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Upper Paleocene radiolarians from DSDP Sites 549 and 550, Goban Spur, NE Atlantic

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Abstract

Upper Paleocene-lower Eocene sequences of mainly pelagic sediments in DSDP Sites 549 and 550 of Goban Spur, NE Atlantic, representing time periods of 10 and 6 m.y. respectively, were examined to investigate the biotic response of radiolarians to the PETM. The preservation of radiolarians in the lower Eocene sequences for both sites is poor. Upper Paleocene radiolarian assemblages, representing a time interval of ~ 59-56 Ma at Site 549 and a much shorter period at Site 550, are generally moderately well-preserved. Fifty four species were identified. Four species occur significantly earlier in the middle high latitude NE Atlantic than in New Zealand, where the sudden appearance during the PETM has been taken as evidence of global pole-ward migration of warm-water radiolarians. Available model shows that the Goban Spur area should belong to the subpolar surface ocean gyre in the early Paleogene. Thus, our investigation questions the validity of the previously used index species of subtropical warm water masses. High-latitude offshore sections across the P/E boundary with well preserved radiolarians are needed to test the hypothesis of pole-ward migration of warm-water radiolarians during this geologically transient global warming period.

Keywords: Upper Paleocene; radiolarians; NE Atlantic; biotic response; PETM

1 Introduction

Biotic responses to the Paleocene – Eocene thermal maximum (PETM) have been extensively studied (e.g., Aubry et al., 1998; Wing et al., 2003) since the associated CIE (Carbon Isotope Excursion) and PETM were first identified in the southern ocean ODP Site 690 (Kennett and Stott, 1991). Radiolarians, the skeletons of which are composed of pure amorphous opaline silica, are extremely diverse and widely distributed marine plankton with a long geologic history (De Wever et al., 2001). Detailed studies of this group across the PETM provide a useful opportunity to investigate the response of siliceous fossils to this geologically transient global warming period, which will contribute to our more general understanding of the biosphere-geosphere interactions in this period.

To investigate the effect of the PETM on radiolarian fauna, the first study was conducted using DSDP/ODP samples by Sanfilippo and Nigrini (1998). They re-examined all of the then available deep-sea sections (DSDP/ODP Legs 1-135) and selected 12 DSDP and ODP sites between 40°N and 30°S containing upper Paleocene-lower Eocene radiolarians. However, no obvious changes in the radiolarian assemblages were reported in this study because there are no continuous sections across the PETM preserved at these sites (Sanfilippo and Nigrini, 1998). Subsequently, radiolarians were reported in upper Paleocene – lower Eocene sections from western Cuba (Sanfilippo and Hull, 1999), but other biostratigraphic evidence shows that the P/E boundary in this section lies within an unconformity. It had been hoped that ODP Leg 165 would provide a good place to examine the paleoenvironmental signals provided by radiolarians during the PETM, but generally very poor preservation of radiolarians made this impossible (Nigrini and Sanfilippo, 2000).

Subsequently, radiolarian assemblages in a well-constrained P/E boundary section from western North Atlantic ODP Hole 1051A were reported (Sanfilippo and Blome, 2001). This section contains the only known record of a well-preserved PETM radiolarian assemblage in the deep-sea. The results show that there is no obvious change in radiolarian composition (number of first and last occurrences of radiolarian taxa) across the PETM interval and only two first occurrences of radiolarian taxa (*Podocyrtis papalis* and *Phormocyrtis turgida*) were identified in the interval of the PETM (Sanfilippo and Blome, 2001).

A recent study provides the only quantitative investigation of radiolarians across the P/E boundary using samples from an onshore section in New Zealand (Hollis, 2006). This section is also the only one that shows a significant faunal change during the PETM with the first occurrences of 13 species in the PETM interval between 157 m and 160.9 m above the K/T boundary (Hollis, 2006; Hollis et al., 2005). The last occurrences of three species in this interval suggest that the faunal turnover is not an artifact of stratigraphic discontinuity (Hollis, 2006). Based on the abrupt appearance of five so-called typical low-latitude species, a pole-ward migration of warm-water radiolarians during the PETM was suggested (Hollis, 2006).

During Deep Sea Drilling Project (DSDP) Leg 80, four sites were drilled on the Goban Spur in the NE Atlantic (Fig. 1). The main objective of this leg was to investigate the development of the continental margin of Western Europe (de Graciansky et al., 1985). Sites 549 and 550 drilled an expanded sequence within Chron C24r that contains part of the PETM interval and records a number of events related to it. Hence, abundant research has been conducted using materials from these sites (e.g., Ali and Hailwood, 1998; Kahn and Aubry, 2004; Knox et al., 1996; Thomas and Bralower, 2005). However, early Paleogene radiolarians from these sites have not been studied until now.

In order to investigate the biotic response of radiolarians to the PETM, we examined samples across the P/E boundary from these two sites (~59-49 Ma for Site 549 and ~57-51 Ma for Site 550). Unfortunately, the results are disappointing in that the preservation of radiolarians is very variable. The radiolarian assemblages above and just below the PETM are so poor that their identification is almost impossible. However, we have found that the upper Paleocene radiolarians are generally well-preserved and several so-called warm-water species used by Hollis (2006) to indicate a pole-ward migration of radiolarians during the PETM occurred significantly earlier in the NE Atlantic than in New Zealand. Thus, the main objectives of this study are to document late Paleocene radiolarian faunas and events from Leg 80 and discuss the implications of the significantly earlier occurrence of these so-called warm-water species in the NE Atlantic compared to New Zealand.

2 Materials and methods

2.1 Sample preparation

This study is based on the paleomagnetic samples used in the study by Ali and Hailwood (1998). Sixty-four samples from DSDP Site 549 between 274.91 mbsf (meters below sea floor) and 381.12 mbsf including the well-constrained P/E boundary and 17 samples from Site 550 between 328.38 mbsf and 424.98 mbsf were processed. For the extraction of radiolarians, the techniques used differ slightly from the traditional method for soft marine sediments introduced by Sanfilippo et al. (1985). Each sample was first put into a 400 cm^3 beaker with about 200 ml of a solution of 10% hydrogen peroxide and in which about 5g sodium pyrophosphate had been dissolved to remove organic materials and disaggregate the sediment. It was then sieved at 400 µm (if lumps remained, the above procedure was repeated), 180 µm (if radiolarians were abundant) and 63 µm. Several drops of dilute hydrochloric acid were then put into the residue to remove the calcareous component and it was again sieved at 63 µm. Finally, the cleaned residue was placed in an oven to dry at about 50°C and then transferred into a plastic bottle for storage.

The cleaned residue was mounted using Norland Optical Adhesive and covered with a 22 × 38 mm cover slip. All radiolarians were counted for samples for which only one slide can be prepared. For richer samples, two slides were prepared and examined. To save time, the following double count method was used. About one thousand specimens were first counted. The remainder was then searched for rare species. Selected specimens were mounted on SEM stubs using a thin brush under a binocular microscope, and then coated with gold. Digital images were captured using a SEM.

The total abundance of radiolarians in each sample was roughly estimated based on the weight of siliceous residue: A (abundant, > 0.1 g), C (common, 0.01 – 0.1 g), F (few, < 0.01 g), B (barren). The following abbreviations are used for species abundance and preservation: A = abundant (> 50 individuals for each species), C = common (5 - 50) and F = few (< five); and W = good (minor dissolution), M = moderate (apparent dissolution with possible identification), P = poor (identification impossible), and S = silicified.

2.2 Age model

The age model for Sites 549 and 550 is based on published biostratigraphic and geomagnetic data (Table 1). Numerical ages assigned to these events were derived from GTS2004 (Gradstein et al., 2005). Linear sedimentation rates were assumed between datum ages.

3. Hiatuses, lithology, and siliceous fossil occurrences

3.1 Site 549

Two holes (549A and 549) were drilled at Site 549 with a water depth of about 2533 m. Lithology at this site has been divided into 11 units (de Graciansky et al., 1985). Our sampled cores belong to lithologic units 2 and 3 of Hole 549 (Table 2).

Samples 549-10-1-41 to -10-3-60 were collected from lithologic unit 2 that mainly consists of nannofossil chalks. Abundant poorly preserved siliceous fossils were extracted from these samples except for sample 549-10-1-41 that generated some moderately preserved radiolarians. Samples 549-10-4-30 to -14-6-86 belong to subunit 3a, which is composed of marly nannofossil chalks in which no siliceous fossils were previously reported (de Graciansky et al., 1985). Siliceous fossils were successfully extracted from samples 549-10-4-30 to -11-2-19 and from 549-13-2-71 to -13-6-107, but the very poor preservation of these samples makes identification impossible. Samples 549-15-1-119 to -16-3-11 belong to subunit 3b that consists of nannofossil chalks. No siliceous fossils were extracted from these samples.

