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28. Calcareous Nannofossils, Pollen, and Spores from Leg 178 Sites 1095, 1097, 1100, and 1103, Western Antarctic Peninsula: Age Constraints and Environmental Implications[1]

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ABSTRACT

Calcareous nannofossils, pollen, and spores were examined on samples from Ocean Drilling Program Leg 178 Site 1095 on the continental rise and Sites 1097, 1100, and 1103 on the outer continental shelf of the western Antarctic Peninsula. Stratigraphically useful specimens of calcareous nannofossils occur in Site 1095 sediments assigned to Zones CN15, CN13b, and CN11. Calcareous nannofossils are rare but occur throughout the sedimentary sequences from seismic Units S1 to S3 on the continental shelf. Most of the calcareous nannofossils in Units S1 and S2 are composed of Cretaceous specimens that have been recycled by glacial processes. The occurrence of *Dictyococcites* in samples within Unit S3 upper Miocene sediments without any reworked specimens suggests those sediments are deposited in an open-ocean environment. These results are consistent with those from foraminifer and radiolarian studies. Pollen and spores including *Nothofagidites,* the genus for fossil pollen referred to as *Nothofagus,* are also observed in Unit S3 sediments. The sparse occurrence of pollen and spores, however, makes it difficult to assess the nature of the Antarctic terrestrial vegetation.

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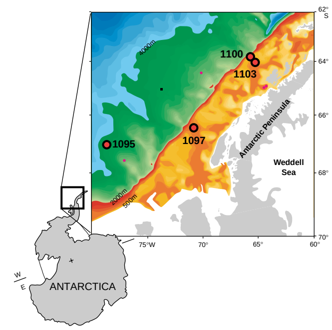
INTRODUCTION

Sedimentary successions on the Antarctic continental margin are a direct record of Antarctic ice-volume fluctuations and allow the resolution of inconsistencies (Barker, Camerlenghi, Acton, et al., 1999) between records of eustatic sea level changes (Haq et al., 1987, 1988), oxygen isotope ratios in deep-water foraminifers (Miller et al., 1987; Shackleton et al., 1995), and Antarctic glacial history inferred from onshore evidence (Webb and Harwood, 1991; Moriwaki et al., 1992). The Pacific margin of the Antarctic Peninsula is a key area of interest because of the sensitivity of the West Antarctic Ice Sheet (WAIS) to temperature changes (Huybrechts, 1993; Barker, Camerlenghi, Acton, et al., 1999).

Ocean Drilling Program (ODP) Site 1095 (66°59.1′S, 78°29.2′W; 3842 m water depth) was the first of three sites (1095, 1096, and 1101) cored on a hemipelagic sediment drift (Rebesco et al., 1997) on the continental rise off the northwestern Pacific margin of the Antarctic Peninsula (Fig. **F1**). One of the key issues of Leg 178 was to establish the biochronological framework at the rise sites and apply it to shelf sites to investigate Antarctic ice history (Barker, Camerlenghi, Acton, et al., 1999). Winter and Wise (**Chap. 26,** this volume) provide calcareous nannofossil biostratigraphy at Sites 1096 and 1101. No age constraints for calcareous fossils, however, have been assigned to sediments at Site 1095.

F1. Site locations with bathymetric counters, p. 12.



Four sites (1097, 1100, 1102, and 1103) on the outer continental shelf were drilled during Leg 178 (Fig. **F1**) to date major changes in depositional geometry and to improve understanding of shelf sedimentation (Barker, Camerlenghi, Acton, et al., 1999). Site 1097 (66°23.5′S, 70°45.3′W) is located on the outer continental shelf of the Antarctic Peninsula at a water depth of 552 m, some 14 km from the continental shelf edge. One hole was drilled at this site, with a total 436.6 m of penetration. Recovery varied from ~2.3% in the uppermost 80 m of Unit S1, where only cobbles were recovered, to 18% in Unit S2 down to 150 mbsf, and to 16% in Unit S3, which had massive diamict, defined as poorly sorted sediment, with clasts supported by a muddy matrix.

