

10. NEOGENE AND QUATERNARY PLANKTONIC FORAMINIFERAL BIOSTRATIGRAPHY OF THE CANARY ISLAND REGION¹

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ABSTRACT

We examined planktonic foraminifers from Sites 953 and 954 in the Canary Island region. Site 953 is stratigraphically the best site with a complete Quaternary to middle Miocene sequence of pelagic and volcanoclastic sediments deposited in the sedimentary basin north of Gran Canaria. At Site 954, on the island flank, several distinct unconformities disrupt the sequence, complicating the biostratigraphy. We adopted the zonation of Berggren (1973, 1977) and Berggren et al. (1983, 1995b) and recognized several of Berggren's zones, although some difficulties arose because of the absence of many zonal markers from the area and the diachronism of several species. Additionally, preservation is poor in the Miocene, hindering zonal assignment by reducing or eliminating the more solution-susceptible species.

We placed the Pliocene/Pleistocene boundary above the last occurrence of *Globigerinoides obliquus extremus* Bolli and Bermudez following the suggestion of Berggren et al. (1995b), because *Globigerinoides fistulosus*, whose last occurrence defines the base of Zone PT1, does not occur in our samples. We did not use the first occurrence of *Globorotalia truncatulinoides* (d'Orbigny) because it is diachronous in the Atlantic Ocean. We consider the highest occurrence of the planktonic foraminifer *Globorotalia juanai* Bermudez and Bolli a useful datum marker to define the Miocene/Pliocene boundary in the Canary Island region, where the last occurrence of *Globoquadrina dehiscens* (Chapman, Parr, and Collins), recorded within upper Chron C5n at Sites 953 and 954, and the first occurrence of *Globorotalia tumida* (Brady), which is rare and sporadic, are not useful for this purpose.

INTRODUCTION

The main purpose of this research was to define biostratigraphic zonal boundaries and events for the Canary Island area. Weaver and Clement (1986, 1987) and Weaver and Raymo (1989) set limits to the applicability of existing subtropical and temperate zonations in the north and equatorial Atlantic regions, where some zonal markers are very diachronous, whereas others are synchronous in their occurrence with latitude. Consequently, we tested the existing zonal schemes (Berggren, 1973, 1977; Berggren et al., 1983, 1995b) which, in the Canary Island region, suffer from the diachronism of several species (e.g., *Globorotalia truncatulinoides*, *Globoquadrina dehiscens*, *Globigerina nepenthes*, and *Globorotalia margaritae*) and the lack of many zonal markers (e.g., *Globigerinoides fistulosus*). Comparisons of identified datum events for the Canary Island region to published events (Berggren et al., 1985, 1995a, 1995b) show a different stratigraphic range for several species. Weaver and Raymo (1989) showed that sea-surface temperature could limit the geographic ranges of some of the tropical planktonic foraminifers, and this seems to be the case at Sites 953 and 954, which lie within the cool Canary Current.

Sites 953 and 954 of Leg 157 are located at a relatively shallow water depth, 3577.8 and 3485.2 m, respectively. We compared preservation and abundance of planktonic foraminifers with variation of the calcium carbonate content downhole, attempting to relate varying amount of dissolution to effective changes of the calcium carbonate compensation depth (CCD).

LITHOLOGY

Sites 953 and 954 are located on the volcanic apron of Gran Canaria with Site 954 in the more proximal position relative to volcanoclastic input. Their sequences consist of pelagic nannofossil oozes with foraminifers interbedded with frequent turbidites and several debris flows and lapilli flows shed from Gran Canaria. The turbidites have two end-member types: (1) a carbonate type dominated by neritic shelly debris, including shallow-water benthic foraminifers and bryozoans, and (2) a volcanoclastic type dominated by pumice and crystals. The turbidite events are frequent, the percentage of sand units per core peaking in the latest Pleistocene, during the Pliocene Roque Nublo events, and the Miocene Fataga and Mogán events (Schmincke, Weaver, Firth, et al., 1995, p. 331). Several distinct unconformities disrupt the sequence at Site 954. Most notable is a Pliocene/Pleistocene hiatus associated with a lapilli flow and poor core recovery, which caused a disruption spanning ~1.5 m.y. Two other unconformities are associated with lapilli and debris flows, and two disconformities occur within pelagic units with no obvious depositional event in association. By contrast, the pelagic units at both sites show remarkably little influence from shallow-water sources, based on the rare occurrences of benthic foraminifers and intermixed volcanoclastic debris. The lack of disturbance to pelagic units combined with apparent minimal erosion caused by depositional events may account for the relatively continuous biostratigraphic record recovered from Site 953.

MATERIALS AND METHODS

We sampled preferentially from pelagic oozes, but in the lower part of the sequence at both sites we took several samples from turbiditic muds, dark volcanic sands, and calcareous sands. One sample in every other section to one sample per section was taken.

Unlithified samples were washed through a 63- μ m sieve with tap water and dried quickly under heat lamps. Lithified samples were

¹Weaver, P.P.E., Schmincke, H.-U., Firth, J.V., and Duffield, W. (Eds.), 1998. *Proc. ODP, Sci. Results*, 157: College Station, TX (Ocean Drilling Program).

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broken into small pieces with a hammer, washed on a stack of sieves with 1-mm and 63- μ m openings, dried under heat lamps, boiled in a 1% (by weight) Calgon solution, and rewashed on a 63- μ m screen. Further details have been already described (Shipboard Scientific Party, 1995a). In this paper, we switched from the composite time scale used during Leg 157 (Shipboard Scientific Party, 1995a) to that used in Berggren et al. (1995a, 1995b).

ABUNDANCE PRESERVATION OF FORAMINIFERS AND CALCIUM CARBONATE CONTENT

At Site 953, in pelagic oozes, preservation was good and abundance was moderate to high for planktonic foraminifers to ~300 meters below seafloor (mbsf). Below this depth, close to the Miocene/Pliocene boundary, abundance and preservation gradually decreased. Preservation deteriorated markedly below ~555.9 mbsf, making zonal assignments difficult. At Site 954, planktonic foraminifers are generally abundant to the base of the Pliocene at ~255 mbsf and are few to common in abundance to the top of the basal basalt breccia (408 mbsf). They are poorly preserved below ~280 mbsf, except in the basalt breccia, where they are well preserved in the lithified matrix. Preservation of calcareous microfossils reflects the pattern of calcium carbonate content of the sediments. Figure 3 (from Schmincke, Weaver, Firth, et al., 1995, p. 332) shows that the calcium carbonate content of pelagic sediments has remained relatively uniform (~56%) to 400 mbsf, but below this depth samples decrease in CaCO₃. A similar trend is observed at Site 954 (fig. 5 from Schmincke, Weaver, Firth, et al., 1995, p. 403), where in the upper part of the section to 300 mbsf, the calcium carbonate content is ~65% (slightly higher than at Site 953), but becomes less and more variable (between 35% and 75%) in the lower part of the section in the interval between 300 and 410 mbsf. Site 954 is located on the outermost edge of the flank of Gran Canaria, ~93 m shallower than Site 953, and it is likely it had a higher elevation also during Miocene times accounting for the slightly larger amount of calcium carbonate.

RESULTS

The Pleistocene

The well-preserved Pleistocene assemblages at Sites 953 and 954 are a mixture of cool subtropical and temperate faunas, and are dominated by dextral *Neogloboquadrina pachyderma* (Ehrenberg), *Globorotalia inflata* (d'Orbigny), *Globigerinoides ruber* (d'Orbigny) white form, *Globigerinita glutinata* (Egger), *Globigerina* cf. *Globigerina bulloides*, *Globigerinella aequilateralis* (Brady), *Globigerina bulloides* d'Orbigny, *Globigerina falconensis* Blow, dextral *Globorotalia truncatulinoides*, and *Orbulina universa* d'Orbigny. The fauna is similar to those from the vicinity of Azores Islands (Colliss, 1975; Weaver, 1987), the African continental margin of Western Sahara (Site 369; Pflaumann and Krasheninnikov, 1979), and the northern Cape Verde Islands (Sites 657 and 659; Weaver and Raymo, 1989). These areas lie within the cool North Atlantic and Canary Currents, which form the north and west limbs of the North Atlantic gyre and which share similar water masses (Sverdrup et al., 1947). At Site 953, the relative proportions of species in the lower Pleistocene assemblage differ distinctly from those of the upper Pleistocene assemblage (below 72.92 mbsf near the last occurrence (LO) of large *Gephyrocapsa* >5.5 μ m; Sblendorio-Levy and Howe, Chap. 8, this volume). The lower Pleistocene assemblage has fewer and sporadic *G. truncatulinoides*, fewer *N. pachyderma* and *G. inflata*, and more *G. glutinata* and *G. ruber*. A short interval of relatively high frequencies of *Neogloboquadrina dutertrei* (d'Orbigny) embraces the Pliocene/Pleistocene boundary, a pattern observed in the central

North Atlantic Ocean (Weaver, 1987). At Site 954, the equivalent lower Pleistocene sequence is entirely missing because of the poor core recovery of a thick lapillistone between 79.2 and 109.7 mbsf.

