP material examined by Tjalsma and Lohmann (1982). Still, both the Velasco-Lizard Springs and deep-water DSDP samples are dominated by Gavellinella (mostly G. beccariformis) and Nuttallides (mostly N. truempyi). This G. beccariformis-N. truempyi assemblage is typical of Velasco-type deep-water Paleocene assemblages (Fig.1).

Comparison of the Velasco Paleocene benthic foraminiferal faunas with Cretaceous benthic faunas shows that, unlike planktonic organisms, there was no crisis in benthic foraminifera at the end of the Cretaceous (= K/T boundary). In Trinidad, most Cretaceous species (~ 82%o) range into the Paleocene Lizard Springs Formation (Beckmann, 1960). Cushman and Renz (1946) also noted the similarity of the lower Lizard Springs fauna with the underlying Cretaceous fauna, although they did not recognize the Tertiary age of the former. Douglas and Woodruff (1982) observed that Maestrichtian and early Paleocene deep-water assemblages are nearly identical on the generic level, although some changes did occur at the species level. All of the Paleocene deep-water species described by Tjalsma and Lohmann (1982) were recorded from Cretaceous strata. The flysch-type agglutinated benthic foraminiferal assemblages found in deep-sea sediments show little change between the Cretaceous and the Tertiary (see Miller et al., 1982 for full references). However, Cushman and Renz (1946) and Webb (1973) suggested that only ~ 50%o of deep-sea benthic foraminiferal species survived the Cretaceous. Although some debate may exist as to the extent of the changes associated with the K/T boundary, catastrophic mass extinctions did not occur in deep-sea benthic foraminifera. As a result, Paleocene deep-water benthic foraminifera are predominantly relict Cretaceous taxa (Tjalsma & Lohmann, 1982).

A similar lack of numerous extinctions apparently occurs in shallow-water benthic foraminifera. Although Plummer (1927) noted that the Midway Formation fauna was distinct from the underlying Navarro Formation (Maestrichtian) fauna on the specific level, the assemblages are similar on the generic level. Olsson (1960) observed the Cretaceous benthic foraminifera assemblages in New Jersey to be similar to early Paleocene fauna on the familial and generic levels. He reported that many Cretaceous species range into the Paleocene (Cibicides marylandicus, Pulsipherina prima, Parrella expansa, Bulimina quadrata, Tappanina selmensis, among others), although many other species are restricted to the Cretaceous or Paleocene sections. It is not clear, therefore, exactly what impact the K/T boundary event had on shallow-water benthic foraminifera. It is clear that the extinctions associated with this group were much less severe than the widespread extinctions suffered by
planktonic organisms. A detailed comparison of Maestrichtian and early Paleocene assemblages is needed to document the extent to which shallow-water benthic foraminifera were affected by the K/T event.

In general, stability characterizes Paleocene deep-sea assemblages studied so far. Most of the faunal variation in the Paleocene is attributable to the gradual bathymetric restriction of the shallower G. beccariiformis assemblage and the bathymetric expansion of the N. truempyi assemblage (Fig. 3). Such depth-migrations, both expansions and restrictions, are prominent among the faunal changes noted in deep-sea benthic foraminifera studies to date, not only for the Paleocene, but for the entire Cenozoic. There is some tendency for Paleocene assemblages to be latitudinally differentiated. Tjalsma and Lohmann (1982) noted that a Nuttallides crassaformis association is more important in tropical sites. However, throughout the Cenozoic, deep-sea benthic foraminifera remain generally cosmopolitan in distribution (Douglas & Woodruff, 1982).

A major benthic faunal crisis occurs in the latest Paleocene (Zone P6a) (Fig. 3). Following the gradual depth-restriction of the G. beccariiformis assemblage, rapid massive extinctions occur at the generic and specific levels (Tjalsma & Lohmann, 1982). Most of the extinctions occur in the shallower G. beccariiformis assemblage, which contained predominately Cretaceous relict species (Tjalsma & Lohmann, 1982). Schneiter (1979a) also suggested that the extinction event occurred primarily at shallow sites such as Site 401 (2.0–2.5 km paleodepth), and that the deepest (N. truempyi) assemblage was characterized more by appearances than extinctions.

![Fig. 3. Distribution of Paleocene-Eocene deep-water benthic foraminifera (after Tjalsma & Lohmann, 1982). The age-paleodepth diagram was obtained by "backtracking" DSDP sites along an empirical age-versus-subsalience curve (Sclater et al., 1971; Parsons & Sclater, 1977) in the manner of Berger and Winterer (1974) and Sclater et al. (1977); this allows an independent estimate of paleobathymetry with geophysical constraints. For other examples of "backtracking" benthic foraminifera see Tjalsma and Lohmann (1982), Douglas and Woodruff (1982), Miller (in press), Miller et al. (in press).]
The Paleocene benthic faunal event was catastrophic, and it resulted in low diversity early Eocene assemblages (Tjalma & Lohmann, 1982). This event constitutes the most dramatic of all Cenozoic deep-sea benthic foraminiferal changes noted to date, yet remains the greatest enigma in Cenozoic deep-sea benthic foraminiferal studies. Although major paleoceanographic changes occurred at the K/T and Eocene/Oligocene boundaries, and various scenarios have been erected to explain these changes (see summaries Haq, 1981; Alvarez et al., 1982; Miller et al., in press), no major paleoceanographic changes have been documented in association with the Paleocene faunal event. Without such corroborative data, the meaning of the event will remain obscure.

