Upper Paleocene-lower Eocene radiolarian biostratigraphy of the San Francisco de Paula section, western Cuba: Regional and global comparisons

Annika Sanfilippo1 and Donna M. Hull2
with a contribution by Emilio Flores Albin3

1 Scripps Institution of Oceanography, University of California at San Diego, La Jolla, CA 92093-0244
e-mail: asanfilippo@ucsd.edu

2 The University of Texas at Dallas, Programs in Geosciences, P.O. Box 830688, Richardson, TX 75083-0688
e-mail: dmhull@utdallas.edu

3 Centro de Investigaciones del Petroleo, CUPET

ABSTRACT: In response to a growing need to define the Paleocene/Eocene boundary and record the events which immediately preceded and followed it within a 5 my span, the San Francisco de Paula section of western Cuba was evaluated for its potential as a boundary stratotype. Radiolarians, reported in previous studies by Cuban geologists as a major component of the faunal assemblages in this section, have been recollected and reanalyzed to determine their stratigraphic utility for recognition of the Paleocene/Eocene boundary in Cuba. On the basis of this and other recent microfossil studies of the San Francisco de Paula section, it is now known that the Paleocene/Eocene boundary in this succession is within an unconformity. Its placement herein is based on the highest occurrence of the planktonic foraminifera Morozovella velascoensis (Fernández-Rodríguez et al. 1999, this volume).

Radiolarians are present throughout the San Francisco de Paula succession with the exception of a barren interval in the middle of the section and two thin barren intervals near the top and the base. The most diverse radiolarian assemblages are from the shaley mudstones, which contain poorly preserved radiolarians that range from abundant to very rare. Other lithologies contain sparse, poorly preserved assemblages that appear strongly affected by dissolution. Thirty-five lowest and highest occurrences are noted within the section; however, because of poor preservation, several of these datums are higher or lower than expected when compared with the known global ranges of these species. The radiolarians from this study of the San Francisco de Paula section can be assigned to the stratigraphic interval from the upper Paleocene Bekoma campechensis to the lower Eocene Buryella clinata Zones. Species typical of the B. campechensis Zone include Bekoma campechensis, B. demissa, Bekoma spp., Buryella pentadica, B. tetradica, B. foremanae and Lamptonium pennatum. Faunas of the Bekoma bidartensis Zone contain Buryella tetradica, Giraffospirys lata, Phormocyrtis turgida, Podocystis (Podocystis) papalis, Pterocodon tenellus, Theocorys physella, Theocotyle nigrinae, Theocotylissa alpha, T. auctor and Thyrsocyrtis (Thyrsocyrtis) hirsuta. The radiolarian assemblage representing the lower part of the Buryella clinata Zone is similar to that of the Bekoma bidartensis Zone, and also includes the marker species Buryella clinata. Assignment of the upper part of the San Francisco de Paula section to the Buryella clinata Zone is tentative, because of poor preservation. In the San Francisco de Paula section, the precise location of the Paleocene/Eocene boundary cannot be determined on the basis of radiolarians. However, taken together, radiolarian and calcareous nannofossil evidence indicate that the Paleocene/Eocene boundary is within an unconformity between samples SFP-22 and SFP-21 at the highest local occurrence of Morozovella velascoensis, equivalent to the top of planktonic foraminifer Zone P5.

In addition to tabulating the stratigraphic ranges of radiolarian species in western Cuba, this study presents a preliminary correlation between the lower Paleogene standard radiolarian low latitude zonation and other zonal schemes presented for the Caribbean region and mid to high latitudes. Although the San Francisco de Paula section does possess some of the characteristics desirable in a stratotype for the Paleocene/Eocene boundary, its usefulness in terms of biostratigraphy is limited.

INTRODUCTION

The Paleocene/Eocene boundary interval is an interesting period in Earth history, characterized by warm high latitudes (Stott and Kennett 1990; Kennett and Stott 1991) and changes in oceanic circulation associated with deep water production at low latitudes (Miller et al. 1987; Kennett and Stott 1991; Thomas 1990a, 1990b, 1993). Consequently, definition of the Paleocene/Eocene boundary takes on increasing significance as it becomes necessary to place these climatic and paleoceanographic events in their correct chronological succession. To meet this need, International Geological Correlation Programme Project #308 was initiated to study Paleocene/Eocene boundary sections worldwide, including potential sections previously documented in western Cuba (e.g., Brönnimann and Rigassi 1963).

In contrast to calcareous microfossil groups for which a considerable amount of lower Paleogene biostratigraphic information is available from land-based sequences in the Caribbean region as well as from Deep Sea Drilling Project (DSDP)/Ocean Drilling Program (ODP) cores, most biostratigraphic information on Cenozoic radiolarians in the Caribbean region is from
deep-sea drilling cores alone. Radiolarians from Cretaceous and lower Paleogene formations in western Cuba have been reported by Flores Albin (1983) and Flores Albin and Fernández-Rodríguez (1985), and a small amount of additional information on Cenozoic radiolarians from Cuba, Barbados and Trinidad is summarized in Riedel and Sanfilippo (1971), and Sanfilippo and Riedel (1976). Maurrasse (1973, 1976, 1979) reported mainly on the paleoecologic and paleobiogeographic implications of radiolarian facies in Caribbean mid-Paleogene deep-sea sediments. DSDP Leg 4 collected useful Caribbean middle Eocene sequences with radiolarians at Site 29 (Riedel and Sanfilippo 1970). Leg 10 in the Gulf of Mexico sampled a similar sequence (Foreman 1973; Sanfilippo and Riedel 1973) and Leg 15 provided Caribbean equivalents of the sediment sequences in the Gulf of Mexico (Riedel and Sanfilippo 1973) which permitted correlation with calcareous microfossils. Subsequent DSDP/ODP Legs (76-78, 96, 100-102 and 110) in the Caribbean region recovered only younger than middle Eocene radiolarian-bearing sediments. Although no Cenozoic Paleocene and lower Eocene samples have been obtained from different parts of the world ocean, the recovery is still intermittent and radiolarian preservation commonly not adequate for detailed biostratigraphic work (Sanfilippo and Nigrini 1998a).

For these reasons it was anticipated that the discovery of a new land-based locality, south of the village of San Francisco de Paula in western Cuba (text-figure 1), would contain a suitable Paleocene/Eocene boundary section that would resolve at least some of the stratigraphic problems around the boundary and at the same time allow correlation between the calcareous and siliceous microfossil groups with the results from paleomagnetic and paleoecologic investigations (M.-P. Aubry, personal communications, 1996, 1997; Fernández-Rodríguez et al. 1999, this volume).

LOCATION AND LITHOSTRATIGRAPHY

The San Francisco de Paula section is located in western Cuba near the city of Habana (text-figure 1). It is 56m thick and consists of the Apolo Formation (Paleocene and lowermost Eocene) and the lower part of the overlying Capdevila Formation (also known locally as the Alcava Formation; lower Eocene, for further explanation see Fernández-Rodríguez et al. 1999, this volume). The lower 40m of the section (text-figure 2), which includes the Paleocene/Eocene boundary interval, is composed of marly mudstones and soft shales which are weathered and, in places, largely covered by vegetation. The base of the section is more massively bedded with coarser-grained rocks and conglomeratic limestones. Forty-three meters above the base of the San Francisco de Paula section, the rock sequence is marked by a distinctive lithologic boundary. The rocks above this boundary are more coarsely-grained and are well indurated with distinctive graded bedding, suggesting storm or turbidite deposition. White marly clasts appear in linear bands just above the lithologic boundary.

Fossils present in the San Francisco de Paula succession include planktonic and benthic foraminifera, large foraminifera, radiolarians, calcareous nannofossils, ostracodes, bryozoans, calcareous algae and mollusk fragments (Flores Albin and Fernández-Rodríguez 1985; Fernández-Rodríguez et al. 1999, this volume). Unfortunately, all fossil groups show varying degrees of preservation, and none occur continuously throughout the sequence. Fernández-Rodríguez et al. (1999, this volume), in their analysis of the planktonic and foraminifera, suggest the presence of four unconformities in the sequence. Recognition of these unconformities is based in part on abrupt changes in abundance, diversity, and preservation of the foraminiferal faunas. They relate these unconformities to the 58 to 54 Ma time span of active local tectonics which has been noted by other authors (Bralower and Ituralde-Vinent 1997; Lewis and Draper 1990).

METHODS AND MATERIALS

Initial discovery and collection of material from the San Francisco de Paula section was made by E. Flores Albin, G. Fernández-Rodríguez and other Cuban colleagues shortly after this section was cut along a new road. Consequently, the original samples are relatively unweathered. The Cuban geologists measured the section, collected samples, described lithofacies, and analyzed the material principally for foraminifera and radiolarians (Flores Albin, Appendix 1; Fernández-Rodríguez et al. 1999, this volume).

In 1993, a group of scientists from the U.S., including A. Sanfilippo and D. Hull, joined the Cuban geologists to revisit the San Francisco de Paula section as well as other potential Paleocene/Eocene boundary sections in western Cuba on behalf of IGCP Project #308. The section was re-measured, described, and 54 samples were collected for studies of planktonic and benthonic foraminifera, radiolarians, and calcareous nannofossils; portions of these same samples were also set aside for carbon/oxygen isotope determinations.

The selection of procedures used to measure and sample the section during the 1993 excursion was based on prior knowledge of the Cuban scientists as to the approximate position of the Paleocene/Eocene boundary within the succession. Below a marked point within the section which represented the position of the Paleocene/Eocene boundary as determined by Cuban studies of the foraminifera (herein called the "boundary layer"), samples were collected at 10-cm intervals to a distance of 2.0m; beyond 2.0m, samples were collected from 0.5 to 6m apart, depending upon the lithologies and the extent of weathering. Above the marked point, samples were collected at intervals of 0.5m to 2.0m. These samples as well as the samples collected previously by Cuban scientists are shown on a stratigraphic column in text-figure 2.

Sample SFE-0 is located within the succession (above the Paleocene/Eocene boundary layer) at a well-defined contact between a hard, coarse sandstone and a mudstone/marl with white marly clasts which can be easily recognized by future investigators; therefore, it was selected as a starting point for measuring the section. Sample SFP-13 was taken from the marked point, or "boundary layer" identified on the basis of planktonic foraminifera in earlier studies by Cuban geologists. By this definition, samples SFP-14 through SFP-37 were presumed to be from the Paleocene part of the section. Samples SFE-0 to SFP-12 and SFE-1 through SFE-16 were presumed to be Eocene.