We adapted the Pleistocene zonation of Berggren et al. (1995a, 1995b) to the Canary Island region (Figs. 1, 2). Zone PT1 is defined as the interval containing *G. truncatulinoides* between the present day and the extinction of *Globigerinoides obliquus extremus*. We used *G. obliquus extremus* in substitution for *G. fistulosus* (Schubert) at Berggren et al.'s (1995b) suggestion, because we did not observe *G. fistulosus* in the Canary Island region. We followed the taxonomic criteria of Bolli and Saunders (1985) for recognition of *G. obliquus extremus*. The Pleistocene sequences at the two sites range from the surface to Samples 157-953A-14H-3, 134-136 cm (125.94 mbsf), and 157-954A-11X-1, 0-2 cm (79.21 mbsf). We divided the Pleistocene into two parts, Subzones PT1b and PT1a (Table 1, back-pocket foldout, this volume, Table 2). The partial range Subzone PT1b is defined as the interval characterized by the partial range of *G. truncatulinoides* following the extinction of *Globorotalia tosaensis* Takayanagi and Saito, which occurs in the early Brunhes Chron (Berggren et al., 1995a). The zone ranges from the surface to Samples 157-953A-4H-CC, 0-2 cm, and 157-954A-6H-2, 47-49 cm (36.09 and 40.97 mbsf, respectively), both of which fall between the highest stratigraphic occurrence of *Pseudoemiliania lacunosa* and the base of the Brunhes Chron at Sites 953 and 954 (B. Herr and M. Fuller, pers. comm., 1996; Sblendorio-Levy and Howe, Chap. 8, this volume). The interval Subzone PT1a is defined as the interval between the extinction of *G. obliquus extremus* and the extinction of *G. tosaensis*, and is recognized at both sites. We explored the utility of Ericson and Wollin's (1968) zonation in the region, but found it unusable because the *Globorotalia menardii* plexus is so exceedingly rare and sporadic that zonal boundaries cannot be placed with any certainty.

Several other important biostratigraphic events characterize the Pleistocene sequences (Table 1, back-pocket foldout, this volume, Table 2). *Globorotalia crassaformis* Galloway and Wissler and its subspecies, although not abundant, are frequent and persistent elements of the fauna. The first occurrence (FO) of *Globorotalia crassaformis hessi* Bolli and Premoli Silva and the last occurrence of *Globorotalia crassaformis viola* Blow (101.41 and 104.48 mbsf, respectively, at Site 953 and 77.66 and 79.21 mbsf, respectively, at Site 954) occur immediately below the last occurrence of *Calcidiscus macintyreii* at Site 953 (Sblendorio-Levy and Howe, Chap. 8, this volume), as it does at Hole 154A in the Caribbean Sea (Bolli and Premoli Silva, 1973; Hay and Beaudry, 1973). These taxa are also used to zone sequences at Sites 366 and 368 near the Cape Verde Islands and the Sierra Leone Rise (Pflaumann and Krasheninnikov, 1979). The *G. crassaformis hessi* and *G. crassaformis viola* datum levels may be useful in other regions of the subtropical and tropical Atlantic Ocean.

True *Globigerina calida calida* with chambers measurably longer in the radial direction than in width (Parker, 1962) are exceedingly rare in the Canary Island region, although forms assignable to *Globigerina calida praecalida* Blow are persistent throughout the Pleistocene. This fact limits the stratigraphic reliability of this datum level in the region. We do use the FO of *G. calida calida* in one application. We suspect that the Holocene and latest Quaternary intervals at Site 953 were removed by a biogenic turbidite containing abundant bryozoans and neritic benthonic foraminifers. The interpretation is supported by the occurrence of *G. calida calida*, which is limited to the core top sample, (Sample 157-953-1H-1, 0-2 cm, 0.01 mbsf) at Site 953. In contrast, the taxon first occurs 11.2 mbsf at Site 954 (Sample 157-954A-3H-1, 67-69 cm).

Two other events are worthy of report. The first occurrence of pink *G. ruber* occurs at 43.71 and 77.2 mbsf at Sites 953 and 954, respectively, the former at the Brunhes/Matuyama boundary (B. Herr and M. Fuller, pers. comm., 1996), and the latter 26 m below the boundary (Figs. 1, 2). The pink form is quite rare and sporadic in the region. *Globorotalia hirsuta* (d'Orbigny) similar to variant 1 of Park-