A short hiatus between subunits 3b and 3c removed the topmost part of the CIE recovery (Thomas and Bralower, 2005) based on the orbitally-tuned age model for ODP Site 690 (Röhl et al., 2000). The top of the PETM at Site 549 is located between 335.16 mbsf and 335.55 mbsf corresponding to the lowest occurrence of nannofossil *Tribrachiatus contortus* (morphotype B) and the highest occurrence of *Fasciculithus tympaniformis* respectively (Aubry et al., 1996) if we follow the orbital age model. The base of the CIE that has been taken as the P/E boundary and assigned a numerical age of 55.8 Ma (Gradstein et al., 2005) is located at 339.68 mbsf at Site 549 (Thomas and Bralower, 2005). Thus our samples 549-16-4-36 and 549-16-5-35 are located between the onset of the CIE and top of the PETM and consequently, become the most important samples to examine if there are so-called excursion taxa or a sudden acme of a certain group such as those that have been reported in several other marine planktonic protozoans including siliceous diatoms (Sluijs et al., 2007). Unfortunately, preservation of siliceous fossils in these two samples is very poor and identification of radiolarian taxa is thus impossible.

Samples 549-16-6-83 to -17-6-138 belong to subunit 3c that is composed of siliceous marly nannofossil chalks. Except for those silicified samples, radiolarians are generally well preserved and abundant in this subunit. Samples 549-17-7-7 to -21-2-62 belong to subunit 3d that is composed of siliceous nannofossil chalks. Radiolarian fossils are generally abundant and well preserved between samples -17-7-7 and -19-2-46 except for those samples that are silicified. However, the preservation deteriorates downhole.

The details of preservation and occurrence of radiolarians of Site 549 are listed in Table 2. The stratigraphic ranges of radiolarian species of this site are presented in Fig. 2.

3.2 Site 550

Two holes were drilled at Site 550, the deepest site of the Goban Spur transect with a water depth of 4432 m. Hole 550 contains a thick section of upper Paleocene-lower Eocene marly nannofossil chalk (lithological subunit 2a) and siliceous marly nannofossil chalk and mudstone (lithological subunit 2b). A short hiatus exists between subunits 2a and 2b. Siliceous fossils are generally sparse in the processed samples of Subunit 2a and no identifiable radiolarians are extracted from these samples. Four samples belong to the Subunit 2b were processed, of which three samples contain identifiable radiolarians. The details of preservation and occurrence of radiolarians of Site 550 are listed in Table 3.

4 Did a pole-ward migration of warm-water radiolarians occur during the PETM?

Based on the abrupt appearance of five species in a New Zealand section including *Amphicraspedum murrayanum*, *A. prolixum* s.s., *Bekoma bidartensis*, *Lychnocanium auxilla* (*Lychnocanoma auxilla* in our paper), and *Phormocyrtis cubensis* that were taken as subtropical index species with upper Paleocene FOs at low latitudes, Hollis (2006) concluded that global warming during the PETM promoted pole-ward migration of warm-water radiolarians. This opinion was also adopted by a comprehensive review paper on the PETM (Sluijs et al., 2007). Our investigation at the Goban Spur area, however, questions the validity of these species as index species of tropical-subtropical warm currents.

Except for *Phormocyrtis cubensis* that is not present in our samples, four of these five species taken as typical low-latitude warm water species (Hollis, 2006) show significantly earlier FOs in Site 549 compared with the New Zealand section (Fig. 2; Table 2). During the late Paleocene, Goban Spur was located at similar latitude to Mead Stream (Fig. 3). Modeled result (Huber et al., 2004) shows that both the Goban Spur and the Mead Stream should belong to the subpolar surface ocean gyres in the early Paleogene times. Although there is no direct proxy data of temperature from NE Atlantic and New Zealand in late Paleocene, available proxy data from Bighorn Basin (Paleolatitude ~45^{0} N, Wing et al., 2000), Arctic regions (Slujis et al., 2006; Tripati et al., 2001; Weijers et al., 2007), and SW Pacific (Bijl et al., 2009) suggest that NE Atlantic is probably not warmer than New Zealand during the late Paleocene. Thus, the occurrence of these four species at the Goban Spur during the late Paleocene indicates that they were probably more cosmopolitan rather than limited to the warm subtropical ocean gyres.

In addition, the PETM is a geologically transient period, which only lasted ~170,000 years (Röhl et al., 2007). If Hollis's (2006) hypothesis that typical warm water radiolarians migrated into the New Zealand region with the expansion of the subtropical warm pool during the PETM is right, these species should disappear from Mead Stream after the PETM as is observed in dynocyst *Apectodinium*, a typical subtropical dinoflagellate whose occurrence in high latitudes is limited to the duration of the PETM (e.g., Sluijs et al., 2006). However, except for *Amphicraspedum murrayanum* which only existed during the PETM at Mead Stream, four of these five species extended above the PETM (Hollis, 2006).

On the other hand, we notice that radiolarians are more poorly preserved in the upper Paleocene at Mead Stream in New Zealand compared with those associated with Eocene strata (Hollis, 2006). Thus, an alternative explanation should be considered, i.e. that the abrupt appearance of these so-called warm-water species is an artifact of severe diagenesis and/or dissolution below the CIE base compared with the section above the CIE base.

Although we doubt the validity of Hollis' subtropical index fossils, we are not saying that an expansion of subtropical warm pool and consequently, a pole-ward migration of warm water radiolarians is impossible during the PETM. To test this hypothesis, however, we need more knowledge about the biogeographic distribution of radiolarians around the P/E boundary, especially from high latitude sites with well preserved radiolarians.

5. Conclusion

Well preserved radiolarians were extracted from the upper Paleocene at DSDP Sites 549 and 550. They permit sufficient identification and provide important data, which will help fill an informational gap in the radiolarian distribution at middle high latitudes in the North Atlantic. Radiolarian preservation is discontinuous throughout the upper Paleocene-lower Eocene and preservation is generally poor in other sections. Four out of five species taken as typical warm water indicators by Hollis (2006) have significantly earlier FOs at Goban Spur compared with Mead Stream leading us to suggest that the abrupt appearances of these species at Mead Stream are likely an artifact caused by severe diagenesis and/or dissolution. The hypothesis of a pole-ward migration of warm water radiolarians during the PETM remains premature at present and needs to be tested by sampling of high latitude sites that across the PETM with well preserved radiolarians.

6. Species list

Reference to the author, the first definition, the first illustration, the currently adopted species concept and consulted illustration are given. Species listed here are in alphabetical order. All illustrated specimens are deposited at Department of Earth Sciences, The University of Hong Kong and can be located with SEM stub number, followed by specimen number on the stub.

***Amphicraspedum murrayanum* Haeckel**

Plate 1, figures 3, 4

Amphicraspedum murrayanum Haeckel, 1887, p. 523, pl. 44, fig. 10; Sanfilippo and Riedel, 1973, p. 524, pl. 10, figs. 3-6; pl. 28, fig. 1; Nishimura, 1987, pl.1, figs. 14, 18; Sanfilippo and Blome, 2001, p. 208, fig. 8a; Hollis, 2006, pl. 1, figs. 18, 19; Jackett et al., 2008, pl. 4, figs. 1, 2.

***Amphicraspedum prolixum* Sanfilippo and Riedel group**
Plate 1, figures 32, 33
Amphicraspedum prolixum Sanfilippo and Riedel group, 1973, p. 524, pl. 10, figs. 7-11; pl. 28, figs. 3, 4; Hollis, 2006, pl. 1, figs. 14, 20, 21; Jackett et al., 2008, pl. 4, figs. 3-5.

***Amphisphaera coronata* (Ehrenberg)**
Plate 1, figure 7
Stylosphaera coronata Ehrenberg, 1873, p. 258; 1875, pl. 25, fig. 4.
Stylosphaera coronata coronata Ehrenberg, Sanfilippo and Riedel, 1973, p. 520, pl. 1, figs. 13-17; pl. 25, fig. 4; Nishimura, 1992, pl. 1, fig. 2; pl. 11, fig. 9. Jackett et al., 2008, pl. 3, fig. 10.
Amphisphaera coronata (Ehrenberg), Hollis, 1997, p. 35, pl. 2, figs. 14-17.

***Amphisphaera goruna* (Sanfilippo and Riedel)**
Plate 1, figure 9
Stylosphaera goruna Sanfilippo and Riedel, 1973, p. 521, pl. 1, figs. 20-22; pl. 25, figs. 9, 10; Nishimura, 1987, pl. 1, fig. 3.
Amphisphaera goruna (Sanfilippo and Riedel), Hollis, 1997, p. 34, pl. 2, figs. 10, 11.

***Amphisphaera macrosphaera* (Nishimura)**
Plate 1, figure 8
Stylosphaera coronata macrosphaera Nishimura, 1992, p. 325, pl. 1, figs. 3, 4; pl. 11, fig. 1.
Amphisphaera macrosphaera (Nishimura), Hollis, 1997, p. 34, pl. 2, figs. 12, 13.