EUSTATIC SEA-LEVEL EFFECTS: AN EARLY EOCENE EXAMPLE

Estimates of Cenozoic eustatic changes in sea level based upon analyses of seismic stratigraphic sequences have been made by P.R. Vail and colleagues at Exxon Production Research (Vail et al., 1977; Vail & Hardenbol, 1979; Vail & Mitchum, 1980; Hardenbol et al., 1981). They noted several major lowstands of sea level in the Cenozoic. However, the relationship of eustatic sea level and the sense of relative sea-level change obtained from benthic foraminifera may differ. Depending upon the rates of subsidence and sediment input, biofacies may be deepening, shallowing, or compensating during a eustatic sea-level rise. A regression indicated by benthic foraminifera (such as the basinward migration of shallow-water biofacies), in fact, may occur during rising sea level (Vail et al., 1977). Still, paleobathymetric changes often follow the sense of sea-level fall, and paleodepths derived from benthic foraminifera can be used in evaluating eustatic sea-level changes if properly corrected for sediment compaction, loading, and tectonic subsidence (e.g. Van Hinte, 1978; Watts & Steckler, 1979; Hardenbol et al., 1981).

Vail et al. (1977) noted a major early Eocene (49.5 Ma) sea-level lowstand. Benthic foraminiferal biofacies show 3 major regressions that correlate with this lowstand (Fig. 4). 1) In the California Coast Ranges, Berggren and Aubert (in press) noted that a marked shallowing occurred in the early Eocene (late Zone P8-early Zone P9). They based this upon a change from a deep-sea benthic foraminiferal assemblage (including *Nuttallides truempyi*, estimated paleodepth ~600m) to a neritic (<200m) *Florilus-Uvigerina-Eponides-Cyclammina-Trochammina* assemblage. 2) In Libya, a change from an upper bathyal *Nuttallides truempyi-Bulimina trilobatensis-B. bradburyi* assemblage to an outer neritic *Bulimina-Uvigerina (B. jacksonensis, B. gardnerae, B. cocoensis)* assemblage and to an inner neritic *Nummulites* assemblage occurs within Zone P9. Barr and Berggren (1982) interpreted this as reflecting a rapid (<1 m.y.) regression of ~400m. 3) In the New Jersey Coastal Plain, Charletta (1980) observed that a marked shallowing occurred near the early/middle Eocene boundary. This shallowing was indicated by local terminations of deep-water benthic foraminifera (including *N. truempyi*), their replacement by shallow water benthic foraminifera, and decreases in abundance of planktonic foraminifera. These three studies vary as to the exact timing of the change in sea level, but agree that a regression occurred in each area near the end of the early Eocene (within Zone P9).
Fig. 4. Comparison of benthic foraminiferal estimates of early Eocene water-depth changes. (Modified after Vail & Hardenbol, 1979).

There are differences as to the magnitude of the regression (Fig. 4) (California and Libya ~ 400m; New Jersey, updip wells, ~ 150m; New Jersey downdip wells 300-400m). Vail et al. (1977) estimated that the early Eocene eustatic sea-level drop was ~ 150-200m (from ~ 250m to 100m above present sea level), although such large estimates are controversial (Watts & Steckler, 1979). The benthic foraminiferal data come from tectonically-varied regimes, and are not corrected for sediment input, crustal response to loading and unloading, and local tectonic changes. It is remarkable, given all of these uncertainties, that the foraminiferal data indicate 3 rapid (Zone P9) regressions that approximately correlate with this assumed eustatic lowering.