Site 1100 (63°53.0′S, 65°42.3′W) is the first site on a shelf transect and is located between Sites 1102 and 1103. Four holes were drilled at Site 1100 with the deepest, Hole 1100D, reaching 110.5 meters below seafloor (mbsf) (recovery = 4.8%). Recovered sediment consists of poorly consolidated massive diamict with a diatom-bearing silty clay matrix throughout the hole, which is assigned to Unit S1. The top of the section has been interpreted as tills and glaciomarine muds, reworked by iceberg grounding (Barker, Camerlenghi, Acton, et al., 1999). A total of four holes were drilled at Site 1102 (63°48.1′S, 65°51.4′W) on the edge of the continental shelf at a water depth of 442 m. However, no sediment samples were recovered at this site.

Site 1103 (63°59.9′S, 65°27.9′W) is located on the inshore end of the shelf transect at a water depth of 494 m. A single hole was drilled to a total depth of 362.7 mbsf. A 250-m-thick section of Unit S1 glacial topset along with deeper Unit S3 glacial sediments were drilled. Recovery from the upper 247 m was only 2.3%, but improved to 34% in the lower 115 m where the matrix became hard. This sediment consists of diamictites, poorly sorted sandstones, and mudstones that are interpreted as sediment gravity flows.

The age of sedimentary sequences on the continental shelf are constrained mainly by diatoms and supported by a radiolarian assemblage with a broader age range (see "Biostratigraphy" sections in each site chapter in Barker, Camerlenghi, Acton, et al., 1999; Iwai, 2000a). Unit S1 is composed of uppermost Pliocene through Pleistocene sediments. The boundary between Unit S2 and the underlying Unit S3 lies within the lower Pliocene *Thalassiosira inura* diatom biostratigraphic zone and radiolarian biostratigraphic Upsilon Zone. The bottom cores from Holes 1097A and 1103A (Unit S3) are assigned to the upper Miocene *Actinocyclus ingens* var. *ovalis* Zone.

The distribution of calcareous nannoplankton is restricted to north of the present Polar Front in the Southern Ocean (Honjo et al., in press) and used as a proxy for the southward oscillation of the frontal system (Burckle et al., 1996; Bohaty and Harwood, 1998). Calcareous nannofossils restrict the age of recycled sediments and the final deposition on the continental shelf. Fossil pollen has been used as a proxy for Antarctic terrestrial vegetation (Webb and Harwood, 1987, 1993; Fleming and Barron, 1996). Fleming and Barron (1996) found the significant increase of *Nothofaidites* cf. *lachlaniae* (pollen) in the mid-Pliocene sediments from Deep Sea Drilling Project (DSDP) Leg 28, Site 274. They thought that this pollen was derived from *Nothofagus* trees that were living in Antarctica during the mid-Pliocene, a result that supports the Pliocene deglaciation hypothesis of Webb et al. (1984). This paper describes the occurrence of calcareous nannofossils, pollen, and spores from the continental rise and shelf along the western Antarctic Peninsula and provides age constraints and implications for subglacial depositional history.

METHODS

All samples used in this study were collected during Leg 178 (Table T1). Smear slides made for biostratigraphic examination during the cruise were used for the shore-based analysis of calcareous nannofossils, with additional slides made postcruise. Calcareous nannofossils were found in a total of 43 samples (10 samples from Holes 1095A and 1095B, 4 samples from Hole 1097A, and 29 samples from Hole 1103A), with an additional 43 samples examined from Site 1095 that were found to be barren of calcareous nannofossils (see the **"Appendix,"** p. 11).

T1. Holes used in this study, p. 14.

For pollen analysis, samples were processed following the standard preparation technique (Faegri and Iversen, 1989). A total of 40 core catcher samples (25, 4, and 11 samples from Sites 1097, 1100, and 1103, respectively) were used for pollen analysis. All samples were weighed after drying at 110°C for >10 hr (0.31–15.34 g; mean = 4.9 g dry weight). The oven-dried samples were prepared by the standard acetolysis treatment (Faegri and Iversen, 1989). Mineral material in the samples was removed by density separation using $ZnCl_2$ solution (specific gravity = 2.0 g/cm^3). A 40% HF treatment was also used on the samples. Residues extracted from the samples were suspended in dilute glycerine jelly. After the mixtures were thoroughly shaken, they were mounted on coverslips. All pollen and spores were counted. When the pollen or spore was mechanically broken and chemically degraded, and therefore could not be identified, it was counted as a decayed grain. Based on the total count, the absolute number of pollen and spores per 10 g dry weight was calculated. Charcoal fragments occurred commonly or often abundantly with fossil pollen and spores in all samples. The occurrence of charcoal fragments in each sample was classified into the following five grades: abundant (5), frequent (4), common (3), rare (2), and very rare (1). Taxonomic references for the pollen and spore taxa identified from the sediments are in Kemp (1975), Martin (1978), Truswell (1983), Pocknal and Mildenhall (1984), Truswell and Drewry (1984), Mildenhall (1989), Dettman et al. (1990), and Hill and Truswell (1993).