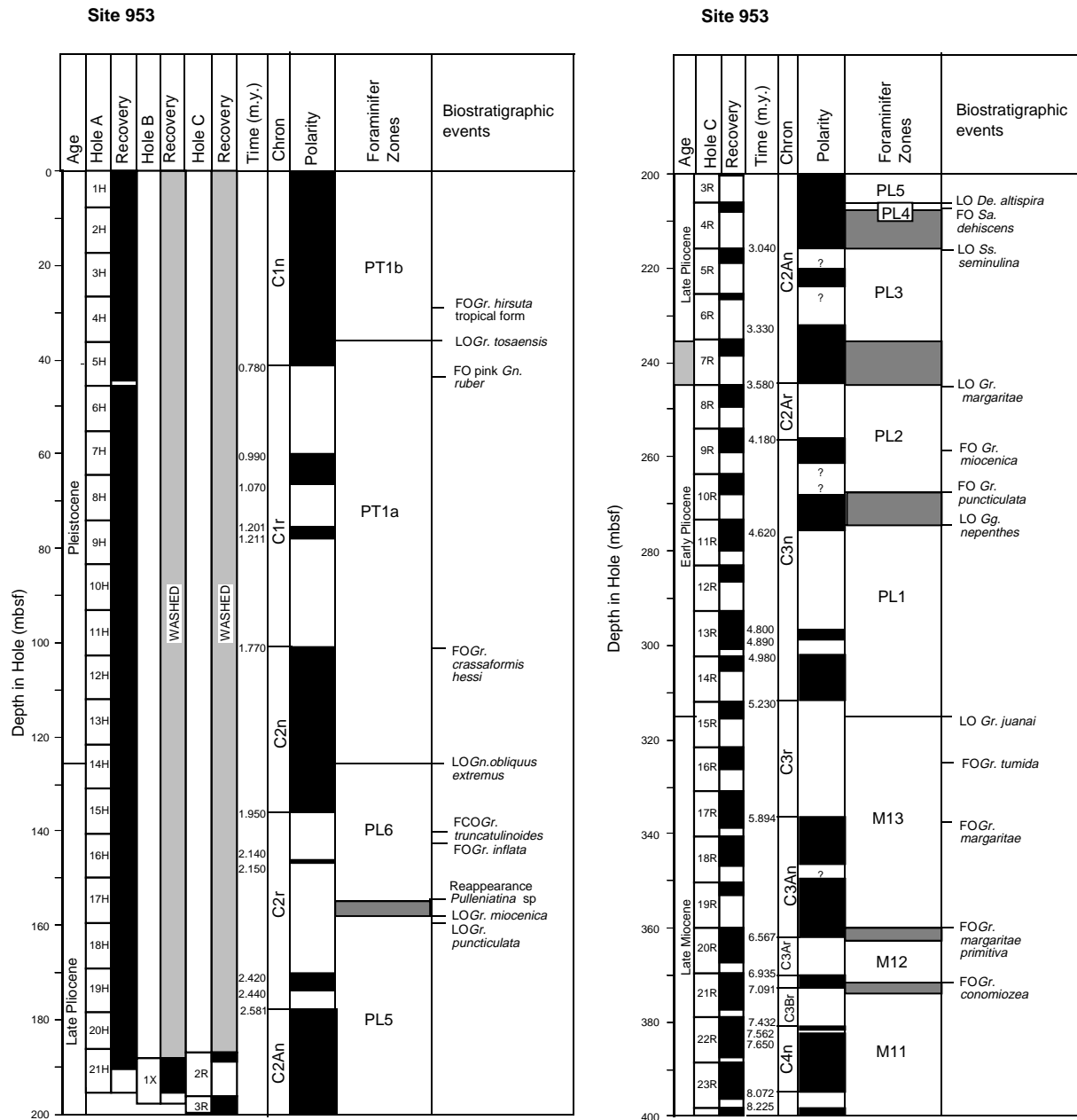


Figure 1. Magnetobiostratigraphy of Site 953 and selected planktonic foraminifers datum levels calibrated to Berggren et al. (1995a, 1995b) time scale. Paleomagnetic datums are from B. Herr and M. Fuller (pers. comm., 1996). The gray areas are intervals of poor biostratigraphic resolution because of lacking core recovery and/or absence of lithologies (hemipelagic marls and pelagic oozes) suitable for stratigraphic analysis. FO = first occurrence, LO = last occurrence, and FCO = first common occurrence.

er (Parker, 1962; Parker, 1967; Blow, 1969) first occurs at 28.96 and 25.11 mbsf in the middle Brunhes Chron (B. Herr and M. Fuller, pers. comm., 1996) at Sites 953 and 954, respectively, and other similar forms (variant 3 of Parker, 1962; *G. crassula* Cushman and Stewart in Parker, 1967; *Globorotalia* aff. *hirsuta hirsuta* in Iaccarino and Salvatorini, 1979) are found sporadically in the Quaternary and late Pliocene. Forms assigned to *G. hirsuta* also occur sporadically throughout Quaternary and late Pliocene sequences at sites near the West African Margin (Pflaumann and Krashennikov, 1979) and other regions of the world oceans, but the neotype described by Blow (1969), which appears equivalent to variant 1 of Parker (1962), occurs only in the latest Quaternary, first appearing in the middle Brunhes Chron (Berggren et al., 1995a) in the southwestern Atlantic

Ocean (Pujol and Duprat, 1983, with reference to variants 1 and 3 of Parker) and the central North Atlantic Ocean (Weaver, 1987).

Both sites contain many volcanoclastic and shallow-water, biogenic turbidites. In fact, the upper cores of Site 954, which is more proximal to Gran Canaria than is Site 953, are dominated by coarse biogenic turbidites (Cores 157-954-2H, 3H, and 5H), so the depth-age relationships of datum levels above the base of the Brunhes Chron stand in question.

The Pliocene/Pleistocene Boundary

Based on planktonic foraminifers, the Pliocene/Pleistocene boundary is approximated by the last occurrence of *G. obliquus extremus*,

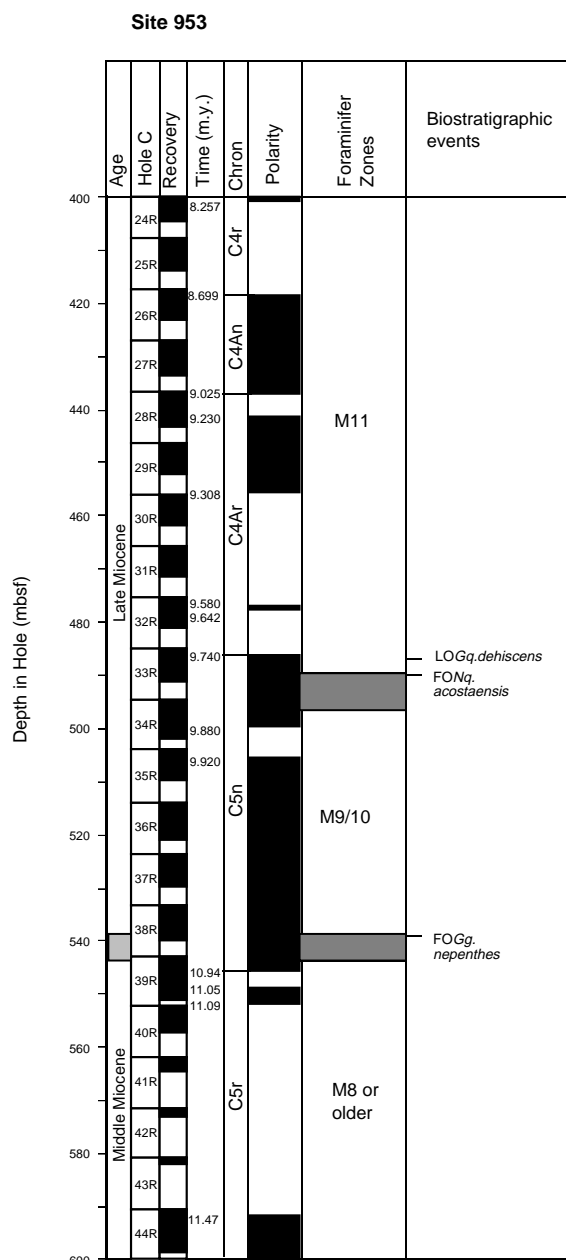


Figure 1 (continued).

which, at Site 953, lies in Sample 157-953A-14H-4, 103–105 cm (127.13 mbsf). The event falls within the lower third of the Olduvai Subchron (~23 m below the top; B. Herr and M. Fuller, pers. comm., 1996) rather than at the top of the subchron, so the species regional last occurrence is older than its true extinction at 1.77 Ma (Berggren et al., 1995a, 1995b; Chapman et al., 1996). The epoch boundary lies in the upper Olduvai at the type section in Vrica (Berggren et al., 1995, and references therein), so our approximation of the boundary is stratigraphically below its placement based on paleomagnetic stratigraphy (Fig. 1). At Site 954, the last occurrence of *G. obliquus extremus*, and, hence, the inferred epoch boundary falls within a disconformity and zone of poor recovery (Fig. 2).

The Pliocene

The well-preserved late Pliocene assemblage is dominated by *G. glutinata*, dextral *N. pachyderma*, *Globigerina rubescens* Hofker, *G.*

ruber, *Globigerina* spp., *Globigerina bulloides*, *Globorotalia puncticulata* (Deshayes), dextral *Neogloboquadrina acostaensis* (Blow), *N. dutertrei*, and *G. inflata*. It is more diverse than the Pleistocene, and it has more *G. rubescens*, *G. crassaformis*, and *Globigerinita glutinata* and fewer dextral *N. pachyderma*, *G. inflata*, and *G. ruber*. Several species important to biostratigraphy are absent or rare in the Canary Island region. Among the tropical species, *G. fistulosus* and *Pulleniatina finalis* Banner and Blow are not observed, and *Globorotalia pertenuis* Beard is too sporadic to be useful for placing datum levels. Among the cool water species, *G. crassula*, and *Globorotalia conomiozea* Kennett are too sporadic to be useful in defining datum levels in the late Pliocene, and *Neogloboquadrina atlantica* is not observed.

The late Pliocene sequences at both Site 953 and 954 were successfully subdivided (Tables 1, 3, 4, back-pocket foldout, this volume) into Zones PL6 to PL3 of Berggren et al. (1995b). We were able to tie most datum levels to the excellent paleomagnetic stratigraphy at Site 954 (B. Herr and M. Fuller, pers. comm., 1996); however, we were unable to do this at Site 953 because the paleomagnetic events remain poorly resolved (Shipboard Scientific Party, 1995b).