FLYSCH-TYPE BENTHIC FORAMINIFERA AND BASIN EVOLUTION

Agglutinated (arenaceous) benthic foraminiferal assemblages (= flysch-type assemblages of Gradstein and Berggren, 1981; = Rhabdammina faunas of Brouwer, 1965) have been noted in various flysch basins. These assemblages consist of predominantly (or exclusively) agglutinated benthic foraminifera. Gradstein and Berggren (1981) described taxonomically similar assemblages from Maestrichtian-Eocene mudstones of the Labrador Shelf/northeast Newfoundland Shelf and North Sea Paleocene-Eocene strata. Miller et al. (1982) differentiated between two types of predominantly agglutinated benthic foraminifera found in DSDP sites. Type A assemblages resemble flysch-type faunas, occur in bathyal-abyssal Late Cretaceous to Early Tertiary sediments, are composed of larger (> 150 µm), coarser-grained tests, and are dominated by "simple" forms. Type-B assemblages are taxonomically distinct from flysch-type faunas, occur in Cretaceous zeolitic and variegated abyssal clays, are composed of smaller, finer-grained tests, and are dominated by Labrospira, Plectocurevoides, and Haplophragmium (see Krashenninikov, 1973, 1974 for illustrations of type-B faunas).
Fig. 5. Location of wells containing flysch-type assemblages from the Canadian margin and North Sea. Structural contours drawn on the base of the Tertiary. (After Gradstein & Berggren, 1981).

Flysch-type agglutinated foraminifera in the Canadian margin and North Sea are associated with high sedimentation rates; highly-diverse flysch-type assemblages are found in organic-rich shales in wells at the depositional center of the basins (Fig. 5). These wells have calcareous benthic foraminifera indicative of deeper water whereas updip wells containing a less diverse assemblage (not flysch-type), are dominated by Bathysiphon and Trochammina. Paleoenvironmental factors controlling the distribution of agglutinated assemblages in the Canadian margin and North Sea were related to rapid deposition of organic-rich, fine-grained clastics (see discussion in Gradstein & Berggren, 1981). Here, differential subsidence resulted in restricted basins which coincided with deltaic outbuilding into the deep basin and the development of agglutinated foraminiferal assemblages. Near the end of the Eocene, infilling of the basins resulted in the demise of the agglutinated assemblages.

Predominantly agglutinated foraminiferal assemblages have been accounted for by water depth, carbonate availability, substrate characteristics, and certain hydrographic properties. The extensive paleobathymetric range of type-A (= flysch-type) assemblages suggests that they are depth-independent. Miller et al. (1982) noted that in the deep southern Labrador Sea (Site 112), type-A assemblages are found in carbonate sediments. Here, the agglutinated foraminiferal assemblages are replaced by calcareous benthic foraminifera near the end of the Eocene. Lithologic characteristics remain constant across this change, but the change correlates with a change in abyssal circulation (inferred from the seismic stratigraphic record; Miller and Tucholke, in press) and hydrographic properties (inferred from the isotopic record, Miller
and Curry, 1982) which occurred near the Eocene/Oligocene boundary in this region. Thus, although low carbonate content and high organic content may be associated with type-A assemblages, these properties are not necessary for development of flysch-type faunas. Rather, certain hydrographic properties (viz. low oxygen, low pH, high CO₂, and more corrosive waters) associated with restricted circulation are critical to the development of the predominantly agglutinated assemblages. Similar conditions may develop in reducing substrates associated with high organic matter and poor circulation. Assemblages of predominantly agglutinated foraminifera are probably favored in such substrates and/or in areas with the given hydrographic properties, and therefore may be used as generally indicative of restricted circulation.

LATE PALEOGENE BENTHIC FORAMINIFERA AND THE DEVELOPMENT OF ABYSSAL CIRCULATION

Various lines of evidence (seismic, lithostratigraphic, isotopic) indicate that a major change in abyssal circulation occurred near the end of the Eocene. Early studies (Savin et al., 1975; Shackleton & Kennett, 1975; Kennett & Shackleton, 1976) showed that a major δ¹⁸O increase in planktonic and benthic foraminifera occurred near the Eocene/Oligocene boundary in the Southern and Pacific Oceans. This was interpreted to represent a cooling of surface waters and the initial formation of cold bottom water of southern (Antarctic) origin. Some of this enrichment may represent the buildup of the Antarctic ice cap (Matthews & Poore, 1980). More recent studies have shown that the bulk of the ¹⁸O enrichment in benthic foraminifera occurred in a < 0.5 m.y. interval just above the Eocene/Oligocene boundary as defined by the extinction of Hantkenina and Globoquadrina cerroazulensis lineage in the Southern, Pacific, and North Atlantic Oceans (Keigwin, 1980; Miller & Curry, 1982; Miller et al., in press). Evidence of widespread unconformities in the Southern and Pacific Ocean (Moore et al., 1978) supports the idea that a major change in abyssal circulation occurred at this time. Based upon studies of seismic stratigraphy and sediment distribution, Miller and Tucholke (in press) noted that major abyssal circulation changes, from a sluggish Eocene ocean to a more vigorously circulating Oligocene ocean, occurred in the North Atlantic. They suggested that the North Atlantic had a northern bottom water source from the Arctic and/or Norwegian-Greenland Sea. Thus, climatic cooling in the late Eocene to early Oligocene (ref. in Miller & Tucholke, in press) resulted in the formation of cold bottom water of northern origin and southern origin.