In the biostratigraphic section we have followed Aubry's (1995, p. 215) concepts of lowest and highest occurrence, and that of first and last appearance datum, explained in the following way. A biozone is a stratigraphic unit defined by two or more paleontologic events that are lowest or highest occurrences (LO and HO, respectively). The temporal interval represented by a biozone varies regionally as diachrony occurs, or is unreliable due to preservation problems or differences in taxonomic concepts. The maximum temporal interval covered by a biozone corresponds to the life span of a given species in the case of a to-
TEXT-FIGURE 1
Location map of the San Francisco de Paula section in western Cuba.

BIOSTRATIGRAPHY
Paleocene/Eocene boundary

Formal redefinition of the Paleocene/Eocene boundary currently awaits the selection of a global stratigraphic section and a point within that section that will serve as the standard definition of this boundary. While awaiting redefinition of the Paleocene/Eocene series boundary, many stratigraphers have recognized a stratigraphic interval between the top of the Thanetian Stage and the base of the Ypresian Stage in which to locate the Paleocene/Eocene series boundary. This interval, referred to as the "Paleocene/Eocene boundary interval," spans approximately 2 million years (from latest Chron C25r to mid-Chron C24r). One of the sources of confusion in determining this boundary is that many authors have equated the Paleocene/Eocene boundary with the NP9/NP10 calcareous nanofossil zonal boundary (55 Ma in Berggren and Aubry 1996; Aubry et al. 1996). It now appears that the age of 55 Ma applies to two horizons. The original 55 Ma age estimate in Chron C24r in DSDP Site 550, which was also used as a calibration point in the construction of the latest geomagnetic polarity time scale, lies at an unconformity separating stratigraphic levels low in Zone NP9 from those low in Zone NP10. The result is a younger (higher) NP9/NP10 zonal/chronal position in Chron C24r (Aubry et al. 1996). Thus, the age of 55 Ma applies to two distinct levels: 1) the 408 mbsf level in Site 550 (Swisher and Knox 1991) which corresponds to a NP9/NP10 biozonal contact; and 2) the NP9/NP10 biochronozonal boundary (Cande and Kent 1992). This has serious implications for correlation to the GPTS. Adding to this, there is a large uncertainty in the age estimates determined for events in Chron C24r; e.g., the uncertainty on the estimated age of the NP9/NP10 biochronal boundary is >0.5 my (For a discussion of the uncertainty on the numerical chronology in Chron C24r and the problems related to the accuracy of the radiometric ages, see Berggren and Aubry 1996.)

At present the series boundary is placed at the base of the Ypresian Stage (represented by the Ieper Clay Formation). The stratigraphic interval that is under consideration for redefining the Paleocene/Eocene boundary is between the top of the Thanetian beds (~56.6 Ma, in latest Chron C25r; Zone NP8; Zone P4) and the base of the Ypresian Stage (~54.37 Ma, in mid-chron C24r; at the NP10a/b zonal boundary, and very close to the P6a/P6b, ~54.0 Ma, zonal boundary [Berggren and Aubry 1998; Aubry 1998]). The younger age estimates for the Paleocene/Eocene boundary found in recent works, which differ from Berggren et al. (1985) and Aubry et al. (1988), are a result...
of the recalibration of the magnetochronologic framework by Cande and Kent (1992, 1995). In the San Francisco de Paula section, the boundary is placed at the LAD of Morozovella velascoensis (= base of Zone P6a in Berggren et al. 1995).

**Lower Paleogene radiolarian biostratigraphic zonations**

Text-figure 3 shows the stratigraphic correlation of six radiolarian biostratigraphic zonations for the Paleocene and lower Eocene. The ideal situation with completely cored and suitably fossiliferous sections spanning the Paleocene and lower Eocene does not exist as yet, and therefore we have had to use various approaches to complete the stratigraphic correlations diagram. It must be pointed out that the absence of a particular fauna does not necessarily mean that this interval is missing or was never deposited within a marine sedimentary sequence but rather, that up to the present time it has not been found for a variety of reasons. In DSDP sedimentary sequences, this interval may correspond to a short duration and thus be very thin, and may have been missed due to spot-coring, poor recovery, gaps in sampling, or, if it was in the older part of the stratigraphic column, lack of penetration. Dissolution of microfossils and paleogeographic distributions are also significant factors to be considered.

Foreman (1973) created the first lower Paleogene low latitude radiolarian zonation based on material from DSDP Leg 10 in the Gulf of Mexico. The zonation includes from oldest to youngest: the "unzoned" interval in the lower upper Paleocene, and the Bekoma bidartensis and Buryella clinata Zones. This zonation has been correlated to the Berggren et al. (1995) integrated magnetobiochronologic Cenozoic scale using data available from co-occurring calcareous microfossils (Bukry 1973a; text-figure 3 herein).

The ideal situation with completely cored and suitably fossiliferous sections spanning the Paleocene and lower Eocene does not exist as yet, and therefore we have had to use various approaches to complete the stratigraphic correlations diagram. It must be pointed out that the absence of a particular fauna does not necessarily mean that this interval is missing or was never deposited within a marine sedimentary sequence but rather, that up to the present time it has not been found for a variety of reasons. In DSDP sedimentary sequences, this interval may correspond to a short duration and thus be very thin, and may have been missed due to spot-coring, poor recovery, gaps in sampling, or, if it was in the older part of the stratigraphic column, lack of penetration. Dissolution of microfossils and paleogeographic distributions are also significant factors to be considered.

Foreman (1973) created the first lower Paleogene low latitude radiolarian zonation based on material from DSDP Leg 10 in the Gulf of Mexico. The zonation includes from oldest to youngest: the "unzoned" interval in the lower upper Paleocene, and the Bekoma bidartensis and Buryella clinata Zones. This zonation has been correlated to the Berggren et al. (1995) integrated magnetobiochronologic Cenozoic scale using data available from co-occurring calcareous microfossils (Bukry 1973a; text-figure 3 herein).

The sediment cores recovered on DSDP Legs 10 and 15 were discontinuously cored. Thus many critical intervals were not observed until Nishimura (1987) tentatively established the upper Paleocene Bekoma campechensis Zone based on material from DSDP Site 603 (lat. 35°29.66'N, long. 70°01.70'W, water depth 4634 meters). Subsequently she formally described and subdivided the B. campechensis Zone into three subzones (Nishimura 1992) based on a continuous sedimentary sequence from North Atlantic DSDP Site 384 (lat. 40°21.65'N, long. 51°39.80'W, water depth 3909 meters). The three subzones are, from oldest to youngest, Pteritiator(?) dimitirica, Orbula discipulus, and Stylochrochus nitidus-Pierocodon(?) poculum. Increased stratigraphic resolution also resulted in a revision of the lower boundary of the Bekoma bidartensis Zone. Age determinations based on co-occurring calcareous nanofossils (Tucholke et al. 1979; Okada and Thierstein 1979) have allowed correlation of these zones with the Berggren et al. (1995) scheme (text-figure 3 herein).

The standard low latitude radiolarian zonation, and its correlation to the geomagnetic polarity scale (text-figure 3) is taken from the Sanfilippo and Nigrini (1998a) re-examination of 24 DSDP sites and their correlation via calcareous nannofossils to the Berggren et al. (1995) time scale. None of the sedimentary sequences investigated by Sanfilippo and Nigrini contained radiolarian-bearing sediments exactly spanning the Paleocene/Eocene boundary interval. In spite of this, Sanfilippo and Nigrini were able to establish a sequence of 70 datums in a 10 my interval spanning the boundary from the upper Paleocene Bekoma campechensis Zone to the upper part of the Buryella clinata Zone in the lower Eocene. Further, they were able to relate these datums via published data on co-occurring calcareous nanofossils to the calcareous nanofossil zonation. Using the definitions applied by Berggren et al. (1995) for determining the stratigraphic position of the Paleocene/Eocene boundary in terms of calcareous nanofossils and foraminifera (i.e., NP9/NP10 boundary, ~55 Ma), they established six reliable lowest radiolarian occurrences which approximate the Paleocene/Eocene boundary: Calycocyclus castum, Thecocorys lissus auctor, Lamptonium fabaeforme fabaeforme, Podocytis (Podocytis) papalis, Giraffospirys lata and Phormocytis turgida. The two major differences between this zonation and that of Foreman (1973) are: (1) the Sanfilippo and Nigrini (1998a) zonation combines radiolarian information from several sites with that of co-occurring calcareous microfossils, making it possible to correlate the radiolarian zonation to the geomagnetic polarity scale (and thus estimate ages for radiolarian datums); (2) the lower boundary of the Bekoma bidartensis Zone has been lowered as a result of Nishimura’s (1992) recognition of the older Bekoma campechensis Zone.

The Caribbean radiolarian zonation proposed by Maurrasse (1973, unpublished thesis) is included herein because it was used by Flores Albin in his initial interpretation of the biostratigraphy in the San Francisco de Paula Section (see Appendix 1 by Flores Albin; see also "Biostratigraphy of the San Francisco de Paula Section" below). This zonation consists of four zones in the upper Paleocene to lower Eocene. From oldest to youngest, they are: Theocorys(?) pseudophyzella, Eucyrtidium cubense (=Phormocytis cubensis), Bekoma bidartensis, and Buryella clinata. We caution against using the Maurrasse zonation because the two “new” radiolarian zones proposed by Maurrasse, Eucyrtidium cubense and Theocorys(?) pseudophyzella, have never been formally described. Maurrasse (1973) correlated his zonal scheme to calcareous microfossil zones and to the radiolarian zonation of Foreman (1973) permitting us to correlate his zonal scheme to the current radiolarian zonation and the current geochronologic scale (Berggren et al. 1995).

Maurrasse did not define the base of the Theocorys(?) pseudophyzella zone. However, he considered the top of the zone approximately synchronous with the extinction of the nominate species and coincident with the base of the Eucyrtidium cubense zone. According to Maurrasse’s correlations, this radiolarian zone spans approximately the upper part of the Globanomalina (=Globorotalia) pseudomenardii Zone (P4) and its uppermost limit is possibly in the G. velascoensis Zone (P5). The zone includes the LOs of Lamptonium pannatum, Buryella tetradica and Lychnocanoma auxilla.