The basal boundary of PL6 was placed above the last occurrence of *Globorotalia miocenica* Palmer, which lies below the Reunion Subchron (Berggren et al., 1995a) and is in good agreement with the same event observed at Ocean Drilling Program (ODP) Site 659 (Chapman et al., 1996). At Site 953, the last occurrence of *G. miocenica* (Fig. 1) is recorded in Sample 157-953-17H-6, 19–21 cm (157.79 mbsf), in the lower Matuyama Chron and below the Reunion Subchron (B. Herr and M. Fuller, pers. comm., 1996) as expected (Berggren et al., 1995a). The sequence at Site 954 is relatively complete, but a large unconformity caused by emplacement of a lapillistone removed all of Zone PL6, except one sample (Sample 157-954C-3R-CC, 0–2 cm; 100.10 mbsf) found in sediment within the lapillistone. Several useful datum levels occur within Zone PL6 at Site 953. The last occurrence of *G. exilis* Blow (Sample 157-953A-16H-3, 116–118 cm; 144.76 mbsf) is 1 m above the top of the Reunion Subchron, slightly higher than expected perhaps because of reworking (B. Herr and M. Fuller, pers. comm., 1996; Berggren et al., 1995a), and the reappearance of *Pulleniatina* (Sample 157-953A-17H-3, 139–141 cm; 154.49 mbsf) occurs below the Reunion Subchron as expected (Berggren et al., 1995a; B. Herr and M. Fuller, pers. comm., 1996).

The first appearance of *G. truncatulinoides* is much earlier than expected at Sites 953 and 954 and merits specific discussion. The species evolved in the Pacific Ocean near the Gauss/Matuyama boundary at ~2.58 Ma, but it is generally held that it did not enter the Atlantic Ocean until ~2 Ma within upper Zone PL6 (Dowsett, 1988; Berggren et al. 1995b; Chapman et al., 1996). This does not appear to be the case in the Canary Island region based on the Leg 157 sequences, in which sporadic invasions occurred in Zone PL5 well below the base of the Olduvai Subchron. At Site 953, the species briefly first appeared at 167.82 mbsf in Zone PL5, 10 m above the Gauss/Matuyama boundary and ~21 m below the base of the Reunion Subchron, then made a first common occurrence (FCO) at 140.56 mbsf just below the Olduvai Subchron (B. Herr and M. Fuller, pers. comm., 1996), where it is expected in the Atlantic Ocean (Dowsett, 1988; Berggren et al., 1995b; Chapman et al., 1996). At Site 954, *G. truncatulinoides* first appeared at 134.39 mbsf and recurred at 112.68 and 112.61 mbsf, all of which are in Zone PL5. The interval above this is disturbed by a lapilli flow that removed the upper part of PL5, most of PL6, and the lower Pleistocene. The puzzling occurrences in PL5 could have been because of downhole caving, but no other taxa from higher in the sequence were observed in the samples, although reworking of older material is evident. The early appearance of this species in Zone PL5 at Sites 953 and 954 requires confirmation at other Atlantic sites. We must point out that *G. truncatulinoides* was not reported in Zone PL5 at nearby Site 659 (Chapman et al., 1996).

Zones PL5, PL4, and PL3 are consistent with the zonal definitions of Berggren et al. (1995b). The base of Zone PL5 is marked by the last occurrence of *Dentoglobigerina altispira* (Cushman and Jarvis)

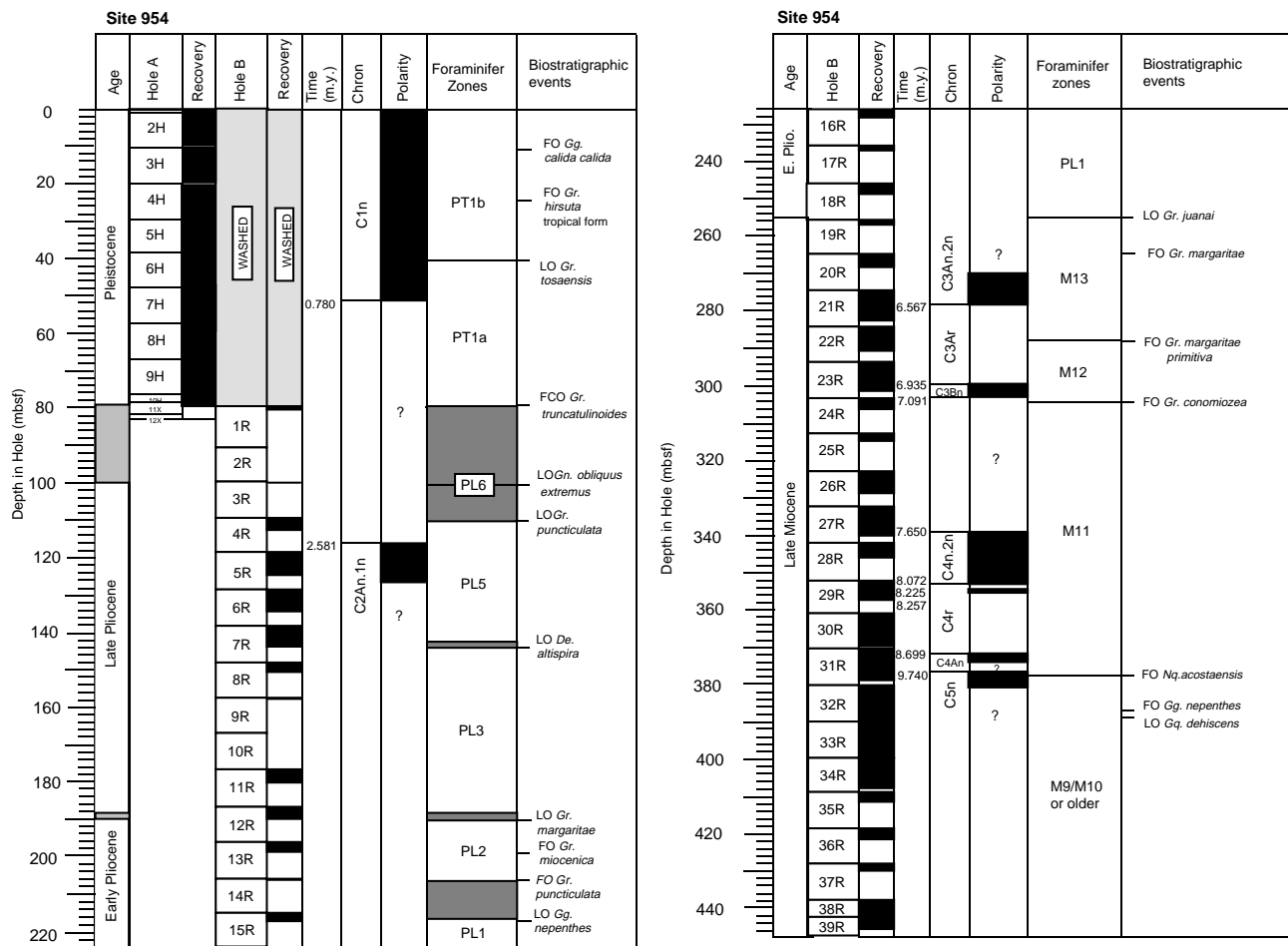


Figure 2. Magnetobiostratigraphy of Site 954 and selected planktonic foraminifers datum levels calibrated to Berggren et al. (1995a, 1995b) time scale. Paleomagnetic datums are from Shipboard Scientific Party (1995b). The gray areas are intervals of poor biostratigraphic resolution because of lacking core recovery and/or absence of lithologies (hemipelagic marls and pelagic oozes) suitable for stratigraphic analysis. FO = first occurrence, LO = last occurrence, and FCO = first common occurrence.

in Sample 157-953C-4R-1, 131–133 cm (207.41 mbsf), almost 9 m above the Kaena Subchron (B. Herr and M. Fuller, pers. comm., 1996), which is higher than expected (Berggren et al., 1995a), perhaps because of reworking evident in overlying samples at 198.57 and 184.80 mbsf (Table 3, back-pocket foldout, this volume). At Site 954 (Fig. 2), the base of PL5 lies above Sample 157-954B-7R-4, 47–48 cm (143.57 mbsf), below the top of the Gauss (Shipboard Scientific Party, 1995b). We observed one useful datum level within PL5. *G. puncticulata* last appeared at Sample 157-953A-17H-CC, 0–2 cm (159.61 mbsf) in the early Matuyama Chron as expected (B. Herr and M. Fuller, pers. comm., 1996; Berggren et al., 1995a; Chapman et al., 1996). Although we found typical *Globorotalia pertenuis*, it was too rare and sporadic to place its last appearance with confidence, and we noted occurrences, apparently caused by reworking, above the top of the Gauss (B. Herr and M. Fuller, pers. comm., 1996; Berggren et al., 1995a). Zone PL5 is relatively complete at Site 953, although small disconformities may occur at major depositional events, like debris flows or lapilli deposits, and the zone suffers from some reworking of older material. In contrast, the top of this zone was lost at Site 954 during emplacement of the large lapillistone, as evidenced by the simultaneous disappearances of *G. puncticulata*, *G. miocenica*, and *G. exilis* at the top of the zone.