As some distributions of modern benthic foraminifera correlate with modern water-mass distributions (see below), benthic foraminifera may be expected to have responded to hydrographic changes associated with the δ¹⁸O increase. Early workers noted that Eocene deep-sea benthic foraminiferal assemblages were distinct from Oligocene assemblages (Douglas, 1973; Berggren, 1972a). Because the late Eocene to early Oligocene interval is associated with numerous hiatuses (Moore et al., 1978), the timing of this faunal change remained debatable. Kennett and Shackleton (1975) and Schnitker (1979a) suggested that a crisis in benthic
foraminifera occurred near the Eocene/Oligocene boundary. However, Corliss (1979a) observed no major benthic foraminiferal changes associated with the boundary in Site 277 in the Southern Ocean; Corliss (1981) evaluated previously published results and concluded that a series of gradual changes in benthic foraminifera occurred between the middle Eocene and the early Oligocene in response to gradual climatic cooling. Tjalsma (1982 and personal communication) and Tjalsma and Lohmann (1982) also noted no change associated with the Eocene/Oligocene boundary; they reported that a series of sequential changes in benthic foraminifera occurred during the middle Eocene to early Oligocene. The most dramatic change seen in their Caribbean/South Atlantic sites is the decrease in abundance of Nuttallides truempyi near the middle/late Eocene boundary (Fig. 3).

The evolution of the late Eocene-Oligocene fauna occurred as a series of events over several m.y. Miller et al. (in press) noted that the decrease in abundance of N. truempyi was apparently a synchronous event in the Atlantic Ocean that occurred just above the middle/late Eocene boundary (Fig. 6) (~38.5-40 Ma). This pre-dates (~2 m.y.) the major 18O enrichment and change in abyssal circulation regime inferred from the seismic stratigraphic record (Fig. 5). In Site 549 in the Bay of Biscay (Fig. 6), the Bulimina spp. assemblage that succeeds dominant N. truempyi is itself replaced by an assemblage dominated by stratigraphically long-ranging and bathymetrically wide-ranging taxa (e.g. Globocassidulina subglobosa, Gyroidinoïdes spp., Cibicidoides ungerianus, Oridorsalis umbonatus) just below the Eocene/Oligocene boundary at approximately 37.5 Ma (Fig. 6). The record at the deepest sites (Sites 119 and 40A; both paleodepths > 3km) shows the greatest changes, for here N. truempyi is associated with many endemic deep-water taxa (Abyssammina, Clinapertina, Aragonia, Alabamina dissonata, among
Fig. 7. Benthic foraminifera assemblage changes during the Late Paleogene, Site 549, Goban Spur. Interval estimates reflect 80% confidence limits. Principal component II represents the dichotomy between *Nuttallides truempyi*-buliminid assemblage (negative loadings) and *Globocassidulina subglobosa*–*Cibicidoides ungerianus*–*Cyclothyriaoides* assemblage (positive loadings) (After Miller et al., in press).

others) that decrease in abundance and become extinct prior to the Oligocene. Unfortunately, the timing of the abundance changes and extinctions in these deepest sites cannot be established due to poor recovery of upper Eocene sections there (Miller, in press). However, in the intermediate depths (Site 549; ~2–2.5km paleodepth), a series of first and last appearances occurred in the late Eocene to earliest Oligocene (Miller et al., in press). Thus, like the K/T boundary, the Eocene/Oligocene boundary was not catastrophic for benthic foraminifera.

The Oligocene abyssal fauna is dominated by stratigraphically long-ranging and bathymetrically wide-ranging taxa (Miller, in press). These taxa, which are interpreted to be tolerant of paleoenvironmental changes, range through Late Paleogene oceanographic changes. Many species that appeared in the Eocene and Oligocene range into the Recent (Boltovskoy, 1980; Douglas & Woodruff, 1982). Oligocene deep-sea faunas were generically similar to modern faunas, and several species important in the modern deep ocean made their appearance in the late Eocene to early Oligocene (e.g. *Nuttallides umbonifera*, *Epistominella exigua*, *Eggerrella bradyi*, among others). Oligocene deep-sea faunas mark
change from Paleocene (Cretaceous relict) and Eocene taxa (e.g. N. truenøyi, Alabamina dissonata, Aragonia spp.) toward the development of modern assemblages. This led Boltovskoy (1980) to claim that modern bathyal assemblages developed no later than the Oligocene. However, many important modern taxa did not make their appearance until the Miocene (see below).