In Maurrasse’s original definition, the base of the Eucyrtidium cubense zone is defined by the LO of Eucyrtidium cubense (Phormocytis cubensis) which is approximately synchronous with the LO of Podocytis (Podocytis) papalis. This zone includes the LOs of Phormocytis turgida, Lamptonium fabaeforme fabaeforme, and Theocorys acorria. The top coincides with the base of Foreman’s Bekoma bidartensis Zone.
Stratigraphic interpretation of the upper Paleocene-lower Eocene interval (Apolo Formation) of the San Francisco de Paula section with lithologic column, showing thickness in meters and sampling intervals. Samples collected in previous field excursions by Cuban geologists are designated Cl through C62; samples collected in this study are indicated by the prefixes SFP and SFE. The Paleocene/Eocene boundary in this section has been recognized, at the unconformity between samples SFP-22 and SFP-21, on the basis of planktonic foraminifera (Fernández-Rodríguez et al. 1999, this volume) and is placed at the LAD Morozovella velascoensis, marker for the P5/P6a zonal boundary used in Berggren et al. (1995) to approximate the boundary. Planktonic foraminiferal biozones follow Berggren et al. 1995; benthic foraminiferal biozones Berggren and Miller 1989; and calcareous nannofossil biozones Martini 1971.
As shown on the stratigraphic correlation diagram (text-figure 3), it is apparent that Maurrasse’s E. cubense zone falls within the Bekoma bidartensis Zone as applied by Sanfilippo and Nigrini (1998a). Examination of his data reveals that many of the reported radiolarian events occur within the Bekoma bidartensis Zone. It is of interest to note that the E. cubense zone includes three of the LOs (Phormocyrtis turgida, Lamptonium fabaeforme fabaeforme and Podocyrtis (Podocyrtis) papalis) that Sanfilippo and Nigrini (1998a) use to approximate the Paleocene/Eocene boundary. However, recognition of B. bidartensis and Phormocyrtis cubensis in the Caribbean sedimentary sequences is commonly hampered by preservation problems. In DSDP Site 152, for example, B. bidartensis is absent throughout the B. bidartensis Zone while the somewhat more robust P. cubensis is present in the upper part of the Bekoma campechensis Zone.

Maurrasse’s recognition of the E. cubense zone between the upper part of the B. campechensis and the lower part of the B. bidartensis Zones may be the result of a local difference in the stratigraphic range of E. cubense due to paleoenvironmental effects, or the result of poor preservation. Furthermore, the absence of P. cubensis in the continuous sequence from North Atlantic DSDP Site 384 prevents recognition of the E. cubense zone at that site. However, Nishimura (1992) observed the evolutionary transition of B. bidartensis from B. campechensis at this site, resulting in a lowering of the base of the B. bidartensis Zone (Nishimura 1992), which removes the necessity of a zone, based on a paleoenvironmentally sensitive marker species, between the B. campechensis and B. bidartensis Zones, at least as presently defined. Sanfilippo and Nigrini (1998a) observed the LO of P. cubensis in the upper part of the B. campechensis Zone prior to the LO of B. bidartensis in the Leg 10 material. This is only doubtfully considered as evidence for the presence of the E. cubense zone in the Caribbean because the Leg 10 sediment sequences are intermittently cored, and total radiolarian abundance is low and preservation poor. The lack of continuously cored material from duplicate sites prevents resolving the biostratigraphic problem of which event takes place first, and to what extent these events are effected by paleoenvironment and preservation. Correlation and standardization of the various radiolarian zonal schemes proposed for the Paleocene and lower Eocene will require much additional work using independent age control provided by isotope and/or paleomagnetic studies.

In contrast to the sequence of events documented in the tropics, the mid to high southern latitude pelagic sediments examined by Hollis (Strong et al. 1995) present a different succession. For example, there is a gap between the HO of Bekoma campechensis and the LO of B. bidartensis. In the Mead Stream section, this stratigraphic gap is represented by a 40 meter thick interval, containing a distinctive fauna lacking many of the tropical taxa diagnostic of the B. bidartensis Zone (e.g., Calocycloma castum, Lamptonium fabaeforme fabaeforme, L. pennatum, Podocyrtis (Podocyrtis) papalis and Thyrsocyrtis tarsipes). This faunal assemblage was described by Hollis (1997) as a local zone, the Bekoma campechensis-bidartensis “gap” zone.

The applicability of Hollis’s New Zealand high latitude zonation (paleolatitude 55°S; Hollis 1993, 1997; Strong et al. 1995) has not been tested in low latitudes due to the lack of radiolarian-bearing lower Paleocene sedimentary sequences, but it has been included here because of its relevancy and potential use in other regions. Results of the integrated foraminiferal, radiolarian and dinoflagellate study by Strong et al.’s (1995) provide a biostratigraphic and paleoenvironmental assessment for the uppermost Cretaceous to upper middle Eocene, spanning the Paleocene/Eocene transition in Marlborough, New Zealand. Hollis (1993) correlated his zones to the Berggren et al. (1985) time scale, using age control from co-occurring foraminifera (e.g., Strong 1977, 1981, 1984; Strong et al. 1987) and calcareous nanofossils (Burns et al. 1973). The South Pacific radiolarian zones have subsequently (Hollis 1997) been correlated to the Berggren et al.’s (1995) time scale, and included herein (text-figure 3) for a comparison with the zonal schemes developed for other regions. Nine of Hollis (1997) South Pacific zones are included herein, from oldest to youngest: Amphisphaera aotea [RP(SPac)1], Amphisphaera kina [RP(SPac)2], Buryella granulata [RP(SPac)3], Buryella formanee [RP(SPac)4], Buryella tetradica [RP(SPac)5], Bekoma campechensis [RP(SPac)6], Bekoma campechensis-Bekoma bidartensis [RP(SPac)7], Bekoma divaricata [RP(SPac)08] and Bekoma divaricata-Theocampe mongolfieri [RP(SPac)9].

The boreal zonal scheme resulting from investigations of lower Paleogene Russian sequences from the eastern side of the Urals, western Siberia, the central Volga and Caspian regions (Kozlova 1983, 1984, 1993) are also included because of their eventual future use. These zones, lacking many of the taxa occurring in tropical and subtropical regions (belonging to the genera Bekoma, Dictyopora (Theocampe) and Thyrsocyrtis), were correlated to the tropical radiolarian zonation using zonal schemes for the boreal assemblages. In some cases the boreal zones have been dated using co-occurring diatoms, or in the case of the assemblages from the Caspian region by co-occurring foraminifera.

Biostratigraphy of the San Francisco de Paula Section

The Paleocene/Eocene boundary in this succession is within an unconformity, and has been placed at the HO of Morozovella velascoensis (Fernández-Rodríguez et al. 1999, this volume).

Weathered and indurated shales in the San Francisco de Paula section contain poorly preserved radiolarians which vary in abundance. Radiolarians from the soft shaley layers are some-what better preserved and present in moderate numbers. Age determinations are constrained by the presence of a few resistant “marker” species. In the middle part of the section (text-figure 4) there is a thick interval (approximately 16m) with poorly preserved, unidentifiable radiolarians, and adjacent, above and below, are two barren intervals (approximately 3.5m and 5m, respectively). The relative abundances of taxa and preservation are reported in Table 1; a species list is presented in Appendix 2. Definitions of the radiolarian zones used in this paper can be found in Appendix 3.

The material examined by us was too poorly preserved for detailed biostratigraphy. The marker species used in this stratigraphic interval have only been doubtfully identified (see Plates 1 and 2). Although numerous taxa of the genus Bekoma are present, they cannot be accurately identified at the species level because the characteristic feet, joined in some taxa, have not been observed intact. In spite of this we have made an attempt to distinguish B. campechensis from other co-occurring taxa of the genus Bekoma by using the characteristic shape of the cephalis for each taxon. Bekoma campechensis has a long dome-shaped to rectangular cephalis, whereas B. demissa has a cephalis with numerous pores that appears slightly depressed into the thorax. The cephalis and proximal elongated part of the thorax in B.
TEXT-FIGURE 3
Stratigraphic correlation of radiolarian, calcareous nannofossil and planktonic foraminiferal zones to the geochronologic time scale of Berggren et al., 1995. The broad band spanning the interval between ~54.6 to 55.5 Ma reflects current opinion on the position of the Paleocene/Eocene boundary. Planktonic foraminiferal specialists commonly use the P5/P6 boundary (~54.7 Ma) and calcareous nannoplankton specialists the NP9/NP10 (CP8/CP9) zonal boundary (~55.0 Ma) to represent the boundary for purpose of correlation (see also p. 20 comments on Berggren and Aubry 1998 and Aubry 1998). Hachured intervals represent intervals not represented by radiolarian-bearing sediments. Subdivision of Bekoma campechensis Zone: a = Peritivator (?) dumitricai; b = Orbula discipulus; c = Stylotrochus nitidus-Pterocodon (?) poculum; P* = P0 + P1. [See notes to text-figure 3 on following 2 pages.]
NOTES TO TEXT-FIGURE 3

Ongoing research on the taxonomy and biostratigraphy of Paleogene planktonic foraminifers has necessitated substantial modifications in the numbering system for zones of the Paleocene to lower Eocene interval. Herein we have followed the modifications made by Berggren et al. (1995). For radiolarian zonal schemes that previously had been correlated to foraminiferal zonations older than the Berggren et al. (1995) scheme we have converted prior age assignments to follow the new framework. This is particularly important for the Paleocene/Eocene boundary interval, where Zone P5 of Berggren and Miller (1988) is no longer thought to exist because of an overlap in the ranges of Globanomalina pseudomenardii and Moreozoea subbotinae. To preserve the numerical continuity, a new Zone P5 was defined by Berggren et al. (1995) that is equivalent to Pg6a of Berggren and Miller (1988) minus a short overlap between G. pseudomenardii and M. subbotinae. For further discussion and emendations concerning the other zones see Berggren et al. (1995).