The base of Zone PL4 is marked by the last occurrence of *Sphaeroidinellopsis seminulina* (Schwager), which should occur in the base of the Kaena (Berggren et al., 1995a). However, the base of the Kaena and the top of the Mammoth are not recognized at Site 953

(Fig. 1), and the Kaena is not recognized at all at Site 954 (B. Herr and M. Fuller, pers. comm., 1996; Shipboard Scientific Party, 1995b). The highest stratigraphic occurrences of *S. seminulina* are found in Samples 157-953C-5R-1, 48–50 cm (216.28 mbsf), and 157-954B-7R-4, 47–48 cm (143.57 mbsf). PL4 is a brief zone of ~30 k.y., represented by only two samples at Site 953 and none at Site 954.

The basal boundary of Zone PL3 is marked by the last occurrence of *G. margaritae* Bolli and Bermudez between 236.25 and 245.11 mbsf at Site 953 and between 188.09 and 190.18 mbsf at Site 954. The event occurs, as expected, at the Gauss/Gilbert boundary, which lies between 244.80 and 244.90 mbsf at Site 953, but is not recognized at Site 954 (Berggren et al., 1995a; B. Herr and M. Fuller, pers. comm., 1996; Shipboard Scientific Party, 1995b).

The basal boundary of Zone PL2 (Tables 3, 4, back-pocket foldout, this volume) is placed in Samples 157-953C-10R-CC, 0–2 cm (267.7 mbsf), and 157-954B-14R-CC, 0–2 cm (206.2 mbsf), above the LO of *G. nepenthes* Todd following Berggren et al. (1995b). At Site 953, the highest occurrence of *G. nepenthes* is close to the bottom of the Nunivak subchron (Fig. 1), whereas Berggren et al. (1985, 1995a) place it at the top of the Cochiti subchron. The LO of *G. nepenthes* at Site 954 (Fig. 2) falls within an interval with no reliable paleomagnetic record (Shipboard Scientific Party, 1995b). Our findings are consistent with Weaver and Raymo (1989), who show that *G. nepenthes* has an earlier LO at all sites affected by the Canary or Benguela currents. The evolutionary trend of *Globorotalia margaritae*

Table 2. Distribution of planktonic foraminifers, Hole 954A.

Zone	Core, section, interval (cm)	Top depth (mbsf)	Bottom depth (mbsf)	Lithology	Group abundance	Preservation	<i>Globigerina bulloides</i>	<i>Globigerina calida calida</i>	<i>Globigerina calida praecalida</i>	<i>Globigerina falconensis</i>	<i>Globigerina quinqueloba</i>	<i>Globigerina rubescens</i>	<i>Globigerinella aequilateralis</i>	<i>Globigerinita glutinata</i>	<i>Globigerinoides conglobatus</i>	<i>Globigerinoides ruber</i>	<i>Globigerinoides sacculifer</i>	<i>Globigerinoides tenellus</i>	<i>Globigerinoides trilobus</i>	<i>Globorotalia crassaformis</i>	<i>Globorotalia crassaformis hessi</i>	<i>Globorotalia crassaformis viola</i>	<i>Globorotalia cultrata</i>	<i>Globorotalia hirsuta</i>	<i>Globorotalia cf. G. hirsuta</i>	<i>Globorotalia inflata</i>	<i>Globorotalia scitula</i>	<i>Globorotalia truncatulinoides</i>	<i>Globorotalia tosaensis</i>	<i>Hasigierina pelagica</i>	<i>Neogloboquadrina dutertrei</i>	<i>Neogloboquadrina pachyderma</i> (dextral)	<i>Orbulina universa</i>	<i>Pulleniatina obliquiloculata obliquiloculata</i>				
PT1b	1H-1, 0-1	0	0.02	Brown ooze	A	G	C	F	C	C	F	C	C	C	F	C	F	C	C	C	F		F	R	C	C	C	C	F	F	C	C	R	F				
	1H-1, 9-11	0.09	0.11	Brown ooze	A	G	F	R	R	R	C	F	C	C	C	C	R	C	C	C	C		R	R	C	C	C	C	C	C	C	C	C	F				
	1H-1, 65-67	0.65	0.67	Turbidite mud	A	G	R	R	R	C	F	F	C	C	C	C	C	R	C	C	C																	
	1H-CC, 0-2	0.85	0.87	Brown ooze	A	G	F	R	C	F	R	C	C	C	C	C	C	C	C	C																		
	2H-1, 2-4	1.02	1.04	Brown ooze	A	G	C	R	R	R	F	C	F	C	C	C	F	R	F	F			R	R	R	R	C	C	F	F	R	C	C	F				
	2H-1, 52-54	1.52	1.54	Brown ooze	A	G	C	R	C	C	R	R	C	C	C	C	F		F	F																		
	2H-CC, 0-2	9.65	9.67	Black ash	F	P																																
	3H-1, 67-69	11.2	11.22	Pelagic ooze	A	M	C	R	C	F	F	F	C	A	C	C		F	F	F	F	R		R	R	A	R	C	C	C	F	A	F	C				
	3H-2, 10-12	12.1	12.12	Pelagic ooze	A	M	C	C	C	C	F	F	F	C	A	C		R	R	F	F	R		R	R	R	A	F	C	C	C	A	F	A	C			
	3H-2, 61-63	12.6	12.62	Calcareous sand	A	G	C	C	C	C	R			C	A	R	C		R	F	F	R		R	C	R	A	F	A	A	A	A	A	A	C			
	3H-CC, 0-2	19.49	19.51	Pumice pebble sand	F	M	F	R	R	R				C	C	C																						
	4H-3, 51-53	23.5	23.52	Brown ooze	A	M	R	R	R	F	R	F	F	F	A	C	F	R	R	F	F	R		R	R	R	A	F	C	C	C	A	F	A	C	F		
	4H-4, 60-62	25.1	25.12	Brown ooze	A	M	C	C	C	F	F	F	F	F	A	C		R	R	F	R	F		F	F	F	A	F	F	F	F	R	A	A	A	F		
	4H-CC, 0-2	29.26	29.28	Pelagic ooze	A	G	R	F	R	F	R			F	F	A	C		R	F	R	F					A	F	C	C	C	R	A	A	A	F		
	5H-1, 23-25	29.7	29.72	Pelagic ooze	A	M	C	C	C	C				R	F	A	C		F	R	F	R	R				A	C	C	C	C	C	C	C	C	F		
	5H-2, 83-85	31.8	31.82	Pelagic ooze	A	M	C	R	C	C				C	A	C		R	R	F	R	F	R		R		A	F	C	A	A	R	A	A	A	F		
5H-4, 16-18	34.15	34.17	Pelagic ooze	A	G	F	F	C					C	C	F	C	R	F	F	F	F				C	F	A	A	F	F	C	A	A	F				
5H-CC, 0-2	38.93	38.95	Calcareous sand	F	M	F																				F	F	F	F	F	F	F	F	F				
6H-2, 47-49	40.96	40.98	Pelagic ooze	A	G	C	C	C	R			F	C	F	R	C	R	R	F	R					A	F	A	F	C	A	A	A	A	A	A			
PT1a	6H-5, 88-90	45.9	45.92	Pelagic ooze	A	M	C	C	C	R		R	C	A	C	C		R			R					A	R	F	A	A	A	A	A	A	A	R		
	6H-6, 121-123	47.7	47.72	Pelagic ooze	A	M	F	F	C	R			F	F	C	C		R	F			R				A	F	R	C	A	A	F	A	F	F			
	6H-CC, 0-2	48.22	48.24	Pelagic ooze	F	P	F	F	R	R			F	F	R	C	F									A	R	R	F	A	A	A	A	A	A	A	A	
	7H-2, 51-53	50.5	50.52	Pelagic ooze	A	M	F	C	F				F	F	A	C	C		F	R		R				A	R	F	C	A	A	A	A	A	A	A	A	
	7H-7, 30-32	57.79	57.81	Pelagic ooze	A	M		R	C				C	C	C	C		R	C			C				A	R	F	C	A	A	A	A	A	A	A	A	
	7H-CC, 0-2	58.05	58.07	Black beach sand	F	M		R																		F	F	F	F	F	F	F	F	F	F	F	F	
	8H-1, 140-142	59.4	50.42	Pelagic ooze	A	M	A	C	F	R			F	F	A	R	C									A	R	F	F	R	A	A	A	A	A	A	A	A
	8H-4, 70-72	63.2	63.22	Pelagic ooze	A	M	C	R	C	R			R	F	A	C										A	R	F	F	C	A	A	A	A	A	A	A	A
	8H-CC, 0-2	67.63	67.65	Pelagic ooze	C	M		R	F	R			C	C	C	R	C									A	R	F	F	C	A	A	A	A	A	A	A	A
	9H-1, 49-51	68	68.02	Pelagic ooze	A	M		R																		A	R	F	F	C	A	A	A	A	A	A	A	A
	9H-2, 28-30	69.3	69.32	Pelagic ooze	A	M	R	F	F	F			R	F	A	C		F	F	R	R	C	F	R		C	R	R	F	R	A	A	A	A	A	A	A	
	9H-2, 57-59	69.6	69.62	Pelagic ooze	A	M	F	F	R	R			R	F	C	A		R		R	F	R	F		A	R	R	F	R	A	A	A	A	A	A	A	A	
	9H-3, 53-55	71	71.02	Pelagic ooze	A	M	F	F	R				R	F	F	C		R		R	F	R	F		A	R	R	F	R	A	A	A	A	A	A	A	A	
	9H-4, 135-137	73.4	73.42	Pelagic ooze	A	M	C	F	R	R			F	F	A	C										A	R	R	F	R	A	A	A	A	A	A	A	A
	9H-6, 109-111	76.1	76.12	Pelagic ooze	A	M		R																		A	R	R	F	R	A	A	A	A	A	A	A	A
	9H-7, 69-70	77.2	77.22	Pelagic ooze	A	M	F	R	F	R			R	F	A	A		R		R	R	F				A	C	R	F	F	A	A	A	A	A	A	A	
9H-CC, 0-2	77.39	77.41	Pelagic ooze	A	M	C	F	F	R			R	C	F	C										A	F	R	C	A	A	A	A	A	A	A	A		
10H-1, 26-29	77.25	77.27	Pelagic ooze	A	M	C	C	C	C			R	F	F	F	C		R							A	F	R	C	A	A	A	A	A	A	A	A		
10H-1, 29-32	77.27	77.3	Pelagic ooze	A	G	F	R	C	C			C	F	C	R	C									A	F	R	C	A	A	A	A	A	A	A	A		
10H-1, 66-69	77.65	77.67	Brown clay	A	G	F	R	C	C			C	F	C	R	C									A	R	R	F	R	A	A	A	A	A	A	A		
11X-1, 0-2	79.2	79.22	Pelagic ooze	A	G		R	F				R	F	F	F	C		F							C	F	F	F	R	A	A	A	A	A	A			