***Axoprunum pierinae* (Clark and Campbell)**
Plate 1, figures 1, 2
Lithatractus pierinae Clark and Campbell, 1942, p. 34, pl. 5, fig. 25.
Axoprunum pierinae (Clark and Campbell) group, Sanfilippo and Riedel, 1973, p. 488, pl. 1, figs. 6-12; pl. 23, fig. 3; Nishimura, 1987, pl. 1, fig. 6.

***Bathropyramis magnifica* (Clark and Campbell)**
Plate 2, figure 11
Sethopyramis magnifica Clark and Campbell, 1942, p. 72, pl. 8, figs. 1, 5, 9.
Bathropyramis magnifica (Clark and Campbell), Jackett et al., 2008, pl. 1, fig. 16.

***Bekoma bidartensis* Riedel and Sanfilippo**
Plate 2, figure 32
Bekoma bidartensis Riedel and Sanfilippo, 1971, p. 1592, pl. 7, figs. 1, 2, 5, 7; Foreman, 1973, p. 432, pl. 3, figs. 20, 21; pl. 10, fig. 6; Nishimura, 1992, pl. 5, figs. 8, 9; Jackett et al., 2008, pl. 1, fig. 12.

***Buryella pentadica* Foreman**

Plate 2, figure 12

Buryella pentadica Foreman, 1973, p. 433, pl. 8, fig. 8; pl. 9, figs. 15, 16; Nishimura, 1987, pl. 2, fig. 9.

***Buryella tetradica tetradica* Foreman**

Plate 2, figure 13

Buryella tetradica Foreman, 1973, p. 433, pl. 8, figs. 4, 5; pl. 9, figs. 13, 14; Nishimura, 1987, pl. 2, fig. 8; Jackett et al., 2008, pl. 2, fig. 20.

Buryella tetradica tetradica Foreman, Hollis, 2002, p. 300, pl. 4, figs, 13, 14.

***Buryella tetradica tridica* O'Connor**

Buryella tridica O'Connor, 2001, p. 11, pl. 2, figs. 9a-15; pl. 4, figs. 14-25.

Buryella tridica O'Connor, Hollis, 2002, p. 300, pl. 4, fig. 12.

Remarks: The discovery of this variant of *Buryella tetradica* in North Atlantic expands its geographical distribution which has previously been suggested as a possible geographically restricted morphotype in South Pacific by Hollis (2002).

***Carposphaera subbotinae* (Borisenko)**

Plate 1, figure 22

Cenosphaera subbotinae Borisenko, 1958, p. 85, pl. 5, figs. 5-7.

Carposphaera subbotinae (Borisenko), Sanfilippo and Riedel, 1973, p. 490, pl. 4, fig. 3; pl. 23, figs. 4, 5; Jackett et al., 2008, pl. 3, fig. 4.

***Cassideus mariae* Nishimura**

Plate 1, figure 49; plate 2, figures 1-3

Cassideus mariae Nishimura, 1992, p. 333, pl. 4, figs. 1-3.

***Clathrocycloma? catherinea* Nishimura**

Clathrocycloma? catherinea Nishimura, 1992, p. 334, pl. 4, figs. 10, 11.

***Cornutella californica* Campbell and Clark**

Cornutella californica Campbell and Clark, 1944, p. 22, pl. 7, figs. 33, 34, 42, 43; Hollis, 1997, p. 71, pl. 17, figs. 13-15; 2002, pl. 6, figs. 4, 5.

***Cromyomma riedeli* Nishimura**

Cromyomma riedeli Nishimura, 1992, p. 322, pl. 1, figs. 6, 7; pl. 11, fig. 7

***Dendrospyris golli* Nishimura**

Plate 2, figures 33, 34

Dendrospyris golli Nishimura, 1992, p. 330, pl. 3, figs. 1, 2; pl. 12, fig. 11.

***Dictyocephalus middouri* s.l. Nishimura**

Plate 2, figures 18-20

Dictyocephalus middouri Nishimura, 1992, p. 336, pl. 9, figs. 10-12.

Remarks: specimens examined here include those with three-bladed apical horn.

***Dictyophimus?* sp. aff. *Pterocodon campana* Ehrenberg**

Pterocodon campana Ehrenberg, 1873, p. 255; 1875, p. 82, pl. 19, fig. 1.

Dictyophimus? sp. aff. *Pterocodon campana* Ehrenberg, Nishimura, 1992, pl. 10, fig. 15.

***Diplocyclas pseudobicorona pseudobicorona* Nishimura**

Plate 2, figures 6-10

Diplocyclas pseudobicorona pseudobicorona Nishimura, 1992, p. 340, pl. 4, figs. 4-6; pl. 13, fig. 14.

***Diplocyclas pseudobicorona teres* Nishimura**

Plate 2, figures 4, 5

Diplocyclas pseudobicorona teres Nishimura, 1992, p. 340, pl. 4, figs. 8, 9; pl. 13, fig. 20.

***Diploplegma?* sp. aff. *D. somphum* Sanfilippo and Riedel**

Diploplegma somphum Sanfilippo and Riedel, 1973, p. 491, pl. 4, fig. 5.

Diploplegma? sp. aff. *D. somphum* Sanfilippo and Riedel, Nishimura, 1992, p. 324, pl. 2, figs. 6, 10; pl. 11, fig. 10.

***Dorcadospyris platyacantha* (Ehrenberg) group**

Plate 2, figures 35, 36

Peralospyris platyacantha Ehrenberg 1873, p. 247; 1875, pl.22, fig. 8.

Dorcadospyris platyacantha (Ehrenberg), Sanfilippo and Riedel, 1973, p. 528, pl. 17, figs. 11-15; pl. 33, fig. 2; Nishimura, 1992, pl. 3, figs. 3, 4; Jackett et al., 2008, pl. 4, fig. 17.

***Hexacontium palaeocenicum* Sanfilippo and Riedel**

Plate 1, figures 15-18

Hexacontium palaeocenicum Sanfilippo and Riedel, 1973, p. 492, pl. 4, fig. 2; pl. 24, fig. 4; Nishimura, 1987, pl. 1, figs. 8, 11; Jackett et al., 2008, pl. 3, fig. 5.

***Hexacontium* sp.**

Plate 1, figures 19-21

Remarks: This form is different from *Hexacontium palaeocenicum* with seven external spines.

***Lamptonium pennatum* Foreman**

Plate 2, figures 30, 31

Lamptonium pennatum Foreman, 1973, p. 436, pl. 6, figs. 3-5; pl. 11, fig. 13; Jackett et al., 2008, pl. 1, fig. 10.

***Lithelius foremanae* Sanfilippo and Riedel**

Lithelius foremanae Sanfilippo and Riedel, 1973, p. 522, pl. 7, figs. 1-6; pl. 26, figs. 4, 5; Jackett et al., 2008, pl. 4, fig. 20.

Lithomespilus coronatus **Squinabol**

Plate 1, figures 10-14

Lithomespilus coronatus Squinabol, 1904, p. 198, pl. 4, fig. 7; Hollis, 1997, p. 37, pl. 4, figs. 1-3.

Lychnocanium carinatum **Ehrenberg**

Plate 2, figures 21-22

Lychnocanium carinatum Ehrenberg, 1875, p. 78, pl. 8, fig. 5; Nishimura, 1987, pl. 3, figs. 6, 11; Jackett et al., 2008, pl. 1, fig. 25.

Lychnocanoma anacolum **Foreman**

Lychnocanoma anacolum Foreman, 1973, p. 437, pl. 1, fig. 19; pl. 11, fig. 7; Jackett et al., 2008, pl. 1, fig. 24.

Lychnocanoma auxilla **Foreman**

Plate 2, figures 23-29

Lychnocanoma auxilla Foreman, 1973, p. 437, pl. 2, fig. 6; pl. 11, figs. 1, 2; Jackett et al., 2008, pl. 1, fig. 20.

Lychnocanoma babylonis **(Clark and Campbell) group**

Dictyophimus babylonis Clark and Campbell, 1942, p. 67, pl. 9, figs. 32, 36.

Sethochytris babylonis (Clark and Campbell) group, Riedel and Sanfilippo, 1970, p. 528, pl. 9, figs. 1-3.

Lychnocanoma babylonis (Clark and Campbell) group, Foreman, 1973, p. 437, pl. 2, fig. 1.

Lychnocanoma sp. aff. *L. babylonis* (Clark and Campbell), Nishimura, 1987, pl. 3, figs. 3-5.

Phormocyrtis striata exquisita **(Kozlova)**

Plate 2, figures 15-16

Podocyrtis exquisita Kozlova, in Kozlova and Gorbovetz, 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; Nishimura, 1987, pl. 2, fig. 13; 1992, pl. 9, figs. 4, 5; Jackett et al., 2008, pl. 1, fig. 18.