One obstacle to determining Oligocene faunal and paleoceanographic changes is that this series is poorly represented in the deep-sea stratigraphic record (Moore et al., 1978; Miller & Tucholke, in press). The records that have been recovered, such as the benthic foraminiferal $\delta^{18}O$ record, show few changes (Shackleton & Kennett, 1975; Miller & Curry, 1982). However, Miller and Curry noted that $\delta^{13}C$ values reach a distinct minimum in the middle Oligocene of the Bay of Biscay, and that this minimum correlates with the acme of Nuttallides umbonifera (Fig. 7). Today, the abundance of $N$. umbonifera is positively correlated with increased corrosiveness of bottom water (Bremer & Lohmann, in press), while lower $\delta^{13}C$ values are often associated with older water masses that are more corrosive to carbonate (Kroopnick et al., 1972; Kroopnick, 1974, 1980). Large numbers of $N$. umbonifera and light $\delta^{13}C$ values in the middle Oligocene were interpreted as reflecting older, more corrosive bottom water (Miller & Curry, 1982; Miller, in press). This inferred increase in bottom water age correlates with a reduction in the intensity of bottom water flow in the North Atlantic inferred from the seismic stratigraphic record of the Rockall region (Miller & Tucholke, in press).

**DSDP SITE 119**

![Graph showing isotopic and faunal record](image)

Fig. 8. Oligocene isotopic and faunal record in the abyssal Bay of Biscay, DSDP Site 119 (Modified after Miller & Curry, 1982; Miller, in press).
Considerable debate exists as to the timing and interpretation of the development of the modern deep-sea assemblage. Berggren (1972) suggested that the modern deep-sea fauna (including Pluulina wuellerstorfi, Uvigerina peregrina, Pyrgo murrhyana) appeared in the middle Miocene - 15 Ma, while Schmitker (1979a) thought that the modern assemblage became established near the end of the middle Miocene. At the other end of the spectrum, Boltovskoy (1980) maintained that the modern fauna originated in the pre-Miocene. These discrepancies may result, in part, from the material studied (as a function of recovery, preservation, geographic location, paleobathymetry) and approach in analysis (viz. size-fraction examined, studying ranges versus abundances, R-mode versus Q-mode principal component, factor, or cluster analyses, plotting against time versus depth). The timing of the faunal change may be resolved, for Woodruff and Douglas (1981) and Douglas and Woodruff (1982) noted that major faunal changes occurred not only in the early middle Miocene (Zones N9-N11) but also in the late Miocene (Zones N16-N17). They stated that the middle Miocene change is due primarily to appearances and extinctions of species, while the late Miocene development is chiefly the result of changes in abundance. Thus, the latter event resulted in assemblages on the Ontong-Java Plateau that resembled Recent assemblages in composition and abundance, while the former resulted in extinctions of deep-water taxa that appeared in the Late Paleogene (Bulimina jarvisii, Buliminella grata, Hanawata cushioni, and Cassidulina havanaensis).

Fig. 9. Stratigraphic distribution of important species compared to bottom water δ18O changes, Site 289. 18O given in °/oo PDB. (After Douglas & Woodruff, 1982).

A major enrichment of 18O in benthic foraminifera occurs in the middle Miocene. This has generally been attributed to global changes in
the $^{18}O$ composition of seawater due to the buildup of continental ice on Antarctica (Savin et al., 1975; Shackleton & Kennett, 1975; Woodruff et al., 1981). (Ice is depleted in $^{18}O$ relative to seawater, thus ice buildup results in seawater enriched in $^{18}O$.) However, Matthews and Poore (1980) argued that, as in the Pleistocene, ice buildup should be reflected in enrichments of $^{18}O$ in both benthic and tropical planktonic foraminifera. This was not the case with the middle Miocene, for tropical planktonic foraminifera became depleted in $^{18}O$. Savin et al. (1975) and Savin (1977) interpreted this as a tropical sea-surface warming. In any case, these authors agree that the middle Miocene $^{18}O$ enrichment (Fig. 8) represents some drop in bottom-water temperature. Douglas and Woodruff (1982) and Woodruff et al. (1981) suggested that this enrichment occurred in Zones N9-N11 (13-16.5 Ma), and that it approximately coincided with the major Miocene benthic foraminiferal changes.

Disagreements exist as to the interpretation of the middle Miocene faunal and isotopic events and the timing of the first influences of cold bottom water formed in the subpolar-polar basins of the North Atlantic and adjacent Norwegian-Greenland Sea or Arctic ocean. Schnitker (1979a, 1980a,b) and Blanc et al. (1980) ascribed the middle Miocene event in the North Atlantic to the first input of bottom water from such northern sources, while Schnitker (1979a, 1980a,b) related Eocene/Oligocene events in the North Atlantic to the initial formation of bottom water derived from the Southern Ocean. In contrast, the Eocene/Oligocene faunal and isotopic events in the North Atlantic have been attributed to the input of northern sources of bottom water (Miller et al., 1982; Miller & Curry, 1982; Miller, in press; Miller et al., in press).