Notes: * = indicate reworked specimens. Specimen abundances and grade of preservation appear as letters (Shipboard Scientific Party, 1995a, p. 32). A = abundant, G = good, F = few, C = common, R = rare, M = moderate, and P = poor.

tae margaritae to *Globorotalia margaritae evoluta* Cita is observed at both sites within Zone PL2, the same zone as described by Cita (1973) and Krasheninnikov and Pflaumann (1978). Dextrally coiled specimens of *Globorotalia* aff. *G. hirsuta* (illustrated in Iaccarino and Salvatorini, 1979) also occur within upper PL2. The forms are close to *G. margaritae evoluta*, which, however, shows a consistently sinistral coiling. The two morphologically similar species *G. margaritae* (*Globorotalia hirsuta praehirsuta* of Blow, 1969) and *G. hirsuta* have been often confused, and the reports of rare and sporadic occurrences of *G. hirsuta* within the Pliocene and early Pleistocene are, according to many authors (see also Blow, 1969; Bolli and Saunders, 1985), taxonomic errors. However, we suspect an evolutionary trend between the two species as already pointed out by Blow (1969). The lowest occurrence of *G. miocenica*, which is rare and sporadic in occurrence at the base of its range, is recorded within Zone PL2 in Samples 157-953C-9R-CC, 0-2 cm (258.9 mbsf), and 157-954B-13R-2, 48-50 cm (198.5 mbsf). *Pulleniatina* sp. and *Globorotalia plesiotumida* Blow and Banner were not observed in Pliocene sections.

The base of Zone PL1 cannot be defined here following Berggren (1977) and Berggren et al. (1995b), because *G. dehiscens* is absent

from the area during the latest Miocene, and *Globorotalia tumida* is rare and sporadic at Site 953 and absent from Site 954. *Globigerinoides conglobatus* Brady is also rare and sporadic within lower PL1 at both sites. It first appears in Samples 157-953C-14R-2, 41-43 cm (304.3 mbsf), and 157-954B-20R-1, 81-83 cm (264.5 mbsf). Dextral *Neogloboquadrina acostaensis* are commonly recorded within PL1. Specimens transitional to *G. margaritae margaritae* (without keel and left coiling) are assigned to *Globorotalia margaritae primitiva* Cita. Zone PL1 also includes dextral menardine globorotalids, and few specimens with convex spiral sides identified as *Globorotalia pseudomiocenica* Bolli and Bermudez. *G. crassaformis* does not occur within the zone.

The Miocene/Pliocene Boundary

A set of biostratigraphic criteria has been developed for recognizing the position of the Miocene/Pliocene boundary (Berggren and Van Couvering, 1974; Ryan et al., 1974; Cita, 1975). These include the last appearances of *G. dehiscens* and *G. plesiotumida*, and the first appearances of *G. margaritae*, *Globorotalia cibaoensis* Bermudez,

G. tumida, and *G. conglobatus* (Berggren and Amdurer, 1972; Berggren, 1973, 1977; Berggren et al., 1985; Berggren et al., 1995a, 1995b; Saito et al., 1975; Thunell, 1981).

Many marker species, such as *G. tumida*, *G. plesiotumida*, and *G. conglobatus*, are rare and sporadic in occurrence at Sites 953 and 954. The highest occurrence of *G. dehiscens* is recorded at both sites within top Chron C5n (Schmincke, Weaver, Firth, et al., 1995, p. 350). The species has a diachronous last appearance datum (Kennett and Srinivasan, 1975; Hodell and Kennett, 1986) and is rare to absent at the end of its range in the region (see also Cita and Vismara-Schilling, 1980; Salvatorini and Cita, 1979; Weaver, 1987; Weaver and Clement, 1986, 1987; Weaver and Raymo, 1989).

We tentatively used the highest occurrence of *Globorotalia juanai* to place the boundary, because the taxon is known only from the late Miocene (Bolli and Saunders, 1985; Chaisson and Leckie, 1993). At both sites, we recorded transitional specimens similar to *G. margaritae primitiva*, but characterized by dextral coiling and the absence of a definite keel, and assigned them to *G. juanai* following the concepts of Bermudez and Bolli (1969) and Bolli and Saunders (1985). The taxon shows a very distinct preference for dextral coiling throughout its range (Bermudez and Bolli, 1969), whereas *G. margaritae* and *G. margaritae primitiva* have a sinistral preference. Weaver (1987) recorded *G. juanai* within the late Miocene *Globorotalia conomiozea* Zone at Site 608, but several other authors do not mention the species or consider it a synonym of *Globorotalia praemargaritae* Catalano and Sprovieri and *G. margaritae primitiva* (Benson and Rakic-El Bied, 1991; Stainforth et al., 1975). Consequently, the Miocene/Pliocene boundary is placed (Tables 3, 4, back-pocket fold-out, this volume; Figs. 1, 2) between Samples 157-953C-15R-3, 15–17 cm (315.25 mbsf), and 15R-CC, 0–2 cm (315.51 mbsf), within upper Gilbert Chron, and between Samples 157-954B-19R-1, 49–51 cm (254.6 mbsf), and 19R-CC, 0–2 cm (255.4 mbsf), within an interval with poor paleomagnetic record. Rare specimens of *G. tumida* have been recorded to Sample 157-953C-16R-3, 40–42 cm (325 mbsf), within the reversed early Gilbert (Berggren et al., 1985; Berggren et al., 1995a, 1995b; Hodell and Kennett, 1986; Schmincke, Weaver, Firth, et al., 1995). The boundary at Site 953 could be moved to the latter sample based on Berggren et al. (1995b). Close to the boundary we found the change in coiling direction of *N. acostaensis* from left to right (Berggren et al., 1985; Salvatorini and Cita, 1979; Stainforth et al., 1975; Zachariasse, 1975) between Samples 157-953C-17R-1, 56–58 cm (331.66 mbsf), and 19R-1, 7–9 cm (350.27 mbsf), within Chron C3An (B. Herr and M. Fuller, pers. comm., 1996) and Samples 157-954B-19R-1, 49–51 cm (254.6 mbsf), and 20R-1, 81–83 cm (265 mbsf), within an interval with no paleomagnetic record (Shipboard Scientific Party, 1995b).