Podocyrtis **sp. aff. *P. papalis*** **Ehrenberg**

Plate 2, figure 14

Podocyrtis papalis Ehrenberg, 1847, p. 55, fig. 2.

Podocyrtis sp. aff. *P. papalis* Ehrenberg, Nishimura, 1992, pl. 10, figs. 1-3; pl. 13, fig. 18.

Prunopyle adelstoma **Kozlova**

Plate 1, figure 37

Prunopyle adelstoma Kozlova, in Kozlova and Gorbovetz, 1966, p. 67, pl. 10, figs. 3, 4; Hollis, 2002, p. 289, pl. 2, figs. 5-8.

***Pseudostaurosphaera?* sp. aff. *P. perelegans* Krasheninnikov**

Pseudostaurosphaera perelegans Krasheninnikov, 1960, p. 276, pl. 1, fig. 6.

Pseudostaurosphaera? sp. aff. *P. perelegans* Krasheninnikov, Nishimura, 1992, p. 324, pl. 1, fig. 5; pl. 11, fig. 4.

***Pterocodon? ampla* (Brandt)**

Theocyrtis ampla Brandt, in Wetzel 1935, p. 56, pl. 9, figs. 13–15.

Pterocodon? ampla (Brandt), Foreman, 1973, p. 438, pl. 5, figs. 3-5; Jackett et al., 2008, pl. 2, fig. 14.

***Pterocodon poculum* Nishimura**

Plate 2, figures 37-39

Pterocodon poculum Nishimura, 1992, p. 350, pl. 8, figs. 1-3; pl. 13, fig. 13; Jackett et al., 2008, pl. 1, fig. 13.

***Saturnalis kennetti* Dumitrica**

Plate 1, figures 5, 6

Saturnalis kennetti Dumitrica, 1985, p. 189, pl. 2, figs. 1, 2; pl. 3, fig. 15; Hollis, 1997, p. 42, pl. 4, fig. 14; 2002, pl. 1, fig. 17.

***Spongodiscus americanus* Kozlova**

Plate 1, figures 39-41

Spongodiscus americanus Kozlova, Kozlova and Gorbovetz, 1966, p. 88, pl. 14, figs. 1, 2; Sanfilippo and Riedel, 1973, p. 524, pl. 11, figs. 9-13; pl. 27, fig. 11; pl. 28, fig. 9; Jackett et al., 2008, pl. 4, fig. 9.

***Spongodiscus cruciferus* (Clark and Campbell)**

Plate 2, figures 40-42

Spongastericus cruciferus Clark and Campbell, 1942, p. 50, pl. 1, figs. 1-6, 8, 10, 11, 16-18.

Spongodiscus cruciferus (Clark and Campbell), Sanfilippo and Riedel, 1973, p. 524, pl. 11, figs. 14-17; pl. 28, figs. 10, 11; Jackett et al., 2008, pl. 4, fig. 8.

***Spongodiscus quartus bosoculus* Sanfilippo and Riedel**

Plate 1, figures 42, 43

Spongodiscus quartus bosoculus Sanfilippo and Riedel, 1973, p. 525, pl. 12, figs. 8-10; pl. 29, fig. 7; Nishimura, 1992, pl. 2, fig. 15.

***Spongurus bilobatus* Clark and Campbell group**

Plate 1, figures 35-36

Spongurus bilobatus Clark and Campbell, 1942, p. 36, pl. 1, figs. 7-9.

Spongurus cf. *bilobatus* Clark and Campbell, Hollis, 1997, p. 47, pl. 7, figs. 15-18.

Spongurus bilobatus Clark and Campbell group, Hollis, 2002, p. 291, pl. 2, figs. 11-14.

***Spongurus? irregularis* Nishimura**

Plate 1, figures 29-31

Spongurus? irregularis Nishimura, 1992, pl. 2, figs. 7-9; pl. 12, figs. 3, 7; Jackett et al., 2008, pl. 4, figs. 6, 7.

***Spongurus? regularis* (Borisenko) group**

Plate 1, figures 25-28

Cromyodruppa regularia Borisenko, 1958, p. 88, pl. 5, figs. 13, 14.

Spongurus? regularis (Borisenko) group, Nishimura, 1992, p. 328, pl. 2, figs. 11, 12; pl. 12, figs. 4-6.

***Stylosphaera minor* Clark and Campbell**

Plate 1, figures 3, 4

Stylosphaera minor Clark and Campbell, 1942, p. 27, pl. 5, figs. 1, 2, 12.

Amphisphaera minor (Clark and Campbell), Sanfilippo and Riedel, 1973, p. 486, pl. 1, figs. 1-5; pl. 22, fig. 4; Nishimura, 1987, pl. 1, fig. 5.

Stylosphaera minor Clark and Campbell, Hollis, 1997, p. 40, pl. 1, figs. 17, 18.

***Stylotrochus alveatus* Sanfilippo and Riedel**

Plate 1, figures 46, 47

Stylotrochus alveatus Sanfilippo and Riedel, 1973, p. 525, pl. 13, figs. 4, 5; pl. 30, figs. 3, 4.

***Stylotrochus nitidus* Sanfilippo and Riedel**

Plate 1, figure 38

Stylotrochus nitidus Sanfilippo and Riedel, 1973, p. 525, pl. 13, figs. 9-14; pl. 30, figs. 7-10; Nishimura, 1987, pl. 1, fig. 12; Nishimura, 1992, pl. 2, fig. 1; pl. 12, fig. 8; Jackett et al., 2008, pl. 4, fig. 13.

***Thecosphaera larnacium* Sanfilippo and Riedel**

Plate 1, figure 24

Thecosphaera larnacium Sanfilippo and Riedel, 1973, p. 521, pl. 3, figs. 4-6; pl. 25, figs. 13, 14; Jackett et al., 2008, pl. 3, figs 1, 2.

***Thecosphaerella ptomatus* Sanfilippo and Riedel**

Plate 1, figure 23

Thecosphaerella ptomatus Sanfilippo and Riedel, 1973, p. 521, pl. 3, figs. 14-18; pl. 26, fig. 2; Jackett et al., 2008, pl. 3, fig. 6.

***Thecosphaerella rotunda* (Borisenko)**

Thecosphaera rotunda Borisenko, 1960, p. 222, pl. 1, fig. 3; pl. 3, figs. 2, 3.

Thecosphaerella rotunda (Borisenko), Sanfilippo and Riedel, 1973, pl. 3, figs. 7-11; pl. 26, fig. 3.

***Theocorys acroria* Foreman**

Plate 2, figure 17

Theocorys acroria Foreman, 1973, p. 439, pl. 5, figs. 11–13; pl. 12, fig. 2; Jackett et al., 2008, pl. 2, fig. 24.

***Velicucullus? palaeocenica* Nishimura**

Plate 1, figure 48

Velicucullus? palaeocenica Nishimura, 1992, p. 331, pl. 3, figs. 7, 9.

***Xiphospira circularis* (Clark and Campbell)**

Plate 1, figures 44, 45

Porodiscus circularis Clark and Campbell, 1942, p. 42, pl. 2, figs. 2, 6, 10.

Xiphodictya amphixiphos (Clark and Campbell), 1942, p. 43, pl. 2, fig. 4.

Circodiscus circularis (Clark and Campbell), Jackett et al., 2008, pl. 4, figs. 10, 12.

Xiphospira circularis (Clark and Campbell), Sanfilippo and Riedel, 1973, p. 526, pl. 14, figs. 5-12: pl. 31, figs. 4-7; Nishimura, 1992, pl. 2, fig. 13; pl. 12, fig. 9.

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Table Captions

1. Stratigraphic depth (mbsf) of the biostratigraphic, chemostratigraphic, and magnetostratigraphic tie-points used to construct the age model.
2. Abundance, preservation, and occurrence of radiolarians in the upper Paleocene-lower Eocene in DSDP Site 549.
3. Abundance, preservation, and occurrence of radiolarians in the upper Paleocene-lower Eocene in DSDP Site 550.

Figure Captions

1. Modern map showing the location of DSDP Sites 549 and 550, Goban Spur.
2. Stratigraphic ranges of radiolarian species in DSDP Site 549.
3. Paleogeographic reconstruction of the late Paleocene (~56 Ma) showing the location of DSDP Leg 80 and Mead Stream (generated from http://www.serg.unicam.it/Reconstructions.htm).

Plates

Plate 1

All illustrations are scanning electron micrographs of upper Paleocene radiolarians from DSDP Site 549. All illustrated specimens can be located with SEM stub number, followed by specimen number on the stub. All scale bars equal 100 µm.