1. Follows correlation made by Foreman (1973) see footnote 12.

2, 3. In material recovered during DSDP Leg 10 the boundary between Buryella clinata and Bekoma bidartensis Zones occurred in a stratigraphic gap between 94-32CC and 96-3-1. However, re-examination by Sanfilippo and Nigrini (1998a) of 24 DSDP cores in this stratigraphic interval determined that the uppermost part of the B. bidartensis Zone and the LO of B. clinata occurred in Cores 13 and 12 respectively at DSDP Site 313 equivalent to nannofossil Zone CP10 and in the Globorotalia subbotinae foraminifera Zone (corresponding to the lower part of CP9b). Precise placement of the B. bidartensis/B. clinata zonal boundary is further hampered by the lack of radiolarian-bearing sediments in the interval equivalent to nannofossil Zone CP9, indicated by hachuring.

4. Sanfilippo and Nigrini (1998a) applied Foreman's (1973) concept of the B. bidartensis Zone, using the morphotypic first appearance of B. bidartensis rather than the evolutionary transition applied by Nishimura (1992) resulting in a lower zonal boundary than that indicated by Nishimura (1992). The first appearance of B. bidartensis is approximated at the CP6/CP7 nannofossil zonal boundary.

5. For placement and correlation to calcareous nannofossil zones of the lower boundaries of Bekoma campechenensis Zone and its subzones see footnotes 18-20.

6. Poor radiolarian coverage in this interval prevented Maurrasse (1973) from determining this zonal boundary and its relationship to calcareous microfossil zones. He suggested that the P. striata striata Zone correlated with the lower part of the Hantkenina aragonensis foraminifera Zone (Zone P10), but that its correlation to the Globorotalia palmerae Zone (Zone P9) could not be determined.

7. Maurrasse implied that the lowermost part of the Buryella clinata Zone may partly correlate to the upper part of foraminiferal Zone Globorotalia subbotinae/Globorotalia wilcoxensis to Globorotalia aragonensis or Globorotalia palmerae Zone. Herein we have correlated the lower boundary of his Buryella clinata Zone with the upper half of nannofossil CP9b.

8. Maurrasse correlated the Bekoma bidartensis Zone in his material with most of the foraminiferal Globorotalia edgari and Globorotalia subbotinae/Globorotalia wilcoxensis Zones and with the material used by Foreman (1973) which we were able to correlate to nannofossil Zone CP8b.

9. The Eucyrtidium cubense zone spans most of the Globorotalia velascoensis foraminiferal Zone and the lowest part of the Globorotalia edgari Zone. Its lower boundary has been approximated at the nannofossil CP8a/CP8b boundary just below the base of foraminiferal Zone P5.

10. Theocorys (?) phyrella zone spans the upper part of the Globanomalina pseudomenardii (P4) Zone. Its lower boundary is undefined. Maurrasse (1973) correlated this zone with the lower part of the 'unzoned interval' represented by DSDP core sections 86-7 and -8, and core section 96-5 (Foreman 1973; Sanfilippo and Riedel 1973). Herein we have given the zone a maximum interval, and thus interpret the base of the zone to lie within nannofossil Zone CP5 as suggested by Bukry's data (1973a).

12. DSDP Leg 10 drilled three discontinuous holes that did not quite overlap in the Paleocene-Eocene interval. Correlation with calcareous microfossil zones from this material [nannofossil zones from Bukry (1973a) and foraminiferal zones from McNeely (1973)] has made it possible to extrapolate the radiolarian zonal boundaries to the geochronological scale. The lowermost sample (94-28CC) in the Phormocystis striata striata Zone lies in the Discoaster lodoensis nannofossil Zone (Zone CP11) and the Hantkenina aragonensis foraminifera Zone (Zone P10). Because samples 94-29CC and 94-30CC in the underlying Buryella clinata Zone are in the foraminiferal Globorotalia aragonensisformosa Zone (P8/7) Zone or nannofossil Zone CP11 we have provisionally placed the unplaced boundary within the lower part of Zone CP11.

13. This boundary falls in a long unrecovered interval between 94-31CC and 94-32CC within the Globorotalia rex foraminiferal Zone. It was not possible to determine a nannofossil age based on the Leg 10 material for this boundary. We have tentatively placed the boundary in the top part of Zone P5 since the Bekoma bidartensis Zone is also within this zone.

14. The boundary between the B. bidartensis Zone and the unzoned interval falls in an unrecovered interval between Cores 96-3 and 96-4, both in nannofossil Zone CP8b. To avoid confusion caused by the Berggren et al. (1995) modifications in the numbering system of the foraminiferal zones we have followed the nannofossil interpretation of Bukry (1973a) and extrapolated the placement of this radiolarian boundary to fall within Zone CP8b.

15. The oldest Paleocene material recovered during DSDP Leg 10 belongs to the foraminiferal Globanomalina pseudomenardii (Zone P4) and Helicolithus kleinpellii nannofossil Zone (= Zone CP5). The lowermost boundary of the unzoned interval is therefore placed at the lower boundary of Zone CP5.

16. Nishimura (1992) correlated her radiolarian zones to the calcareous nannofossil zones reported for DSDP Site 384 by Okada and Thierstein (1979). No foraminiferal zones are available except for the lower part of the Paleogene section. At Site 384 coring was continuous between Cores 5 and 6 but the entire lower Eocene and the top part of the Paleocene are missing. The section is interrupted in the lower part of a normal polarity magnetochron which represents Chron C25n. The youngest part of the Bekoma bidartensis Zone recovered at Site 384 in Core 6, not necessarily the top part of the zone, is correlated with nannofossil Subzone Campylosphera eodela (CP8b) and given maximum time equivalence.

17. The Bekoma campechenensis/B. bidartensis zonal boundary is within nannofossil Zone CP7 arbitrarily placed in the lower part of the zone to accommodate radiolarian Subzone
27. The *Thecosphaera larnacium* Zone is correlated with nanofossil Zone CP6 and the lower part of Zone CP7.

28. The *Buryella (?) alifera* Zone has no tropical equivalent, however, Kozlova (1984) considered the assemblage similar in age to that described by Dumitrica (1973) and estimated as Danian in age (equivalent to foraminiferal Zones P1 and P2). The *Cromyocarpus ovatus* assemblage is an impoverished version of the *B. (?) alifera* zonal assemblage with which it is also equivalent in age. Co-occurring diatoms from the *Trinacria helbergiana* Zone make it possible to estimate the age as equivalent to nanofossil Zone CP4 through CP1b or lower. Radiolarians have not been found near the upper and lower limits of the *C. ovatus* and *B. (?) alifera* Zones.

29-31. Hollis (1997) calibrated his new radiolarian zones [RP(SPac)6-RP(SPac)9] with the revised Paleogene time scale (Berggren et al. 1995) by direct dating of radiolarian events using dates from co-occurring foraminifera and dinoflagellates at Mead Stream, Marlborough, New Zealand (Strong et al. 1995).

32. The primary reason for placing the RP(SPac)5/RP(SPac)6 boundary no lower than calcareous nanofossil zone CP5 in the New Zealand region is that the HO of the *Buryella tetradica* assemblage is within Zone CP5 at DSDP Site 208 (Hollis 1993). The top of *Buryella tetradica* Zone [RP(SPac)5] is defined by the LO of *Bekoma campechensis*. Thus, Hollis (1993) placed the upper boundary of the *B. tetradica* Zone at the base of foraminiferal Zone P4, based on age control for the earliest occurrences of *Bekoma campechensis* in the Gulf of Mexico (Foreman 1973), which, lacking further evidence, coincides with its lowest occurrence in the South Pacific. However, the oldest Tertiary radiolarians recovered on Leg 10 are from sample 86-8-CC (dated by foraminifera as upper Paleocene Zone P4, and by calcareous nanofossils as Zone CP5), and no radiolarian samples were recovered below this sample. Therefore, the LO of *Bekoma campechensis* cannot be determined at this site. Subsequent work by Nishimura (1992) in the North Atlantic established the LO of *Bekoma campechensis* in this region within the upper part of CP3, equivalent to foraminiferal Zone P2 (see comment 20) which is significantly lower than the LO in the Gulf of Mexico. Herein we have placed the top of the New Zealand *Buryella tetradica* Zone within nanofossil Zone CP5 as indicated by Hollis (1993, 1997).

33. At DSDP Site 208 the LO *Buryella tetradica* is in the middle of nanofossil Zone CP3 approximately at the lower/upper Paleocene boundary (Hollis 1993).

34. Reliable age control is lacking at DSDP Site 208 and in the Marlborough sections from New Zealand, and these events have therefore been approximated at the upper nanofossil Zones CP1b and lower CP2 respectively. The LOs of *Buryella granulata* and *Buryella foremanae* are within nanofossil Zones CP1b to CP2 at DSDP Site 208 but their location within this interval is unknown (see Strong et al. 1995; Hollis 1997).

35. The LO of *Amphisphaera kina* is below the base of nanofossil Zone CP1b but above the base of foraminiferal Zone P1b, and therefore placed in the uppermost part of CP1a.

36. The LO *Amphisphaera aotea* is placed directly above the K/T boundary; see discussion in Hollis (1993, p. 308).
campechensis are poreless with a thick hyaline wall, whereas in B. bidartensis this feature is not so prominent. In B. divaricata the length of the cephalis and thorax, and the poreless part of the thorax is markedly shorter. Thus we are confident that in the lower part of the section we have identified Bekoma campechensis correctly, and separated it from other co-occurring taxa belonging to the genus Bekoma, which have been lumped in the category Bekoma spp. In the higher part of the section (SFP-14 - SFP-8) we have used the Bekoma spp. category to include all taxa belonging to the genus that cannot be positively identified. However, it is possible that a high proportion of the observed specimens are in fact B. bidartensis based on the fact that the HOs of B. campechensis, B. demissa and B. divaricata are usually below the LOs of Giraffosporys lata, Podocyclatis (Podocyclatis) papalis, Theocycla phyella and Thyrsocyrtis (Thyrsocyrtis) hirsuta (Sanfilippo and Nigrini 1998a). Buryella climaxata, the nominate species for the lower Eocene zone has been questionably identified in the upper part of the section (with exception of sample SFP-10) since we are unable to observe the characteristic diagonal pore alignment on the third segment (PL 2, figs. 14, 15). However, remnants of the broad-based, ridged horn have been a useful morphological characteristic for identifying this taxon and aid in its identification in the absence of good preservation. Three assemblages representing the B. campechensis, B. bidartensis and B. climaxata Zones were recognized as follows.