The Miocene

The sequence was subdivided following Berggren et al. (1983). We could not apply the revised Miocene zonation of Berggren et al. (1995b) because of the total absence or sporadic presence of many zonal markers such as the *Globorotalia fohsi* group, *Globorotalia mayeri* Cushman and Ellisor, *Globorotalia linguaensis* Bolli, *G. plesiotumida*, and *G. tumida*. Particularly, *Globorotalia linguaensis* is absent from the area during the late Miocene, and we did not assign any sample to Zone M14.

Samples from 157-953C-15R-CC, 0–2 cm (315.5 mbsf), to 20R-1, 67–69 cm (360.47 mbsf), and from 157-954B-19R-CC, 0–2 cm (255.4 mbsf), to 22R-4, 76–78 cm (288.1 mbsf), therefore are assigned to Zone M13 (Berggren et al., 1983) because they contain *G. margaritae primitiva* (Figs. 1, 2). However, the basal boundary is tentatively placed because *G. margaritae primitiva* is rare and sporadic in occurrence, and its FO is difficult to pick. The first regional occurrence of *G. margaritae* is placed with confidence at Site 953, within C3An.1n Subchron (B. Herr and M. Fuller, pers. comm., 1996), and is consistent with previous published ages in the North Atlantic region (Berggren et al., 1985; Weaver and Clement, 1986;

1987). At Site 954, the event lies in an interval interrupted by several slumps. The lowest appearance of *G. margaritae* is known to be diachronous, and ranges from Chron C3An to basal Chron C3r (Weaver and Clement, 1986, 1987; Hodell and Kennett, 1986; Weaver and Bergsten, 1991).

The basal boundary of Zone M12, marked by the FO of *G. conomiozea*, occurs in Samples 157-953C-21R-2, 100–103 cm (372 mbsf), and 157-954B-24R-2, 52–54 cm (304 mbsf), at the bottom of Chron C3Bn, as expected (Berggren et al., 1995b). However, we question the reliability of the event at both sites because it lies close to intervals of repeated slumps. The species was consistently recorded in the Bou Regreg section near Rabat (Bossio et al., 1976; Wernli, 1977), whereas it was absent in the Cape Bojador cores (Deep Sea Drilling Project [DSDP] Site 397, Salvatorini and Cita, 1979; Mazzei et al., 1979). Zone M12 contains sinistral *N. acostaensis*, and both dextral and sinistral menardine globorotalids.

The base of Zone M11 is defined by the FO of *N. acostaensis*, and is placed in Samples 157-953C-33R-4, 59–62 cm (490 mbsf), and 157-954B-31R-6, 90–92 cm (377.5 mbsf). Zone M11 is represented by more solution resistant species such as *N. acostaensis*, *G. nepenthes*, *S. seminulina*, *Neogloboquadrina* sp., dominantly sinistral menardine globorotalids, and rare *Globorotalia tumida plesiotumida*. Proximal to the base of Zone M11, we found the highest stratigraphic occurrence of *G. dehiscens* in Samples 157-953C-33R-2, 104–106 cm (487.44 mbsf), and 157-954B-32R-7, 88–90 cm (388.36 mbsf). The event falls within an interval of moderate to poor preservation and seems to be close to the FO of *N. acostaensis* (above it at Site 953 and below at Site 954) within upper Chron C5n (Figs. 1, 2). At Site 953, samples between 157-953C-34R-2, 103–105 cm (497 mbsf), and 38R-5, 84–86 cm, bear *G. nepenthes* without *N. acostaensis* and are assigned to undifferentiated Zone M9/M10, because *Globorotalia paralenguaensis* is absent in our samples (Table 3, back-pocket fold-out, this volume). Below 539 mbsf (Site 953) and 377.5 mbsf (Site 954), any precise zonal assignment is difficult because of poor preservation.

DISCUSSION

Diachronous Datum Levels

The estimated ages of most biostratigraphic events at Site 953, calculated from age/depth curves based on paleomagnetic data (Fig. 3; Table 5) closely match recently published events within the error inhere in such a model (Berggren et al., 1995a, 1995b). Several events however, are diachronous and merit discussion.

The FO of *G. truncatulinoides* is widely recognized as a diachronous event (Dowsett, 1988, 1989; Hills and Thierstein, 1989). The first occurrence of the taxon generally occurs near the base of the Olduvai subchron (Hays et al., 1969; Keigwin, 1982; Berggren et al., 1985; Chapman et al., 1996), except in the South Pacific Ocean, where it first occurs close to the Gauss/Matuyama boundary (Kennett, 1973; Dowsett, 1988). Dowsett (1988, 1989) suggests that *G. truncatulinoides* evolved in the south Pacific Ocean and then migrated to the South Atlantic Ocean, and subsequently to the tropical and North Atlantic Ocean. The late first occurrence of *G. truncatulinoides* at ~2 m.y. is confirmed by Weaver (1987) and Chapman et al., (1996) in the North Atlantic Ocean (Sites 606 and 659) and by Weaver and Raymo (1989) in the equatorial Atlantic Ocean. At higher latitude North Atlantic Site 611, Weaver and Clement (1987) report the age of 1.35 Ma. Therefore, we question whether the repeated occurrences below the Olduvai Subchron at Sites 953 and 954 could suggest earlier periodic invasions of *G. truncatulinoides* into the Atlantic Ocean, just after its evolution in the Pacific Ocean.

The LO of *G. dehiscens* at Sites 953 and 954 is recorded within Chron C5n.1n (~9.740–9.880 m.y.) and clearly predates previous published ages (Table 5). The event is within early Gilbert reversed interval (~5.8 m.y.) according to Berggren et al., (1995a, 1995b), and ranges from Chron C3Bn (~6.8 m.y.) in subtropical regions to Chron

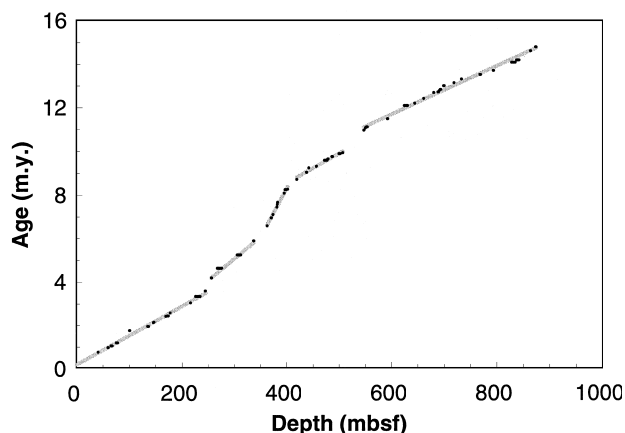


Figure 3. Age model used to estimate the ages of foraminifer first and last appearances at Site 953. The model uses polarity events (B. Herr and M. Fuller, pers. comm., 1996) plotted using the time scale reported in Berggren et al. (1995a, 1995b). Regression lines are lightly sketched through the polarity events. The plot suggests that it is reasonable to assume constant average sedimentation rates during five discrete intervals.

Table 5. Estimated ages of planktonic foraminifer datums at Site 953 compared to the published ages from Berggren et al. (1995a, 1995b).