1. *Axoprunum pierinae* (Clark and Campbell). 549-17-1-82-A, 3.
2. *Axoprunum pierinae* (Clark and Campbell). 549-17-2-99, 110.
3. *Stylosphaera minor* Clark and Campbell. 549-17-2-99, 50.
4. *Stylosphaera minor* Clark and Campbell. 549-18-1-43, 3.
5. *Saturnalis kennetti* Dumitrica. 549-17-2-99, 55.
6. *Saturnalis kennetti* Dumitrica. 549-19-1-64, 4.
7. *Amphisphaera coronata* (Ehrenberg). 549-17-3-79-A, 87
8. *Amphisphaera macrosphaera* (Nishimura). 549-18-2-116, 51.
9. *Amphisphaera goruna* (Sanfilippo and Riedel). 549-18-2-116, 77.
10. *Lithomespilus coronatus* Squinabol. 549-17-3-79-A, 51.
11. *Lithomespilus coronatus* Squinabol. 549-18-2-116, 45.
12. *Lithomespilus coronatus* Squinabol. 549-17-6-138, 12.
13. *Lithomespilus coronatus* Squinabol. 549-17-3-79-A, 52.
14. *Lithomespilus coronatus* Squinabol. 549-17-3-79-A, 17.
15. *Hexacontium palaeocenicum* Sanfilippo and Riedel. 549-19-4-112, 85.
16. *Hexacontium palaeocenicum* Sanfilippo and Riedel. 549-17-3-79-A, 31.
17. *Hexacontium palaeocenicum* Sanfilippo and Riedel. 549-17-3-79-A, 22.
18. *Hexacontium palaeocenicum* Sanfilippo and Riedel. 549-18-2-116, 75.
19. *Hexacontium* sp.. 549-17-1-82-B, 2.
20. *Hexacontium* sp.. 549-17-2-99, 41.
21. *Hexacontium* sp.. 549-17-3-79-B, 1.
22. *Carposphaera subbotinae* (Borisenko). 549-17-2-99, 76.
23. *Thecosphaerella ptomatus* Sanfilippo and Riedel. 549-17-2-99, 88.
24. *Thecosphaera larnacium* Sanfilippo and Riedel. 549-17-2-99, 1.
25. *Spongurus? regularis* (Borisenko) group. 549-17-3-79-A, 9.
26. *Spongurus? regularis* (Borisenko) group. 549-17-6-138, 47.
27. *Spongurus? regularis* (Borisenko) group. 549-17-3-79-A, 28.
28. *Spongurus? regularis* (Borisenko) group. 549-17-3-79-A, 50.
29. *Spongurus? irregularis* Nishimura. 549-19-4-112, 60.
30. *Spongurus? irregularis* Nishimura. 549-17-6-138, 42.
31. *Spongurus? irregularis* Nishimura. 549-17-3-79-A, 14.
32. *Amphicraspedum prolixum* Sanfilippo and Riedel group. 549-17-6-138, 54.
33. *Amphicraspedum prolixum* Sanfilippo and Riedel group. 549-17-2-99, 116.
34. *Amphicraspedum murrayanum* Haeckel. 549-17-3-79-A, 1.
35. *Spongurus bilobatus* Clark and Campbell. 549-18-2-116, 92.
36. *Spongurus bilobatus* Clark and Campbell. 549-17-6-138, 51.
37. *Prunopyle adelstoma* Kozlova and Gobovets. 549-17-2-99, 70.
38. *Stylotrochus nitidus* Sanfilippo and Riedel. 549-17-3-79-A, 7.
39. *Spongodiscus americanus* Kozlova. 549-17-2-99, 89.

40. *Spongodiscus americanus* Kozlova. 549-17-3-79-B, 56.
41. *Spongodiscus americanus* Kozlova. 549-17-2-99, 111.
42. *Spongodiscus quartus bosoculus* Sanfilippo and Riedel. 549-17-3-79-B, 21.
43. *Spongodiscus quartus bosoculus* Sanfilippo and Riedel. 549-17-3-79-B, 22.
44. *Xiphospira circularis* (Clark and Campbell). 549-17-3-79-B, 28.
45. *Xiphospira circularis* (Clark and Campbell). 549-19-1-64, 11.
46. *Stylotrochus alveatus* Sanfilippo and Riedel. 549-17-2-99, 34.
47. *Stylotrochus alveatus* Sanfilippo and Riedel. 549-17-3-79-B, 19.
48. *Velicucullus? palaeocenica* Nishimura. 549-17-3-79-B, 58.
49. *Cassideus mariae* Nishimura. 549-17-6-138, 50.

Plate 2

All illustrations are scanning electron micrographs of upper Paleocene radiolarians from DSDP Site 549. All illustrated specimens can be located with SEM stub number, followed by specimen number on the stub. All scale bars equal 100 µm.

1. *Cassideus mariae* Nishimura. 549-17-1-82-B, 18.
2. *Cassideus mariae* Nishimura. 549-17-2-99, 16.
3. *Cassideus mariae* Nishimura. 549-17-2-99, 17.
4. *Diplocyclas pseudobicorona teres* Nishimura. 549-17-2-99, 22.
5. *Diplocyclas pseudobicorona teres* Nishimura. 549-17-2-99, 73.
6. *Diplocyclas pseudobicorona pseudobicorona* Nishirnura. 549-17-2-99, 18.
7. *Diplocyclas pseudobicorona pseudobicorona* Nishirnura. 549-17-2-99, 19.
8. *Diplocyclas pseudobicorona pseudobicorona* Nishirnura. 549-17-2-99, 20.
9. *Diplocyclas pseudobicorona pseudobicorona* Nishirnura. 549-17-2-99, 104.
10. *Diplocyclas pseudobicorona pseudobicorona* Nishirnura. 549-19-1-64, 26.
11. *Bathropyramis magnifica* (Clark and Campbell). 549-17-3-79-A, 35.
12. *Buryella pentadica* Foreman. 549-19-1-64, 43.
13. *Buryella tetradica tetradica* Foreman. 549-17-3-79-A, 6.
14. *Podocyrtis* sp. aff. *P. papalis* Ehrenberg. 549-17-6-138, 49.
15. *Phormocyrtis striata exquisita* (Kozlova). 549-17-3-79-A, 47.
16. *Phormocyrtis striata exquisita* (Kozlova). 549-17-3-79-A, 80.
17. *Theocorys acroria* Foreman. 549-17-2-99, 109.
18. *Dictyocephalus middouri* s.l. Nishimura. 549-17-2-99, 14.
19. *Dictyocephalus middouri* s.l. Nishimura. 549-17-2-99, 15.
20. *Dictyocephalus middouri* s.l. Nishimura. 549-17-3-79-B, 32.
21. *Lychnocanium carinatum* Ehrenberg. 549-18-2-116, 76.
22. *Lychnocanium carinatum* Ehrenberg. 549-18-2-116, 12.
23. *Lychnocanoma auxilla* Foreman. 549-17-2-99, 8.
24. *Lychnocanoma auxilla* Foreman. 549-17-2-99, 9.
25. *Lychnocanoma auxilla* Foreman. 549-17-2-99, 10.
26. *Lychnocanoma auxilla* Foreman. 549-17-2-99, 95.
27. *Lychnocanoma auxilla* Foreman. 549-17-2-99, 96.
28. *Lychnocanoma auxilla* Foreman. 549-17-3-79-B, 54.
29. *Lychnocanoma auxilla* Foreman. 549-17-2-99, 114.

30. *Lamptonium pennatum* Foreman. 549-17-3-79-B, 52.
31. *Lamptonium pennatum* Foreman. 549-17-2-99, 4.
32. *Bekoma bidartensis* Riedel and Sanfilippo. 549-17-3-79-A, 91.
33. *Dendrospyris golli* Nishimura. 549-17-1-82-A, 11.
34. *Dendrospyris golli* Nishimura. 549-17-2-99, 106.
35. *Dorcadospyris platyacantha* (Ehrenberg) group. 549-17-6-138, 28.
36. *Dorcadospyris platyacantha* (Ehrenberg) group. 549-18-2-116, 26.
37. *Pterocodon poculum* Nishimura. 549-17-3-79-A, 69.
38. *Pterocodon poculum* Nishimura. 549-17-3-79-A, 58.
39. *Pterocodon poculum* Nishimura. 549-18-2-116, 17.
40. *Spongodiscus cruciferus* (Clark and Campbell). 549-17-2-99, 74.
41. *Spongodiscus cruciferus* (Clark and Campbell). 549-17-2-99, 75.
42. *Spongodiscus cruciferus* (Clark and Campbell). 549-17-3-79-B, 59.