Biostratigraphic zones recognized in the San Francisco de Paula section

We have interpreted the co-occurrences of Bekoma campechensis, B. demissa, Bekoma spp., Buryella bidentata, B. tetradica, B. foremanae and Lamptonium pennatum to indicate that the lower part of the section (SFP-30A at 20.0 m below SFE-0 through SFP-37 at 43.44 m below SFE-0) is in the lower part of the Bekoma campechensis Zone. Evidence from Nishimura (1992) and Sanfilippo and Nigrini (1998a) confirm the HO of B. pentadica at the Bekoma campechensis/B. bidartensis zonal boundary. The HO of Buryella foremanae has been documented in DSDP Site 208 and in sections from Mead Stream, Marlborough, New Zealand in the lower Paleocene (Hollis 1993; Strong et al. 1995), where it ranges from the B. foremanae Zone to the top of the New Zealand zonal equivalent of the Bekoma campechensis Zone. Comparison of the stratigraphic ranges of taxa present in the San Francisco de Paula section with those observed in the pelagic sediments from New Zealand has offered insight into the complexity of the problems involved in comparing stratigraphic ranges of taxa from different biogeographic regions. The faunas represented in the Mead Stream section are diverse, but many of the marker species used in the Cenozoic radiolarian zonation established for the low latitudes (Riedel and Sanfilippo 1978; Sanfilippo et al. 1985; Sanfilippo and Nigrini 1998a) and for the North Atlantic (Nishimura 1987, 1992) are either absent or occur only sporadically, and vice versa (Strong et al. 1995). However, a sufficient number of age diagnostic taxa occur in both regions to attempt a preliminary correlation between the mid to high southern latitude zonal scheme developed by Hollis (1993, 1997; Strong et al. 1995) and that established for the low latitudes. As a result of this comparison we have found that some taxa encountered by Hollis in the Mead Stream section, e.g., Amphicraspedum prolaxis, Bekoma bidartensis, B. campechensis, B. divaricata, Buryella tetradica, Lamptonium pennatum, Phormocystis striata exquisita and Podocyclatis (Podocyclatis) papalis have their LOs higher, and for some of them (B. bidartensis and B. divaricata) their HOs lower, than in the tropics (see also discussion under the subheading “Lower Paleogene radiolarian zonations” above).

A second assemblage (SFP-11 at 1.1m below SFE-0 through SFP-15 at 1.5m below SFE-0) composed of Theocycla alpha, T. auctor, Theocyclas phyella, Thyrsocyrtis (Thyrsocyrtis) hirsuta, Theocycla nigriniae, Pterocodon tenellus, Podocyclatis (Podocyclatis) papalis and Phormocystis sanguinea is indicative of the Bekoma bidartensis Zone. The third assemblage includes many of the nassellarian taxa present in the B. bidartensis Zone and in addition rare Buryella climaxata in sample SFP-10, as well as questionably identified B. climaxata in SFP-9A, -9, -8 and SFE-14. Although preservation in most samples prevents positive identification of the marker species (see above), we assign the entire sequence from SFP-10 through SFE-16 to the Buryella climaxata Zone. This assignment is supported by evidence from co-occurring Podocyclatis (Podocyclatis) papalis and Theocyclas alpha, represented by later morphotypes than those encountered in the underlying Bekoma bidartensis Zone, and by the fact that the Thyrsocyrtis (Thyrsocyrtis) hirsuta population consists of a mixture of early, small morphotypes (PL 2, figs. 12) together with the more typical later forms which are larger, with medianly thickened feet (PL 2, figs. 10, 11).

Familiarity with evolving lineages may serve as a useful guide in determining stratigraphic position of one sample versus another by deciding where in the evolutionary development the morphotypes of a given lineage belong. If the phylogenetic characters of a morphotype can be considered closer (in resemblance) to those of the ancestor, then the morphotype is said to be an “early form” indicating that it is from the early part of its lineage. Later morphotypes would thus bear a closer resemblance to the descendant. For example, the genus Podocyclatis developed from the genus Cryptocarpium (Sanfilippo and Riedel 1992, p. 8) in the upper Paleocene Bekoma bidartensis Zone as described by Sanfilippo and Riedel (1973, p. 531, pl. 36, figs. 1-3). The earliest morphotypes of Podocyclatis (Podocyclatis) papalis have the two cephalic lateral lobes separated from the unpaired eucephalic lobe by furrows that extend from the point of junction of the primary lattice bars with the lattice shell to a point just below that at which the apical spine leaves the cephalic surface, the apical bar extends freely within the cephalis. Thus early forms can be distinguished from later forms, in which the lateral furrows join the apical bar at a lower point, and the apical bar is incorporated in the cephalic wall. Furthermore, in the early forms the cephalis is uniformly porous while in later forms the eucephalic part of the cephalis is poreless or sparsely pored. Recognition of the various stages of the evolving members of the Theocyclatidae lineage is important for interpreting the stratigraphy in the San Francisco de Paula section. In this lineage, Theocyclatida alpha evolved from T. auctor and gave rise to its descendant T. fics by reduction of its three triangular feet and an increase in relative size of the abdomen (Sanfilippo and Riedel 1982). Thus one would refer to morphotypes of T. alpha having a relatively large abdomen and a peristome bearing three undulations instead of three short feet as “later forms”. An additional clue is the size of the horn, which in the “late forms” has been reduced to about half the size of the stout horn inherited from its ancestor T. auctor, to resemble the horn present in the descendant T. fisus.
Stratigraphic range chart of radiolarians collected in 1993 from the San Francisco de Paula section. Radiolarian taxa arranged in approximate stratigraphic order of LO as suggested in Sanfilippo and Nigrini (1998a). LO of the six taxa marked in bold approximate the Paleocene/Eocene boundary. For stratigraphic position of the samples refer to text-figure 2 caption.
Interpretation of the data presented by E. Flores Albin (Appendix 1)

In addition to the interpretation based on our own data we present an explanation of the data given by E. Flores Albin (Appendix 1). (As noted previously, Flores Albin and his colleagues obtained samples from the San Francisco de Paula section shortly after the section was exposed. His assemblages are better preserved than those collected by us). In text-figure 5 we illustrate 35 radiolarian events recognized by Flores Albin (Appendices 1, 2) within the San Francisco de Paula section. Species included in his range chart with first occurrences above the San Francisco de Paula section include: Lamptonium pennatum, Bekoma sp. cf. B. bidartensis, Spongiscus americanus, Spongurus illepidus and Theocotylissa alpha. Species on his range chart with first occurrences below the section are: Bekoma campechensis, B. demissa, B. divaricata, Carposphaera subbotinae, Hexaconium palaecenicum, Lamptonium colymbus, L. incohatum, Lithomespilus mendosa, Orbula comitata, O. discipulus, O. ducalis and Theocotphaera larnacium. Taxa that have only single occurrences within the section and therefore are not included on the range chart are: Calocycloma amppula, Giraffospyris lata, Lamptonium fabaeforme chaenotherax, Phormocytis striata exquisita, Phormocytis turgida, Spongiscus quadrus quadrus, Stylossphaera goruna and Theocotylissa sp. cf. T. fimbria. The stratigraphic position of these taxa within the San Francisco de Paula section is considered less important since their stratigraphic ranges are not restricted to the zones represented in the San Francisco de Paula section. However, their presence confirms the events established by Sanfilippo and Nigrini (1998a).

A comparison of the species ranges in the San Francisco de Paula section as observed by Flores Albin (text-figure 5) with those known from other sedimentary sequences (Foreman 1973; Sanfilippo and Nigrini 1998) results in the following observations. Most of the differences in the species ranges in the San Francisco de Paula section from those reported elsewhere are due to poor preservation.

1. The LO of Theocotylissa auctor occurs much higher than the LO of Bekoma bidartensis in the San Francisco de Paula succession. It does not correspond to the LO of T. auctor that is synchronous with the LO of B. bidartensis as postulated by Foreman (1973). However, it is consistent with the order of the events established by Sanfilippo and Nigrini (1998a);

2. The evolutionary transition of Lamptonium pennatum to Lamptonium fabaeforme fabaeforme, an evolutionary event occurring in the B. bidartensis Zone, cannot be determined in this section, where L. pennatum appears to have a much longer stratigraphic range than L. fabaeforme, contrary to evidence from many other localities;

3. The HO of Rhopalocanium ornatum is older in this section than recorded elsewhere. It is known to occur throughout the Eocene in other sections worldwide;

4. The HO of Amphicraspedum murrayanum, A. prolixum and Eucyrtidium cubense (Phormocytis cubensis) are considered low in this section. Globally these HO's are above the HO of Theocotylissa auctor (Sanfilippo and Nigrini 1998a);

5. The HO of A. murrayanum is high; it is usually below the HO of Bekoma bidartensis; and,

6. The HO of A. prolixum is above, rather than below (its usual position), the HO of B. campechensis.

Discussion of differences in zonal assignments

Although there is general agreement between our zonal assignments and those made by Flores Albin (Appendix 1), our stratigraphic interpretations differ in the following way (text-figures 2, 4, 5; Table 1):

Flores Albin, using Maurasse’s zonation, recognized two radiolarian zones, the Eucyrtidium cubense and Bekoma bidartensis Zones. We are uncertain of the justification for his placement of the lower boundary of his Bekoma bidartensis Zone, which he places at the level of sample C23 (corresponding to our sample SFP-28). Sample C23 is from an approximately 19 meter-thick part of the section in which the radiolarians are very rare and poorly preserved, or absent due to dissolution. We interpret this interval as a zone of uncertainty between the B. campechensis and B. bidartensis Zones.

Flores Albin (Appendix 1) assigned the upper part of the San Francisco de Paula section (his sample numbers C23-C62, our corresponding sample numbers SFP-28 to SFE-16) to the upper Paleocene/lower Eocene Bekoma bidartensis Zone. In contrast, based on the identification of Buryella clinata (in sample SFP-10) we divide the upper part of the section into two zones. We place the short interval (0.5 m) represented by our samples SFP-15 to SFP-11, just above a barren interval, in the B. bidartensis Zone, and the upper part of the section (our samples SFP-10 through SFE-16, see discussion below) in the lower Eocene Buryella clinata Zone. This age assignment is supported by calcareous nannofossil stratigraphy which places the interval between samples SFP-12 and SFE-16 in calcareous nannofossil Zone NP12 (Aubry 1999, this volume).