Datum events	Depth (mbsf)	Age (m.y.)	Est age (m.y.)	Difference (m.y.)
FO <i>Gg. calida calida</i>	0	0.22	0.2	0.02
	1.3	0.22	0.22	0
FO <i>Gr. hirsuta tropical form</i>	28.96	0.45	0.59	-0.14
	33.48	0.45	0.65	-0.2
LO <i>Gr. tosaensis</i>	36.1	0.65	0.69	-0.04
	36.21	0.65	0.69	-0.04
FO pink <i>Gn. ruber</i>	43.71	0.76	0.79	-0.03
	44.35	0.76	0.8	-0.04
LO <i>Gn. obliquus extremus</i>	125.94	1.77	1.89	-0.12
	127.12	1.77	1.9	-0.13
FCO <i>Gr. truncatulinoides</i>	140.56	2	2.08	-0.08
	140.95	2	2.09	-0.09
FO <i>Gr. inflata</i>	141.71	2.09	2.1	-0.01
	144.76	2.09	2.14	-0.05
LO <i>Gr. exilis</i>	151.65	2.15	2.23	-0.08
	154.49	2.15	2.27	-0.12
Reapp. of <i>Pulleniatina</i>	154.49	2.3	2.27	0.03
	154.71	2.3	2.27	0.03
LO <i>Gr. miocenica</i>	154.71	2.3	2.27	0.03
	157.79	2.3	2.31	-0.01
LO <i>Gr. puncticulata</i>	157.79	2.41	2.31	0.1
	159.61	2.41	2.34	0.07
LO <i>Gr. multicamerata</i>	200.25	3.09	2.88	0.21
	206.47	3.09	2.97	0.12
LO <i>De. altispira</i>	206.47	3.09	2.97	0.12
	207.41	3.09	2.98	0.11
LO <i>Ss. seminulina</i>	207.96	3.12	2.99	0.13
	216.28	3.12	3.1	0.02
LO <i>Gr. margaritae</i>	236.24	3.58	3.36	0.22
	245.1	3.58	3.48	0.1
FO <i>Gr. puncticulata</i>	267.8	4.5	4.41	0.09
	274.61	4.5	4.55	-0.05
LO <i>Gg. nepenthes</i>	267.8	4.2	4.41	-0.21
	274.61	4.2	4.55	-0.35
LO <i>Gr. juanai</i>	315.25	5.4	5.35	0.05
	315.51	5.4	5.36	0.04
FO <i>Gr. tumida</i>	325	5.6	5.55	0.05
	325.57	5.6	5.56	0.04
FO <i>Gr. margaritae</i>	337.59	6	5.79	0.21
	338.76	6	5.82	0.18
FO <i>Gr. conomiozea</i>	372.02	7.12	7.05	0.07
	373.91	7.12	7.14	-0.02
LO <i>Gq. dehiscens</i>	485.5	5.8	9.7	-3.9
	487.44	5.8	9.73	-3.93
FO <i>Nq. acostaensis</i>	489.99	10.9	9.76	1.14
	497.03	10.9	9.86	1.04
FO <i>Gg. nepenthes</i>	539.47	11.8	11.01	0.79
	543.77	11.8	11.06	0.74

Notes: FO = first occurrence, LO = last occurrence, and FCO = first common occurrence.

C3r (early Gilbert, ~5.5 m.y.) in the tropics, according to Hodell and Kennett (1986). We observe that the LO of *G. dehiscens* is a diachronous event from the north to the south Atlantic Ocean. The taxon is virtually absent in the upper Miocene of the Legs 37 and 94 sites near the Azores Islands (Miles, 1977; Weaver and Clement, 1987). At Site 397, (Cape Bojador, North Atlantic, Salvatorini and Cita, 1979), it ranges to Blow's Zone N16 and is very sporadic in the latest Miocene. The estimated ages of the LO of *G. dehiscens* are progressively younger from Site 659 (8.20–10.50 m.y.) near Cape Verde Island to Sites 661, 664, and 667 near the Sierra Leone Rise (Weaver and Raymo, 1989). The ages in the latter three sites approximate more closely the published ages given in Berggren et al. (1985, 1995a, 1995b) than the ones in northern areas do. Consequently, we think that the cool Canary Current, which widely affected the area off northwest Africa (Sarnthein et al., 1982), strongly influenced the stratigraphic range of *G. dehiscens* at Sites 953 and 954 as well as in northern Atlantic sites (see also Weaver and Raymo, 1989). The LO of *G. nepenthes* at Site 953 (close to the bottom of Nunivak subchron) is older than previous published ages (Berggren et al., 1985; 1995a) and, seems also to be affected by the cool Canary Current.

The FO of *G. margaritae*, which is known to be widely diachronous, is quite close to the reported ages from other north Atlantic sites (Weaver and Clement, 1986, 1987).

Other datum levels are slightly different from the published events in Berggren et al., (1995a, 1995b). The first occurrences of *N. acostaensis* and *G. nepenthes* appear at our Site 953 higher than in other regions. Both events fall within an interval of moderate to poor preservation and are not reliable. Additionally, the stratigraphic position of the FO of *N. acostaensis* is different from Site 953 to Site 954. It lies below the LO of *G. dehiscens* at Site 953 and above it at Site 954.

Preservation

At both sites, preservation follows a similar trend, which is generally good to moderate in the Pleistocene and Pliocene sediments, and decreases markedly in the upper and middle Miocene sections. These findings are consistent with those previously observed in nearby areas (DSDP Leg 94, Weaver, 1987; ODP Leg 108, Weaver and Raymo, 1989; DSDP Leg 41, Krasheninnikov and Pflaumann, 1978; DSDP Site 397, Salvatorini and Cita, 1979; DSDP Site 398, Iaccarino and Salvatorini, 1979) and must represent a regional change in the depth of the CCD. In fact, the calcite compensation depth has fluctuated throughout the Cenozoic in response to changing oceanographic conditions, and its shoaling during the late and middle Miocene is recognized as a global event in the Atlantic, Pacific, and Indian Oceans (Heath, 1969; Berger and Von Rad, 1972; Berger and Winterer, 1974; Van Andel and Moore, 1974; Van Andel, 1975; Van Andel et al., 1975; Ramsay, 1977; Thunell, 1981). Ryan et al. (1974) suggested that the CCD rose dramatically in the late Miocene to compensate for the large amount of carbonate deposited in the Messinian evaporites within the Mediterranean. Its shoaling could be also the result of increased production of Antarctic cold bottom waters triggered by Antarctic glaciations (Van Andel et al., 1975) or a response to the global transgression that occurred during the middle Miocene (Van Andel, 1975).

Specifically, the depth of the CCD in the North Atlantic off northwest Africa (Leg 14 Sites) was ~5000 m during the Pleistocene and Pliocene and much shallower, ~3500–4000 m during the Miocene (Berger and Von Rad, 1972). Previous downcore variations in percentage of calcium carbonate from North Atlantic DSDP sites show that during the late Miocene, Site 364 (Angola margin, 2448 m water depth) apparently laid within the lysocline (10% to 30% CaCO₃ content), whereas deeper sites (Sierra Leone Rise and Cape Verde Basin, respectively, 4588 and 4148 m water depth) fell to zero carbonate, and they were clearly deeper than the top of the CCD (Thunell, 1981). At Sites 953 and 954 (located, respectively, at 3578 and 3485 m dur-

ing the late and middle Miocene, the carbonate content did not fall to zero. Consequently, we can assume that both sites fell within the lysocline but remained consistently above the CCD, which was at least as shallow as 4000 m, as suggested by Thunell (1981).

CONCLUSIONS

The planktonic foraminiferal fauna at Sites 953 and 954 indicates water masses similar to North Atlantic areas similarly affected by the cool North Atlantic and Canary currents. Estimated ages of datum events, calibrated to an excellent paleomagnetic stratigraphy for Site 953, tie well with previous data from North Atlantic sites within the error of the age model. A unique and still puzzling record is the lowest regional occurrence of *G. truncatulinoides*, which appears at both sites much earlier than in other neighboring areas, within Zone PL5, and requires confirmation at other sites.

The redefined Pliocene/Pleistocene zonation of Berggren et al. (1995b) can be successfully applied in the Canary Island region, but we prefer the Miocene zonation of Berggren et al. (1983) for the poorly preserved Miocene sections, because of the absence of many zonal markers.

Preservation of planktonic foraminifers and calcium carbonate content in the Canary Island region sites follows a regional trend linked to a definite shoaling of the CCD during late to middle Miocene times.

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