Table 1

Site 549			
Datum	Age (Ma)	Depth (mbsf)	References
C22n/C22r	49.427	276.61	de Graciansky et al., 1985
C22r/C23n	50.73	286.52	de Graciansky et al., 1985
C24n.1r/2n	53.116	304.08	Ali and Hailwood, 1998
C24n.2n/2r	53.167	305.21	Ali and Hailwood, 1998
C24n.2r/3n	53.286	307.62	Ali and Hailwood, 1998
C24n.3n/3r	53.808	318	Ali and Hailwood, 1998
NP11/10	54.23	335.16	Knox et al., 1996
HO *Fasciculithus tympaniformis*	55.63	335.55	Knox et al., 1996
CIE base	55.8	339.68	Thomas and Bralower, 2005
NP9/8	56.5	352.3	de Graciansky et al., 1985
C25r/C26n	58.379	374.12	de Graciansky et al., 1985
Site 550			
Datum	Age (Ma)	Depth (mbsf)	References
C23r/C24n	52.648	342.07	Cramer et al., 2003
ETM 2 base	53.55	362.74	Cramer et al., 2003
Base of Ash -17	55.07	400.04	Knox, 1984
CIE base	55.8	409.79	Cramer et al., 2003
C24r/C25n	56.665	422.12	Cramer et al., 2003
C25n/C25r	57.18	425.09	Cramer et al., 2003

Table 2

Epoch	Site 549 sample No.	Depth (mbsf)	Absolute age (Ma)	Lithologic Unit	Preservation	Sample weight (g)	Radiolarian abundance
Early Eocene	10-1-41	274.91	49.2207	Unit 2 nannofossil chalks	P/M	12	A
	10-2-72	276.72	49.456		P	12	A
	10-2-105	277.05	49.4989		P	12.1	A
	10-3-60	278.1	49.6354		P	12	A
	10-4-30	279.3	49.7914	Sub Unit 3a marly nannofossil chalks	P	12	A
	10-5-62	281.12	50.028		P	12	A
	10-6-87	282.87	50.2555		P	12	A
	11-1-46	284.46	50.4622		P	12	F
	11-2-19	285.69	50.6221		P	12	C
	11-3-28	287.28	50.83326651			12	B
	11-3-136	288.36	50.98001367			10.88	B
	11-4-138	289.88	51.1865467			11.73	B
	11-5-99	290.99	51.33737016			12.18	B
	11-6-105	292.55	51.54933827			11.85	B
	12-1-118	294.68	51.83875626			11.87	B
	12-2-117	296.17	52.04121298			12.09	B
	13-1-42	303.42	53.02632118			12	B
	13-2-71	305.21	53.167		P	11.7	F
	13-3-34	306.34	53.22279668		P	12	C
	13-6-107	311.57	53.48464162		P	12	C
	14-2-38	314.38	53.62595376			12.54	B
	14-3-94	316.44	53.72954913			12	B
	14-5-60	319.1	53.83505128			13.09	B
	14-6-86	320.86	53.87833333			12	B
	15-1-119	323.19	53.93563287	Sub Unit 3b nannofossil chalks		10.04	B
	15-3-95	325.95	54.00350699			12	B
	16-1-143	332.93	54.17515967			12	B
	16-3-11	334.61	54.21647436			12	B
PETM	16-4-36	336.36	55.6633414	Sub Unit 3c siliceous marly nannofossil chalks	P	12	C
	16-5-35	337.85	55.72467312		P	12	A
Late Paleocene	16-6-83	339.83	55.80832013			12	B
	17-1-82	341.82	55.91870048		M	12	F
	17-2-99	343.49	56.01133122		W	12	C
	17-3-79	344.79	56.08343899		W	10.14	C
	17-3-126	345.26	56.10950872			12	B
	17-4-110	346.6	56.18383518		W	12	A
	17-5-74	347.74	56.24706815		S	6	A
	17-6-35	348.85	56.30863708		S	6	A
	17-6-138	349.88	56.36576862		S	5.72	A
	17-7-7	350.07	56.37630745	Unit 3d siliceous nannofossil chalks	S	6	A
	18-1-43	350.93	56.42400951		W	12	C
	18-1-77	351.27	56.44286846		M/W	12	C
	18-1-123	351.73	56.46838352		M/W	12	C
	18-2-25	352.25	56.49722662		W	12	C
	18-2-116	353.16	56.57405775		S	5.96	A
	18-3-35	353.85	56.63347617		W	12	A
	18-3-95	354.25	56.66792163		S	6	A
	18-3-117	354.67	56.70408937		S	6	A
	19-1-64	360.64	57.2181879		W	12	A
	19-2-46	361.96	57.33185793		W	12	C
	19-3-70	363.7	57.48169569		M	12	F
	19-4-11	364.61	57.56005912			12	B
	19-4-112	365.62	57.64703391		P/M	11.47	F
	19-5-24	366.24	57.70042438			12	B
	20-1-57	370.07	58.03023969		P/M	12	F
	20-2-82	371.82	58.18093859		P/M	12	F
	20-3-34	372.84	58.26877452		P/M	12	C
	20-4-42	374.42	58.4048341		P/M	12	C
	20-4-127	375.27	58.47803071		P/M	12.1	C
	20-5-80	376.3	58.56672777		P	12	C
	20-6-22	377.22	58.64595234		P	12	C
	21-1-103	380.03	58.88793171		P	12	F
	21-1-137	380.37	58.91721036		P	12.29	F
	21-2-62	381.12	58.9817956			12	B

Site 549 sample No.	*Amphicraspedum murrayanum*	*Amphicraspedum prolixum* group	*Amphisphaera coronata*	*Amphisphaera goruna*	*Amphisphaera macrosphaera*	*Axoprunum pierinae*	*Bathropyramis magnifica*	*Bekoma bidartensis*	*Buryella pentadica*	*Buryella tetradica tetradica*	*Buryella tetradica tridica*	*Carposphaera subbotinae*	*Cassideus mariae*	*Clathrocycloma ? catherinea*	*Cornutella californica*	*Cromyomma riedeli*	*Dendrospyris golli*	*Dictyocephalus middouri s.l.*	*Dictyophimus ? sp. aff. Pterocodon campana*	*Diplocyclas pseudobicorona pseudobicorona*	*Diplocyclas pseudobicorona teres*	*Diploplegma ? sp. aff. D. somphum*	*Dorcadospyris platyacantha* group	*Hexacontium palaeocenicum*	*Hexacontium* sp.	*Lamptonium pennatum*	*Lithelius foremanae*	*Lithomespilus coronatus*	*Lychnocanium carinatum*	*Lychnocanoma anacolum*	*Lychnocanoma auxilla*	*Lychnocanoma babylonis* group	*Phormocyrtis striata exquisita*	*Podocyrtis* sp. aff. *P. papalis*	*Prunopyle adelstoma*	*Pseudostaurosphaera ? sp. aff. P. perelegans*	*Pterocodon? ampla*	*Pterocodon poculum*	*Saturnalis kennetti*	*Spongodiscus americanus*	*Spongodiscus cruciferus*	*Spongodiscus quartus bosoculus*	*Spongurus bilobatus*	*Spongurus ? irregularis*	*Spongurus ? regularis*	*Stylosphaera minor*	*Stylotrochus alveatus*	*Stylotrochus nitidus*	*Thecosphaera larnacium*	*Thecosphaerella ptomatus*	*Thecosphaerella rotunda*	*Theocorys acroria*	*Velicucullus ? palaeocenica*	*Xiphospira circularis*
17-1-82	F	F	F	F	C	F	F	F		F			F				F						F	F	F			F	F		F		F	F	F			F		F				C	F		F	C	F		F			F
17-2-99	F	F	C	C	C	C	F	F		F		F	C	F		F	F	F		C	F		F	C	F	F		F	F	F	F	F	F	F	F	F	F	C	F	F	F	F	F	A	A	F	C	C	C	F	C	F		F
17-3-79		F	C	C	C	F	F	F		F		F						F				F	F	F	F	F	F	C				F	F	F				C		F	F	F	F	C	A	F	F	F	C	F	C		F	F
17-4-110	F	F	C	C	C	F	F		F	C			F		F				F	F		f	C		F		F	F			F	F		F	F			F		F	F	F	C	C	C	F	C	C	C	C	F	F	F	C
18-1-43		F	C	C	C	F	F	F		C		F		F	F							F	F	F	F		C	F			F	C		F	C			C		F		F	F	C	C	C	F	C	F	F	C			C
18-1-77	F		F	F	F		F			F												F	F	F		F	F				F	F						F			F	F	F	F	A	F		F	F	F	F			C
18-1-123				C	C		F	F		F												F	F	C							F				F			F						F	C		F	F	F		C			
18-2-25	F	F		F		F	F	F				F	F										F	C		F	F	F		F	F	F	F		F			C		F	F		F	F	C		C	C	F	C	C			C
18-3-35	F	F	F	F	F	F	F	F					C	F	F					F			F	F			F	F			F	F	F					F	F	F			C	F	C	F	F	F			F			C
19-1-64	F	F	C	F	F	F	C	C	F				F	F						C	F		C	C			F	F	F	F			F	F	F				F	F	F	C	F	F	C	F	C	C	F	F	F	F		C
19-2-46		F	F					F		F				F			F						F	C			F						F					F						C	C			C	F	F	F			
19-3-70	F	F	F							F														F			F								F						F			F	C		F	C			F			
19-4-112	F		F	F	F	F	F		F	F	F												F	F									F	F									F	F	C			F			F			
20-1-57			F				F			F																																		C	C						F			
20-2-82									F																		F																	C	C									
20-3-34				F						F																																		F	C									
20-4-42																																			F									C	C									
20-4-127			F	F	F		F			F														F																			F	C	F									