It is clear from the data reviewed here that there are two major post-Paleocene events in the development of deep-sea foraminiferal assemblages and isotopic composition. Some of the ambiguity in interpretation of these events results because changes in deep-sea benthic foraminifera alone do not indicate bottom water sources. Although benthic foraminiferal isotopic data potentially can be used to indicate bottom water sources (especially $\delta^{13}C$ data, Curry & Lohmann, in press), insufficient isotopic data exist to resolve these ambiguities. The seismic stratigraphic record provides less ambiguous evidence for changes in abyssal circulation. Miller and Tucholke (in press) used seismic stratigraphic evidence to indicate that northern sources of vigorously circulating bottom water began in the latest Eocene to earliest Oligocene in the North Atlantic. This suggests that the middle Miocene faunal and isotopic events did not represent the first influx of northern sources of cold bottom water into the North Atlantic. Woodruff and Douglas (1981) attributed the middle Miocene faunal event to increased production of southern bottom water. It is reasonable to speculate that the middle Miocene event represents variations in production of both southern and northern sources of bottom water in response to climatic changes. However, there is not a simple relationship between bottom-water temperature change and faunal changes. The Eocene/Oligocene faunal changes begin prior to a temperature drop (Figs. 6,7), while the middle Miocene changes lag a temperature drop (Fig. 9). The benthic faunas may have responded to other paleoenvironmental changes associated with changing bottom waters (corrosiveness, $O_2$ content, etc.).
OLIGOCENE-PLIOCENE SHALLOW WATER BENTHIC FORAMINIFERAL AND SEA-LEVEL

Due to the paucity of Oligocene sediments and to difficulties in Oligocene biostratigraphy, the chronostratigraphic distribution of Oligocene shallow-water strata and thus the precise record of sea-level changes is equivocal. One or more major sea-level lowstands occurred in the late Eocene to middle Oligocene interval, but the timing of the event(s) is unclear. Vail et al. (1977) placed the lowest sea-level lowstand of the Cenozoic in the "middle" Oligocene (base of Zone P21A; 29 Ma). Based upon a widespread upper Eocene to lower Oligocene disconformity in the Middle Atlantic Coastal Plain of the U.S. (and a similar record in the Canadian margin, Gradstein & Srivastava, 1981), Olsson et al. (1980) suggested that this sea-level drop occurred prior to deposition of Zone P20, probably near the Eocene/Oligocene boundary. The sea-level curve of Vail et al. (1977), in general, corresponds well with the $\delta^{18}O$ record (Vail & Hardenbol, 1981), due to the linkage of sea-level, climate (lower sea level results in greater continentality and cooler climates), and ice volume (increasing ice volume lowers sea level). However, there is a striking lack of correspondence between their late Eocene to Oligocene sea-level curve and the $\delta^{18}O$ record (Miller, in press). No $^{18}O$ enrichment is associated with their middle Oligocene sea-level drop (Fig. 6; also see Shackleton & Kennett, 1975; Savin et al., 1975). The major late Eocene to early Oligocene $^{18}O$ enrichment (Fig. 6) correlates only with a minor sea-level drop (Vail & Mitchum, 1980). In fact, the most recent estimates of sea-level from the Exxon group (Baum et al., 1982) suggest that the late Eocene to early Oligocene was actually a highstand and that the numerous disconformities associated with this boundary are attributable to basin starvation. This serves to accentuate the differences between the $\delta^{18}O$ and sea-level records.

Examples of Oligocene inner, middle, and outer neritic faunas have been described from the Gulf Coast, Atlantic Coastal Plain, and Europe. Poag (1966) noted an inner neritic assemblage of Hansawaia-Diaporbita-Elphidium in the Gulf Coast (upper Oligocene Paynes Hammock Fm). A middle neritic late Oligocene assemblage was described from the U.S. middle Atlantic Coastal Plain: Buliminella elongata, B. elegansisima, Cassidulina crassa, Cibicides ornatus, C. lobatulus, Epistominella pontoni, Florilus pizzarenai, Hansawaia concentrica, Melonis affinis, Trifarina bradyi, and Uvigerina juncea (Olsson et al., 1980). A similar fauna has been noted in the late Oligocene of SW France (Butt, 1966) and the Stampian stage of the Paris Basin (Cushman, 1928a). In the NW European Rupelian stage (early Oligocene), Batjes (1958) and Ulleberg (1974) described faunas, indicative of outer neritic-upper bathyal depths (Berggren, 1977), with Turritilina alatica, Angulogerina tenuestrata, Melonis affinis, Gyroidina girardana, and Sphaeroidina bulloides (= Rupelian fauna, Fig. 1).