Correlation to foraminiferal zones

Four planktonic foraminiferal zones have been recognized in the San Francisco de Paula section (Fernández-Rodriguez et al. 1999, this volume): Globonomalina pseudomenardii Total Range Zone (Zone P4), Morozovella velascoensis Interval Zone (Zone P5), Morozovella formosa formosa/Morozovella lensiformis-Morozovella aragonensis Interval Subzone (Subzone P6b) and Morozovella aragonensis/Morozovella formosa formosa Concurrent Range Zone (Zone P7). According to initial correlations by E. Flores Albin and G. Fernández-Rodriguez (in Flores Albin, Appendix 1, and Fernández-Rodriguez et al. 1999, this volume), in the San Francisco de Paula section, the Bekoma campechensis Zone (approximately equivalent to the informal Eucyrtidium cubense zone) can be correlated with the Globonomalina pseudomenardii Total Range Zone (Zone P4) and the lower part of the Morozovella velascoensis Interval Zone (Zone P5). The Bekoma bidartensis Zone, as recognized by Flores Albin (Appendix 1), correlates with the remainder of the Morozovella velascoensis Interval Zone (Zone P5), the Morozovella formosa formosa/Morozovella lensiformis-Morozovella aragonensis Interval Subzone (Subzone P6b), an unzoned interval and the Morozovella aragonensis/Morozovella formosa formosa Concurrent Range Zone (Zone P7) (text-figure 2).

It should be noted that these correlations differ somewhat from those established by Maurasse (1973), which were based on the tropical planktonic foraminiferal zonation as applied by authors working on the same DSDP samples as Maurasse. He correlated the base of his Eucyrtidium cubense zone to the lower part
TEXT-Figure 5

Highest and lowest occurrences of radiolarian species recorded by E. Flores Albin (Appendix 1) in the San Francisco de Paula section. See text for discussion.
of the Globorotalia (=Morozovella) velascoensis Zone, and the upper boundary to the lowermost part of the Globorotalia edgari Zone, which is not represented in Cuba. Further, Maurrasse correlated the base of his B. bidartensis Zone to the lower part of the Globorotalia edgari Zone, and the upper boundary to the upper part of the Globorotalia (=Morozovella) subbotinae/Globorotalia (=Morozovella) wilcoensis Zone (and not higher into the Morozovella formosa formosa Zone).

Herein, we correlate the stratigraphic interval represented by the Bekoma campechensis radiolarian Zone with the Planorotalites pseudomenardii Total Range Zone (Zone P4). The short interval unequivocally representing the Bekoma bidartensis radiolarian Zone is correlated with the Morozovella formosa formosai/Morozovella lensiformis-Morozovella aragonensis Interval Subzone (Subzone P6b). The interval between the B. campechensis and B. bidartensis Zones, represented by Zone P5 and part of Subzone P6b, cannot be assigned to either radiolarian zone. The uppermost part of the section, that is stratigraphically equivalent to the Buryella clinata Zone, is correlated with the remainder of Subzone P6b, an unzoned interval and part of the Morozovella aragonensis/Morozovella formosa formosa Concurrent Range Zone (Zone P7).

Correlation with nanofossil zones

The following calcareous nanoplankton zones have been recognized in the San Francisco de Paula section (Aubry 1999, this volume: NP6 in Sample SFP-34; NP10 in Samples SFP-13 through SFP-23; and NP12 in Samples SFE-16 through SFP-12 (Table 1, text-figures 2, 4). On the basis of calcareous nanofossil evidence, there is an unconformity between SFP-12 and SFP-13 (a 5 cm stratigraphic interval just below the previously identified Paleocene/Eocene boundary by Cuban geologists). In this part of the succession, calcareous nanofossil assemblages characteristic of Zone NP12 occur directly above assemblages characteristic of Subzone NP10d. A second possible unconformity lies between Samples SFP-24 and SFP-25. Samples collected from other intervals within the section cannot be firmly dated on the basis of nanofossil biostratigraphy.

Sample SFP-34 has been assigned to Zone NP6, which correlates with the Bekoma campechensis radiolarian Zone. Samples SFP-13 through SFP-15, in the Bekoma bidartensis Zone, correlate with the uppermost part of Zone NP10 (Subzone NP10d). Samples SFE-16 through SFP-12 in the Buryella clinata Zone correlate with Zone NP12.

Placement of the Paleocene/Eocene boundary in the San Francisco de Paula Section

As noted earlier, the Paleocene/Eocene boundary in this succession is between samples SFP-22 and -21, and coincides with the NP10a/NP10d unconformable zonal contact (Aubry 1999, this volume). The HO of Morozovella velascoensis in the San Francisco de Paula section coincides with an unconformity, and the Bekoma bidartensis radiolarian Zone extends above it. The LO of Buryella clinata, which marks the top of the Bekoma bidartensis Zone, is placed between samples SFP-10 and SFP-11 in Zone NP12. This supports the observations made by Sanfilippo and Nigrini (1998a) who determined that the LO of Buryella clinata at DSDP Site 313, and thus the uppermost part of the Bekoma bidartensis Zone are in Zone NP12 (= Zone CP10). The six radiolarian events used by Sanfilippo and Nigrini (1998a) to approximate the Paleocene/Eocene boundary occur in the San Francisco de Paula section although their presence is somewhat patchy. Our data here show that the LOs of Calocyclus caustum, Lampotomium fabeforme fabeforme, Phoreucyrtis turgida and Theocotylissa auctor are younger than the Paleocene/Eocene boundary (about 0.4 my younger than the boundary, based on the calcareous nannoplankton biochronology of Aubry et al. 1996). The LO’s of Giraffocyrtis lata and Pedocytis (Podocytis) papalis support placement of the boundary below sample SFP-15.

In Berggren et al. (1985), the Paleocene/Eocene boundary was placed at the boundary between calcareous nannofossil Zones NP9 and NP10. Detailed work by Berggren et al. (1998) and Aubry (1998) recalibrated this boundary and raised it into the middle part of Zone NP10. Although Zone NP10 has been recognized in the San Francisco de Paula section, its upper boundary is unconformable and its lower boundary is uncertain (text-figures 2, 4 and Table 1). Thus, the placement of the Paleocene/Eocene boundary in this section on the basis of nannofossils is uncertain.

Based on previous studies, the Paleocene/Eocene boundary is known to fall within the Bekoma bidartensis radiolarian Zone. In the San Francisco de Paula section it can only be recognized in a short interval extending from Samples SFP-15 through SFP-11. The lower extension of the Bekoma bidartensis Zone in the San Francisco de Paula section is uncertain due to poor preservation and barren intervals. The recognition of its upper boundary is less uncertain, but still hampered by poor preservation. Thus, the Paleocene/Eocene boundary cannot be determined in this section on the basis of radiolarians.

CONCLUSIONS

(1) The San Francisco de Paula section in western Cuba contains three radiolarian zones for the upper Paleocene and lower Eocene: Bekoma campechensis (informally Eucyrtidium cubense zone), Bekoma bidartensis and Buryella clinata Zones;

(2) Radiolarian abundance varies from rare to abundant, diversity is low, and preservation is poor. This is likely due in part to weathering;

(3) Thirty-five datum events are noted within the section. Several of these datums are higher or lower than expected when compared with the known global ranges of these species; and

(4) Based on biostratigraphic data collected in this study, the San Francisco de Paula section is undesirable as a stratotype for the Paleocene/Eocene boundary.

ACKNOWLEDGMENTS

The authors would like to thank Richard H. Fluegeman, Ball State University, and the Center for Tropical Conservation for their support in this project. Partial funding has been provided by UNESCO. We thank Joseph J. Morley for his help in acquiring literature necessary for the completion of this paper, Florentin J.M.R. Maurrasse for helpful discussions, and John A. Barron for identification of diatoms. We would also like to thank Marie Pierre Aubry, William A. Berggren and Christopher J. Hollis who reviewed earlier versions of this article and offered many suggestions for its improvement. Special thanks to Kathryn L. Meyerhoff for drafting the locality map. This paper is a contribution to IGCP Project #308, Paleocene/Eocene Boundary Events in Space and Time. This work was supported in part by NSF grant number OCE91-23712 (to A. Sanfilippo).
TABLE 1
Radiolarian occurrences in samples collected in 1993 in the San Francisco de Paula section. LOs of the six radiolarian taxa, indicated in bold in the heading of the table, approximate the Paleocene/Eocene boundary. A=abundant; C=common; F=few; R=rare; VR=very rare; ++=present; B=barren; ?=questionable identification. M=moderate; P=poor; VP=very poor; D=dissolved and unrecognizable radiolarians. Abundances marked with an asterisk in the Bekoma spp. column indicate probable presence of *Bekoma bidartensis*. For stratigraphic position of the samples refer to text-figure 2 caption.
REFERENCES


PLATE 1
Magnification X280 unless otherwise noted.

1 Spongodiscus cruciferus (Clark and Campbell). SFP-9 Cs.1 H2/0, magn. 180X.

2 Amphicraspedum murrayanum Haeckel. SFP-9 Cs.1 Y29/3, magn. 180X.

3 Stylotrichus quadribachiatus quadribachiatus Sanfilippo and Riedel. SFP-9 Cs.1 W4/3, magn. 180X.

4-6 Lamptonium pennatum Foreman. 4) SFP-9 Cs.2 D12/2; 5) Ph.1 H1/1; 6) SFP-36 Ph.2 R30/0.

7,8 Lamptonium fabaeforme fabaeforme (Krasheninnikov). SFP-9 Ph.1 D25/0; 8) SFP-8 L6/4.

9,10 Buryella pentadica Foreman. SFP-33 V12/0; 10) SFP-36 Ph.2 R7/3.

11 ?Bekoma (?) demissa Foreman. SFP-33 W36/0.

12,13 ?Bekoma campechensis Foreman. SFP-36 Ph.1 D44/4; 13) SFP-33 Z39/1.