Table 3

Epoch	Site 550 sample No.	Depth (mbsf)	Absolute age (Ma)	Preservation	Sample weight (g)	Radiolarian abundance	Lithologic Unit	***Amphisphaera coronata***	***Amphisphaera goruna***	***Amphisphaera macrosphaera***	***Bathropyramis magnifica***	***Buryella pentadica***	***Buryella tetradica tetradica***	***Carposphaera subbotinae***	***Cromyomma riedeli***	***Dendrospyris golli***	***Dorcadospyris platyacantha* group**	***Hexacontium palaeocenicum***	***Hexacontium* sp.**	***Lithomespilus coronatus***	***Lychnocanoma anacolum***	***Lychnocanoma babylonis* group**	***Phormocyrtis striata exquisita***	***Pterocodon poculum***	***Spongurus ? irregularis***
Early Eocene	26-1-88	328.38	52.0505941	P	10.787	F	Subunit 2a marly nannofossil chalk																		
	27-2-69	339.19	52.52232221	P	10.87	F																			
	28-1-34	346.84	52.85615385	P	11	F																			
	28-2-116	349.16	52.95739429	P	11.732	C																			
	28-3-116	350.66	53.02285148	P	11.791	F																			
	28-4-76	351.76	53.07085341	P	12	F																			
	29-3-135	360.35	53.44570489	P	12	F																			
	29-4-125	361.75	53.50679826	P	12.142	F																			
	30-2-78	367.78	53.75538338	P	12	F																			
	31-2-36	376.86	54.12539946		12	B																			
	32-2-90	386.9	54.53453619		11	B																			
	33-1-81	394.81	54.85687399		11	B																			
	34-2-95	405.95	55.31083646		10	B																			
Late Paleocene	35-2-49	414.99	56.164	P/M	10	F	Subunit 2b siliceous nannofossil chalk and mudstone		C	C		F											F		F
	35-6-12	420.62	56.5581	W	9.03	C			C	C			C	F	F	F	C	F	F	F	F	C		C	F
	36-1-22	422.72	56.76904	P/M	9	F		F	F	F	F	F												F	
	36-2-98	424.98	57.160924	P	8.974	C																			

Figure 1

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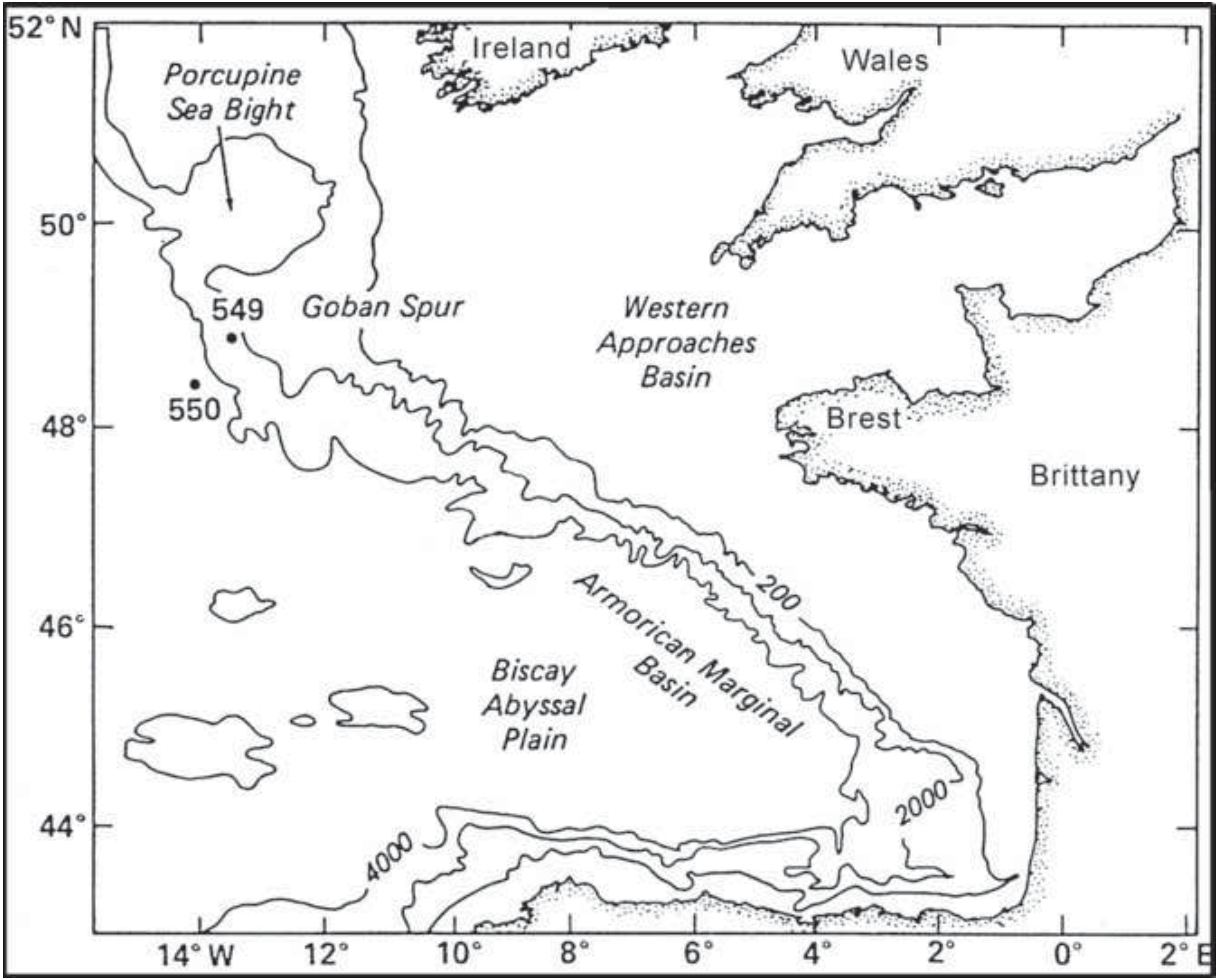

Figure 2
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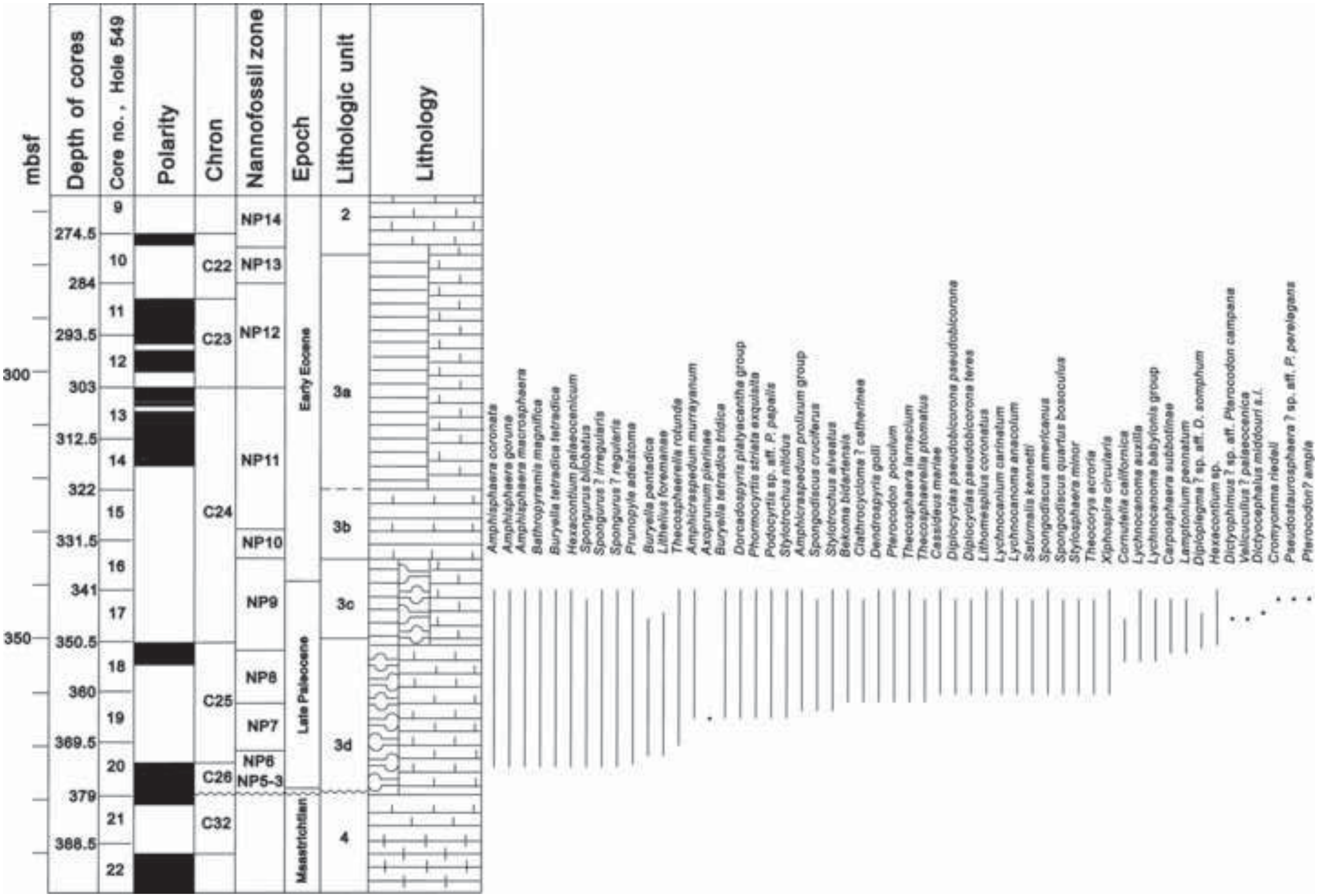