Neogene shallow-water benthic foraminifera are poorly represented in the U.S. Atlantic Coastal Plain, Gulf Coast outcrops, and Western Europe (Berggren, 1977). Many of the middle neritic fauna found in the late Oligocene of the U.S. Atlantic Coastal Plain are also found in the Miocene there (Cushman & Cahill, 1933; McLean, 1956). Gibson (1967) and
Schnitker (1970) discussed neritic benthic foraminifera from Miocene strata in North Carolina (Fungo River and Yorktown fms.). These assemblages are similar to the late Oligocene assemblages in the middle Atlantic Coastal Plain, with dominant Florilus pizzarensis, B. elegantissima, Cassidulina norcrossi, C. crassa, Uvigerina, Nonionella surfis, and Oribicides lobatus. Although Oligocene North American and European shallow-water faunas have close affinities, similarities between European and North American faunas decrease in the middle Miocene. Berggren and Phillips (1971) noted that circum-Mediterranean benthic foraminifera exhibited a marked drop in similarity with North American forms at this time. They attributed this to isolation of the Mediterranean due to the rotation of Iberia towards Africa.

Poag (in press) discussed the Neogene stratigraphy of the subaerial U.S. Atlantic Coastal Plain. He noted a correspondence of the major middle Miocene (Zones N9–N14) highstand of sea level (Vail et al., 1977) with widespread deposition on the margin. Early Miocene strata (mostly Zones N4–N5) are less well represented, and late Miocene to Pliocene strata are very poorly represented; these coincide with lowerstands of sea level. In the southeast Georgia Embayment, he noted a neritic Buliminella elongata-Florilus-Epistominella assemblage similar to that discussed above, and attributed it to increased upwelling. An upper bathyal Brizalina-Siphogenerina-Uvigerina assemblage was also observed in upper Miocene strata in this region.

Perhaps the most dramatic Late Neogene oceanographic event is the desiccation of the Mediterranean Sea (Hsu et al., 1972, 1973; Van Couvering et al., 1976). Benthic foraminiferal evidence from the

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**Fig. 10.** Estimated paleobathymetry of the upper Miocene-lower Pliocene sequence at Carmona-Dos Hermanas, SW Spain. Modern upper depth limits and stratigraphic range in the section are shown for the benthic foraminifera (after Berggren & Haq, 1976).
Andalusian (late Miocene) stage shows evidence of shallowing (Fig. 9) that may represent the desiccation event. Berggren and Haq (1976) and Berggren et al. (1976) showed that in a 4-5 m.y. interval of the late Miocene, a lower bathyal assemblage (Cibicidoides mediocris-Melonis soldanii-Planulina rueffersti) was succeeded by an upper bathyal assemblage that was, in turn, succeeded by an inner neritic assemblage (Fig. 9). In the latest Miocene (~5.5 Ma), a sharp decrease in water depth occurred (~50-70 m, Fig. 9). This sharp drop was interpreted to represent a eustatic sea-level drop (see Vail et al., 1977) that served to isolate fully the already partially-isolated Mediterranean, resulting in its desiccation. Berggren and Haq believed that the absence of rapid variations of sea level in the uppermost Andalusian section argued against periodic refilling of the Mediterranean as suggested by Hau et al. (1972). Wright (1979) reported that following the early Pliocene reconnection and refilling of the Mediterranean, North Atlantic benthic foraminifera quickly (~0.5 m.y.) repopulated the former evaporite basin.

QUATERNARY DEEP-SEA BENTHIC FORAMINIFERA, WATER MASSES, GLACIAL HISTORY

Deep-sea benthic foraminiferal bathymetric distribution patterns are not maintained interregionally, and downcore analyses show that changes in bathymetric distribution of greater than 1 km occurred in the Pleistocene (Lohmann, 1978a). Thus, the distribution of deep-sea taxa cannot be controlled by depth alone. The abundances of some deep-sea benthic foraminifera are correlated with water masses (T, S, O2) and properties that covary with water masses independent of depth (Streeter, 1973; Schnitker, 1974, 1979b; Lohmann, 1978b; Corliss, 1979b; Bremer & Lohmann, in press). These water-mass benthic foraminiferal relationships have been extended into the Pleistocene record in order to determine the response of the deep ocean to glacial-interglacial changes.

Presently, deep and bottom waters formed in the Norwegian-Greenland Sea overflow the Greenland-Scotland Ridge (Worthington, 1976) and influence hydrography as far away as the deep Pacific (Reid & Lyon, 1971). However, during the last glacial period, the Norwegian-Greenland Sea apparently was covered with ice year-round (Kellogg, 1975), and convection necessary for the formation of the Norwegian-Greenland Sea overflow (Worthington, 1976) probably could not have occurred. Thus, bottom water in the North Atlantic may have become warmer and "older" (lower O2, higher nutrients, more corrosive) during glacial times. Such a scenario has been supported by δ18O analyses of benthic foraminifera that indicated warmer bottom-water temperatures during glacia (Streeter & Shackleton, 1979), although this interpretation has been recently disputed (Duplessy et al., 1980). Glacial benthic foraminiferal assemblages in the North Atlantic show evidence of older bottom water. Uvigerina peregrina expanded in abundance and bathymetric distribution during the last glaciation. Since this species is often associated with lowered oxygen values (Lohmann, 1978a; Schnitker, 1979b), this was interpreted as reflecting older bottom water (Streeter & Shackleton, 1979; Schnitker, 1979b). Such an interpretation may be valid, but needs to be evaluated in view of the fact that abundant U.
**peregrina** is not consistently associated with low oxygen values in the modern ocean (Miller & Lohmann, 1982).