14,16,17 Bekoma spp. SFP-33 X34/3; 16) Q40/0; 17) SFP-36 Ph.2 X19/2.

15 Spongodiscus quartus quartus (Borisenko). SFP-9 Cs.1 G24/3, magn. 180X.

18 Giraffospyris lata Goll. SFP-9 Ph.1 040/0.

19,20 Buryella tetradica Foreman. SFP-36 Ph.2 L28/3; 20) F7/4.

21 Calocycloma castum (Haeckel). SFP-9 Cs.2 P38/2.
A. Sanfilippo and D.M. Hall: Upper Paleocene - Lower Eocene radiolarian biostratigraphy of the San Francisco de Paula Section, western Cuba


--- Plate 2 ---

Magnification X280 unless otherwise noted

1.2 Phormocytis cubensis (Riedel and Sanfilippo). SFP-9 Cs.1 S24/3; 2) Ph.1 K2/1.

3.4 Phormocytis striata exquisita (Kozlova). SFP-9 Ph.1 J19/1; 4) J29/1.

5 Phormocytis striata striata Brandt. SFP-9 Ph.1 U32/1.

6 Phormocytis turgida (Krasheninnikov). SFP-9 Cs.1 G24/3, magn. 180X.

7-9 Theocotylissa auctor Foreman. SFP-9 SI.3 J23/0; 8) Q37/4; 9) Ph.1 B13/0.

10-12 Thyrsocytis (Thyrsocytis) hirsuta (Krasheninnikov). SFP-9 Ph.1 V19/3; 11) SI.3 H21/3; 12) SFP-10 G36/1.

13 Pterocodon (?) tenellus Foreman. SFP-9 Ph.1 U37/4.

14,15 ? Buryella clinata Foreman. SFP-9 Ph.1 W15/0; 15) SFP-10 O24/1.

16,17 Theocotyle nigriinae Riedel and Sanfilippo. SFP-9 Ph.2 S3/3; 17) Ph.1 N38/1.

18,19 Theocotylissa alpha Foreman. SFP-9 Cs.1 F36/0; 19) W16/0.

20,21 Theocorys (?) phyzella Foreman. SFP-9 Ph.2 T5/2; 21) Ph.1 P5/2.

22 Podocyrtis (Podocyrtis) papalis Ehrenberg. SFP-9 Ph.1 W38/2.
A. Sanfilippo and D.M. Hull: Upper Paleocene - Lower Eocene radiolarian biostratigraphy of the San Francisco de Paula Section, western Cuba


PLATE 3

Scanning electron micrographs of radiolarians collected from the San Francisco de Paula section by Emilio Flores Albin (Appendix 1). Sample locations unknown. Identifications by A. Sanfilippo; photographs were taken by D. Hull at the University of Texas at Dallas. Scale (upper right) = number of microns cited for each figure.

1. ?Orbula discipulus Foreman. Scale = 150μm.
2. Lamptonium (?) colymbus Foreman. Scale = 85.8μm.
3. ?Buryella tetradica. Scale = 60μm.
4. ?Bekoma sp. Scale = 60μm.
5. Lamptonium fabaeforme fabaeforme (Krasheninnikov). Scale = 60μm.
6. Theocotylissa alpha Foreman. Scale = 85.8μm.
7. ?Orbula discipulus Foreman. Scale = 85.8μm.
8. ?Bekoma sp. Scale = 60μm.
9. Orbula comitata Foreman. Scale = 85.8μm.
10. Lamptonium (?) incohatum Foreman. Scale = 85.8μm.
11. Orbula ducalis Foreman. Scale = 85.8μm.
12. Bekoma sp. Scale = 60μm.
13. Clathrocycloma capitaneum Foreman. Scale = 60μm.
14. Bekoma (?) demissa Foreman. Scale = 60μm.
15. Thyrsocyrtis (Thyrsocyrtis) hirsuta Foreman. Scale = 60μm.


A. Sanfilippo and D.M. Hull: Upper Paleocene - Lower Eocene radiolarian biostratigraphy of the San Francisco de Paula Section, western Cuba


Buryella clinata interval-chronozone (Riedel and Sanfilippo STRONG, C. P., HOLLIS, C. J. and WILSON, G. J., 1995. Paula section, is placed at the evolutionary bottom of the top, which has not been recognized in the San Francisco de Paula section shown on text-figure 5. Some forms are illustrated on Plate 3. [For a complete species list, additional photographs and taxonomic references: see Appendix 2 and Plates 1, 2].

The most common radiolarians recognized in the Paleocene assemblages by this author (EFA) are:

- **Bekoma campechensis** Foreman
- **Bekoma (?) demissa** Foreman
- **Bekoma divaricata** Foreman
- **Clathrocycla capitaneum** Foreman
- **Diploplegma somphum** Sanfilippo and Riedel
- **Hexacontium palaeocenicum** Sanfilippo and Riedel
- **Lamptonium (?) colymbus** Foreman
- **Lamptonium (?) incohatum** Foreman
- **Lithomespilus mendoza** (Krasheninnikov)
- **Orbula complita** Foreman
- **Orbula discipulus** Foreman
- **Orbula ducalis** Foreman

Paleocene species which extend into the lower and middle Eocene and are present in the succession include:

- **Bekoma bidartensis** Riedel and Sanfilippo
- **Eucyrtidium cubense** Riedel and Sanfilippo (= *Phormocyrtis cubensis* (Riedel and Sanfilippo) Foreman)
- **Lamptonium pennatum** Foreman
- **Phormocyrtis striata exquisita** (Kozlova)
- **Spondgodiscus quartus quartus** (Borisenko)
- **Stylosphaera goruma** Sanfilippo and Riedel
- **Theoctyliassa auctor** Foreman

Species which appear for the first time in lower Eocene sediments are:

- **Lamptonium fabaeforme chaunothorax** Riedel and Sanfilippo
- **Lamptonium fabaeforme fabaeforme** (Krasheninnikov)
- **Theoctyliassa alpha** Foreman
- **Theoctyliassa fimbria** Foreman

Four planktonic foraminiferal zones are recognized in the San Francisco de Paula section: **Globanomalina pseudomenardii**, **Morozovella velascoensis**, **Morozovella subbotinae** and **Morozovella formosa formosa** Zones (Fernández-Rodríguez et al. 1999, this volume). In the San Francisco de Paula section, the **Eucyrtidium cubense** zone can be correlated with the Globanomalina pseudomenardii (= *Phormocyrtis cubensis* (Riedel and Sanfilippo) Foreman) **Lamptonium pennatum** Foreman **Phormocyrtis striata exquisita** (Kozlova) **Spondgodiscus quartus quartus** (Borisenko) **Stylosphaera goruma** Sanfilippo and Riedel **Theoctyliassa auctor** Foreman **Theoctyliassa fimbria** Foreman

Two radiolarian zones were recognized in early studies of the San Francisco de Paula section: the **Eucyrtidium cubense** zone and the **Bekoma bidartensis** Zone (upper Paleocene-lower Eocene; text-figures 2, 3, 5). The **Eucyrtidium cubense** zone was proposed as an informal partial range zone by Maurrasse (1973, unpublished thesis) for the Caribbean region, the Atlantic and part of the Pacific Ocean. Its base is defined by the earliest morphotypic appearance of **E. cubense**. The top of this zone is recognized by the first occurrence of **Bekoma bidartensis**, which is in the upper Paleocene. The **Bekoma bidartensis** Zone was defined by Foreman (1973). Its base is recognized by the earliest morphotypic appearance of **Bekoma bidartensis**; the top, which has not been recognized in the San Francisco de Paula section, is placed at the evolutionary bottom of the **Buryella clinata** interval-chronozone (Riedel and Sanfilippo 1978).
APPENDIX 2
Species List (Species indicated by an asterisk are from Flores Albin’s tabulation, text-figure 5).

*Amplicraspedum murrayanum* Haeckel 1887, p. 523, pl. 44, fig. 10; Sanfilippo and Riedel 1973, p. 524, pl. 10, figs. 3-6, pl. 28, fig. 1. [Plate 1, figure 2]

*Amplicraspedum prophylum* Sanfilippo and Riedel 1973, p. 524, pl. 10, figs. 7-11, pl. 28, figs. 3-4.

*Bekoma bidartensis* Riedel and Sanfilippo 1971, p. 1592, pl. 7, figs. 1-7; Foreman 1973, p. 432, pl. 3, figs. 20-21, pl. 10, fig. 6; Sanfilippo et al. 1985, p. 667, figs. 15.1a, b; Nishimura 1992, p. 332, pl. 5, figs. 8-9.

*Bekoma sp. cf. B. bidartensis*. We do not know how Flores Albin’s concept differs from the original description.

*Bekoma campechensis* Foreman 1973, p. 432, pl. 3, fig. 24, pl. 10, figs. 1-2, 4; Nishimura 1992, p. 332, pl. 5, figs. 1-4, pl. 13, fig. 1. [Plate 1, figures 12, 13]. Not a single specimen belonging to the genus *Bekoma* was observed with feet. In spite of this we have made an attempt to distinguish *B. campechensis* from other co-occurring taxa of the genus *Bekoma* by using the characteristic shape of the cephalis for each taxon. *Bekoma campechensis* has a long dome-shaped to rectangular cephalis, while *B. demissa* has a cephalis with numerous pores that appears slightly depressed into the thorax. The cephalis and proximal elongated part of the thorax in *B. campechensis* are poreless with a thick hyaline wall, while in *B. bidartensis* this feature is not so prominent. In *B. divaricata* the length of the cephalis and thorax, and the poreless part of the thorax is markedly shorter.

*Bekoma (?) demissa* Foreman 1973, p. 432, pl. 3, fig. 22, pl. 10, figs. 5-6. See comment for *B. campechensis* above. [Plate 1, figure 11; Plate 3, figure 14]

*Bekoma divaricata* Foreman 1973, p. 433, pl. 3, fig. 23, pl. 10, figs. 3-4.

*Bekoma sp. A*. This species is from Flores Albin’s original study. We have no further information.

*Bekoma* spp. In this category we have included two-segmented *Buryella* clinata Foreman 1973, p. 433, pl. 1, figs. 1-3, pl. 8, figs. 1-3, pl. 9, figs. 1-4, pl. 13, fig. 1. [Plate 1, figures 12-13].