Figure 3

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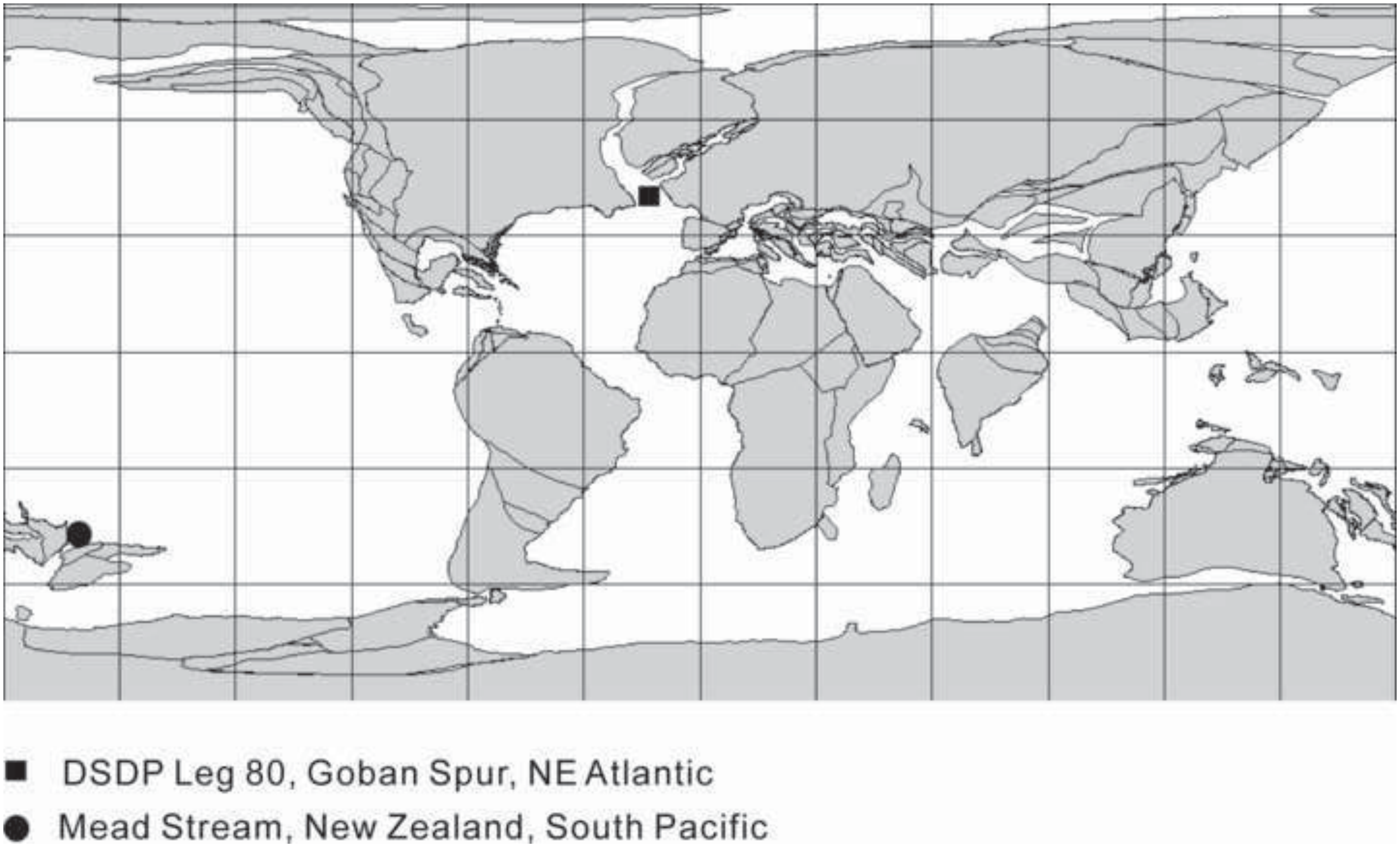

Plate 1
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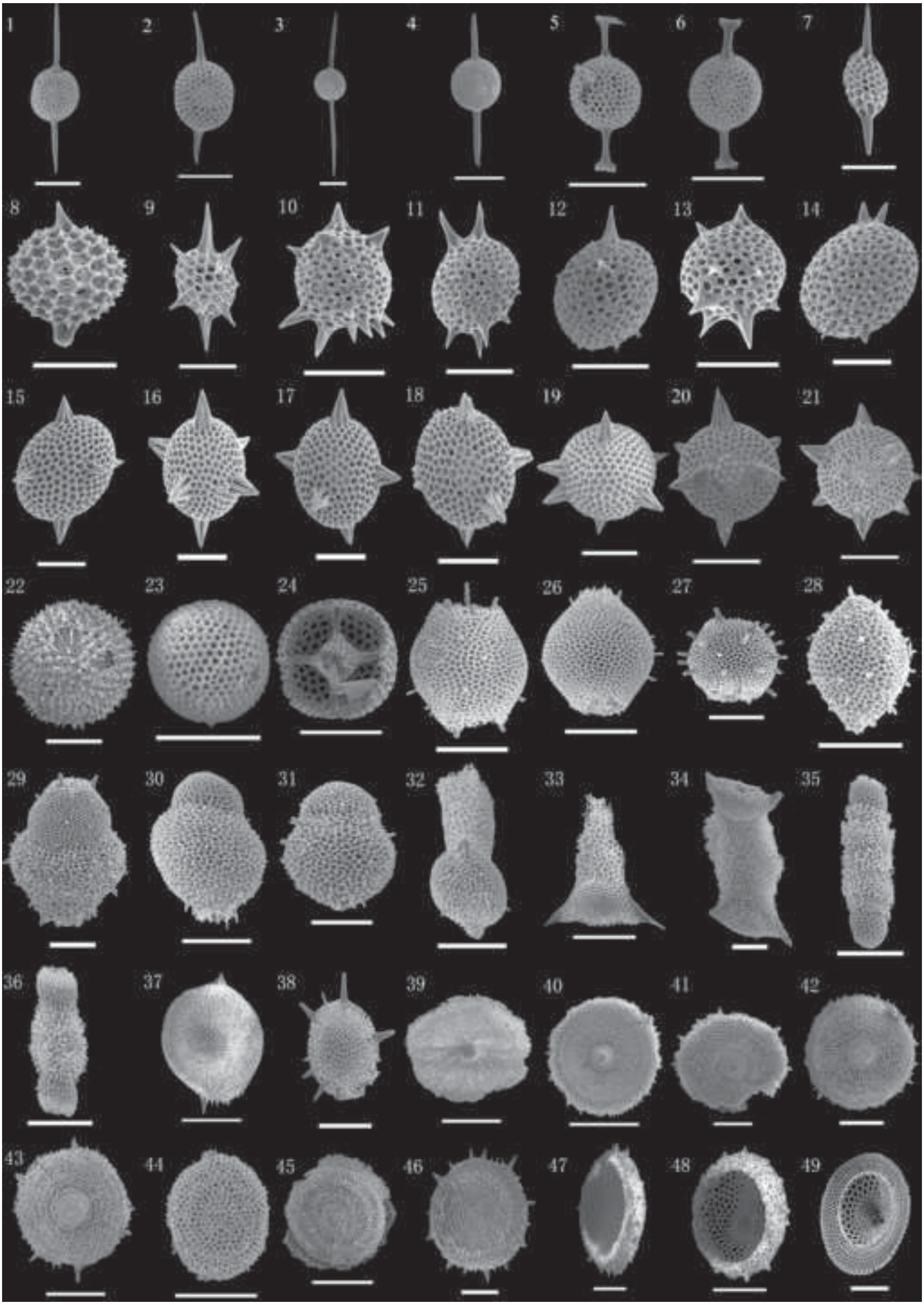

Plate 2
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