Lohmann (1978a) found very little correlation between glacial-interglacial cycles and benthic foraminiferal response in the South Atlantic. Here, the major faunal change, from a Circumpolar Deep Water (CPDW) fauna, dominated by *Uvigerina peregrina* and *Globoconulina subglobosa*, to an Antarctic Bottom Water (AABW) fauna, dominated by *Nutpsilides umbonifera*, occurred between 700 and 900 kyr ago. This change correlates with general climatic deterioration (Peterson and Lohmann, 1982). In the southeast Indian Ocean, Corliss (1979b) also found no simple relationship of benthic foraminiferal variations and inferred water masses with glacial-interglacial cycles. However, based upon abundant *Uvigerina* and *Melonis* in the glacial southeast Indian Ocean, Corliss (in press) suggested that there was reduced influence of NADW on CPDW during glacial periods. Thus, although benthic foraminifera (and by inference, bottom water masses) show coherent responses to oceanographic changes in the Pleistocene, their response to climatic changes has been more irregular than the response of the surface ocean (Lohmann, 1978b).

It should be noted that the Pleistocene-Recent studies outlined here were conducted on different size fractions (Schnitker, 1974; 1979b: > 123 μm; Lohmann, 1978a,b, Peterson and Lohmann, 1981: > 250 μm; all others, >149 μm). Differences in size fraction can yield significantly different results. This is illustrated by differences between biofacies mapped in the modern western North Atlantic by Streeter (1973) and Schnitker (1974). Similar differences arise in comparing fine-fraction studies of Paleogene benthic foraminifera with studies typically performed on >150 μm size fraction; such biases may be present in the quantitative data reviewed here (Poag, personal communication).

**USES AND LIMITS IN BIOSTRATIGRAPHY, PALEOBATHMETRY, AND PALEOCEANOGRAPHY**

The foregoing discussion of Cenozoic benthic foraminifera is far from complete in detail. The examples discussed here illustrate that benthic foraminifera can yield valuable supportive data to solving geological problems. However, potential pitfalls in using benthic foraminiferal data lie in failure to recognize several factors. 1) Benthic foraminiferal zonal schemes, although satisfactory for local zonations and use in the absence of planktonic age criteria, are liable to be diachronous due to control by local changes in paleoenvironment (substrate, water depth, water masses). 2) Paleobathymetric assignments made using benthic foraminifera are estimates, and probably can be used to indicate Cenozoic depth zonations no finer than marginal marine (and various subdivisions, see Scott & Mediali, 1978), neritic (inner, middle, and outer), bathyal (upper, middle and lower), and abyssal zones (Fig. 1) (although Tjalsma & Lohmann (1982) and Miller (in press) have shown that the abyssal zone may be further subdivided). The uncertainties inherent in making these assignments must be understood before these data can be used in basin analysis (e.g. Van Hinte, 1978; Watts & Steckler, 1979).
3) Although distributions of deep-sea benthic foraminifera correlate with water masses or properties that covary with water masses, changes in assemblages are not diagnostic of the nature of deep-sea circulation changes. Supplementary geological and geophysical data (e.g. isotopic, lithologic, seismic) are needed to help interpret the significance of deep-sea benthic foraminiferal changes.

The benthic foraminiferal case histories reviewed here show a sharp change from earlier studies, which were more of a taxonomic nature. While establishing a firm taxonomic base is crucial to further interpretations of benthic foraminifera, modern foraminiferal studies need to integrate a wide range of data. Isotopic stratigraphy, planktonic biostratigraphy, lithostratigraphy, seismic stratigraphy, magnetostratigraphy, physical and chemical oceanography, geophysically constrained subsidence models ("backtracking") and well-histories ("backstripping"), and plate tectonic reconstructions and history are critical to interpreting benthic foraminiferal changes, while benthic foraminiferal studies form integral parts of such geologic and geophysical studies. The procedure in the past has been to evaluate fossil benthic foraminiferal changes in view of the distribution of modern taxa, and then to use benthic foraminifera to interpret changes in paleoenvironment, often largely independent of other constraints. While it is valid to base paleoenvironmental changes upon Recent analogues, the case histories illustrate that benthic foraminiferal changes alone cannot be used to unequivocally interpret abyssal circulation and sea-level changes. The need for supportive data will continue to draw paleontologists and paleontologist-to-be out of isolation. With the continued integration of benthic foraminiferal and other geological and geophysical data, "...the near future of this science is rather..." optimistic.

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