*Lithochytris archaea* Riedel and Sanfilippo 1970, pl. 9, fig. 8; Sanfilippo and Riedel 1973, p. 529, pl. 23, figs. 7, 8.


*Lanptomium pennatum* Foreman 1973, p. 436, pl. 6, figs. 3-5, pl. 11, fig. 13; Sanfilippo et al. 1985, p. 674, fig. 18.1. [Plate 1, figures 7, 8; Plate 3, figure 5]

*Lanptomium (?) pennatum* Foreman 1973, p. 436, pl. 6, figs. 3-5, pl. 11, fig. 13; Sanfilippo et al. 1985, p. 674, fig. 18.1. [Plate 1, figures 7, 8; Plate 3, figure 5]

*Lanptomium (?) incohatum* Foreman 1973, p. 436, pl. 6, fig. 1, pl. 11, fig. 18. [Pl. 3, fig. 10]

*Lanptomium pennatum* Foreman 1973, p. 436, pl. 6, figs. 3-5, pl. 11, fig. 13; Sanfilippo et al. 1985, p. 674, fig. 18.1. [Plate 1, figures 4-6]

*Lanptomium sanfilippioae* Foreman 1973, p. 436, pl. 6, figs. 15, 16, pl. 11, figs. 16, 17.

*Lithochytris archaea* Riedel and Sanfilippo 1970, p. 9, fig. 8; Foreman 1973, p. 436, pl. 2, figs. 4, 5.

*Lithomespilus mendosum* (Krasheninnikov). *Ellipsidium (?) mendosum* Krasheninnikov 1960, p. 281, pl. 1, fig. 14; Sanfilippo and Riedel 1973, p. 517, pl. 4, figs. 6, 7, pl. 24, fig. 10, 11.

*Orbula comitata* Foreman 1973, p. 437, pl. 3, fig. 11, pl. 10, figs. 5, 7, 8. [Plate 3, figure 9]

*Orbula discipulus* Foreman 1973, p. 438, pl. 3, fig. 10, pl. 9, figs. 9, 10. [Plate 3, figures 1-7]

*Orbula ducalis* Foreman 1973, p. 438, pl. 3, fig. 12, pl. 10, figs. 11, 12, [Plate 3, figure 11]


*Phormocyrtis striata exquisita* (Kozlova). *Podocyrtis exquisita* Kozlova in Kozlova and Gorbovets 1966, p. 106, pl. 17, fig. 2. *Phormocyrtis striata exquisita* (Kozlova) Foreman 1973, p. 438, pl. 7, figs. 1-4, 7, 8, pl. 12, fig. 5 (with synonymy); Sanfilippo et al. 1985, p. 678, figs. 20a-c. [Plate 2, figures 3, 4]

*Phormocyrtis striata Striatula* Brandt. *Phormocyrtis striata Striatula* Brandt 1935, p. 53, pl. 9, fig. 12; Riedel and Sanfilippo 1970, p. 532, pl. 10, fig. 7; Foreman 1973, p. 438, pl. 7, figs. 5, 6, 9; Sanfilippo et al. 1985, p. 679, figs. 21.1a, b. [Plate 2, figure 5]

*Phormocyrtis turgida* (Krasheninnikov). *Lithocampe turgida* Krasheninnikov 1960, p. 301, pl. 3, fig. 17. *Phormocyrtis*
Podocyrtis (Podocyrtis) papalis Ehrenberg. Podocyrtis papalis
Ehrenberg 1847, p. 55, fig. 2; 1854, pl. 36, fig. 23; 1873,
p. 251; Riedel and Sanfilippo 1970, p. 533, pl. 11, fig. 1;
Sanfilippo and Riedel 1973, p. 531, pl. 20, figs. 11-14, pl.
36, figs. 2, 3, 5; Sanfilippo and Riedel 1992, pl. 3,
figs. 9, 10. [Plate 2, figure 22]

Pterocodon (?) tenellus Foreman 1973, p. 439, pl. 5, fig. 7; pl.
*Spongodiscus cruciferus (Clark and Campbell).

Stylotrochus quadribrachiatus quadribrachiatus Sanfilippo
* Spongodiscus americanus Kozlova, in Kozlova and
*Spongodiscus quartus quartus (Borisenko). Staurodictya
*Spongurus illepidus Krasheninnikov 1960, p. 283, pl. 2, fig.
Theocotyle nigriniae Riedel and Sanfilippo. Theocotyle
Theocorys (?) phyzella Foreman 1973, p. 440, pl. 5, fig. 8; pl.
* Theocosphaera auctor Foreman 1973, p. 441, pl. 5, figs. 4-6, pl.
* Spongasteriscus cruciferus Clark and Campbell, 1942, p.
* Stylostropha lorata Kutuzov 1970, p. 525, pl. 6, fig. 5 (non 6);
Theocotylissa alpha -> Theocotylissa
* Stylostropha lorata Kutuzov 1970, p. 525, pl. 6, fig. 5 (non 6);
Theocotylissa alpha Foreman 1973, p. 441, pl. 4, figs. 13-15 (non 14), pl.
* Stylostropha lorata Kutuzov 1970, p. 525, pl. 6, fig. 5 (non 6);

APPENDIX 3
The definitions of the radiolarian zones applied herein are from

Phormocyrtis striata striata Interval Zone (Foreman 1973; emend. Riedel and Sanfilippo 1978)

TOP: evolutionary transition from Theocotyle nigriniae to
Theocotyle cryptocephala; coincident with the lower limit of the
Theocotyle cryptocephala Zone.

BASE: morphotyptic LO of Theocorys anaclasta; coincident with the upper limit of the Burrella clinata Zone.

Events included in the zone are:
Spongatractus balbis -> Spongatractus pachystylus
LAD Lamptonium sanfilippoae
FAD Thyrsocorys (Thyrsocorys) rhizodon
FAD Podocyrtis (Podocyrtiges) diamesa

The lower limit of the zone is approximately synchronous with FAD Lamptonium fabaeforme constrictum; Phormocyrtis
striata exquisita -> Phormocyrtis striata striata; FAD Podocyrtis (Lamptonium) acales; LAD Phormocyrtis cubensis; FAD Lychnocanoma bellum.

Burrella clinata Interval Zone (Foreman 1973; emend. Foreman 1975; emend. Riedel and Sanfilippo 1978)

TOP: morphotypy LO of Theocorys anaclasta; coincident with the lower limit of the Phormocyrtis striata striata Zone.

BASE: evolutionary transition from Pterocodon ?anteclinata to
Burrella clinata; coincident with the upper limit of the Bekoma bidartensis Zone.

Events included in the zone are:
LAD Pterocodon ampla; LAD Bekoma bidartensis; LAD Burrella tetradica; LAD Thyrsocorys (Thyrsocorys) tarsipes
FAD Lithocyclia ocellus group; FAD Thyrsocorys (Pentalacorys) tensa; Theocotylissa alpha -> Theocotylissa
ficus
FAD Calocyclas hispida

The lower limit of the zone is approximately synchronous with FAD Spongatractus balbis; FAD Lamptonium sanfilippoae; FAD Theocotyle nigriniae; FAD Thyrsocorys (Thyrsocorys) hirsuta

Remarks: This zone corresponds to the stratigraphic range of B. clinata (above its evolutionary transition from P. (?) anteclinata) below the LO of T. anaclasta.

Bekoma bidartensis Interval Zone (Foreman 1973; emend. Nishimura 1992; emend. Sanfilippo and Nigrini 1998b)

TOP: evolutionary transition from Pterocodon ?anteclinata to Burrella clinata; coincident with the lower limit of the Burrella clinata Zone.

BASE (redefined in Sanfilippo and Nigrini 1998b): morphotypic LO of Bekoma bidartensis; coincident with the upper limit of the Bekoma campechensis Zone. Nishimura (1992) revised the definition of the base of this zone to the evolutionary
transition from *Bekoma campechensis* to *Bekoma bidartensis*. Sanfilippo and Nigrini (1998b) rejected this emendation because, in practice, they found that recovered sediment sequences of this age are short and discontinuous and thus unsuitable for recognizing evolutionary transitions. The definition was therefore emended back to the original definition of Foreman 1973.

The Paleocene/Eocene boundary lies within this zone (Sanfilippo and Nigrini 1998a)

Events included in the zone are:

- **FAD** *Theocotylissa alpha*
- **FAD** *Lamptonium fabaeforme chaunothorax*
- **FAD** *Pterocodon ? anteclinata; FAD Lophocyrta (Lophocyrta) jacchia*
- **FAD** *Calocycloma castum; Lamptonium pennatum -> Lamptonium fabaeforme fabaeforme*
- **FAD** *Podocyrta (Podocyrta) papalis*
- **LAD** *Bekoma campechensis*

**Bekoma campechensis Interval Zone** (Nishimura 1987; emend. 1992; emend. Sanfilippo and Nigrini 1998b)

**TOP** (redefined in Sanfilippo and Nigrini 1998b): the morphotypic LO of *Bekoma bidartensis*. The definition is emended (ibid.) to coincide with the lower limit of the *Bekoma bidartensis* Zone.

**BASE**: morphotypic LO of *Stylotrochus nitidus* and *Pterocodon(?) poculum*, coincident with the upper limit of the *Orbula discipulus* Interval Subzone.

**Orbula discipulus Interval Subzone** (Nishimura 1992; emend. Sanfilippo and Nigrini 1998b)

**TOP** (defined in Sanfilippo and Nigrini 1998b): morphotypic LO of *Stylotrochus nitidus* and *Pterocodon(?) poculum*, coincident with the lower limit of *Stylotrochus nitidus - Pterocodon(?) poculum* Interval Subzone.

**BASE** (defined in Sanfilippo and Nigrini 1998b): morphotypic HO of *Peritiviator(?) dumitricai*, coincident with the upper limit of *Peritiviator(?) dumitricai* Interval Subzone.

**Peritiviator(?) dumitricai Concurrent Range Subzone** (Nishimura 1992)

**TOP**: morphotypic HO of *Peritiviator(?) dumitricai*, coincident with the lower limit of *Orbula discipulus* Interval Subzone.

**BASE**: morphotypic LO of *Bekoma campechensis*