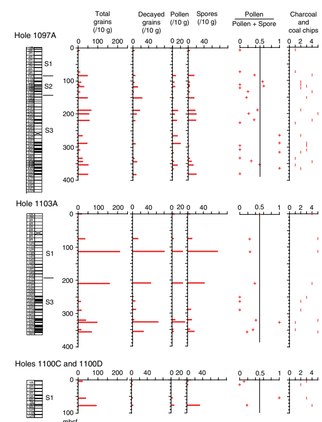
RESULTS AND DISCUSSION

The occurrence of calcareous nannofossils are shown in Tables T2 and T3, and pollen and spores are shown in Table T4. Stratigraphic distribution of pollen and spores is shown in Figure F2.

T2. Calcareous nannofossils, Hole 1095A, p. 15.

T3. Calcareous nannofossils, Holes 1097A and 1103A, p. 16.

T4. Range chart, pollen and spores, p. 17.



F2. Stratigraphic distribution grains, pollen, spores, and charcoal, p. 13.

Rise Site

Holes 1095A and 1095B

Hole 1095A contains some stratigraphically important species of calcareous nannofossils in the upper part of the core. *Emiliania huxleyi,* whose appearance defines the base of the calcareous nannofossil Zone CN15 (Okada and Bukry, 1980), is found only in Sample 178-1095A-1H-2, 70 cm (2.16 mbsf). Samples 178-1095A-3H-5, 18.5 cm, through 5H-1, 90 cm (16.64–31.25 mbsf) contain *Pseudoemiliania lacunosa* without *E. huxleyi,* which suggests that this interval belongs to Zone CN13. The presence of larger specimens of *Gephyrocapsa* (~5 µm) in Sample 178-1095A-5H-1, 90 cm (31.25 mbsf), indicates a possible correlation with Subzone CN13b. The disappearance of this species occurs in this subzone at 1.24 Ma (e.g., Takayama and Sato, 1987; Raffi and Flores, 1995).

Although samples from Hole 1095A contain a few diagnostic species, they are rare in Hole 1095B. In this hole, the presence of only *Reticulofenestra pseudoumbilica* indicates that the samples from Hole 1095B should be correlated with Zone CN11 and older.

Onset termination of Chron C1r.1n (1.07 Ma) (Cande and Kent, 1995) occurred at 29.75 mbsf in Hole 1095A (Barker, Camerlenghi, Acton, et al., 1999). The last occurrence of large *Gephyrocapsa* spp. (1.22–1.24 Ma) occurred between Samples 178-1095A-4H-6, 14 cm, and 5H-1, 90 cm (27.94–31.25 mbsf). Age assignment of calcareous nannofossils is consistent with those suggested by magnetostratigraphy. Unfortunately, however, there are no age constraints near the possible hiatus, which was suggested to occur at ~60 mbsf (see "Magnetostratigraphy" in Shipboard Scientific Party, 1999).

Decreasing biosiliceous sediments and increasing biocalcareous sediments in the uppermost Pliocene to the mid-Pleistocene have been observed at Sites 1096 and 1101 on the continental rise (Barker, Camerlenghi, Acton, et al., 1999). The lower number of calcareous microfossils at Site 1095 may be affected by its deeper (3842 m) water depth relative to Sites 1096 (3152 m) and 1101 (3280 m), or may be due to a missing section in Hole 1095A. The occurrence of calcareous nannofossils between Samples 178-1095A-4H-4, 114 cm, and 5H-1, 90 cm (26.44–31.25 mbsf) (1.03–1.10 Ma, based on the magnetostratigraphic control points in Barker, Camerlenghi, Acton, et al., 1999), show the same pattern as those of diatoms at Site 1095 (Iwai, 2000b). Cowan (2000) found 19 foraminifer-bearing units separated by thicker barren laminated clayey silts at Site 1101 in the interval correlating to between 2.2 and 0.76 Ma. Biogenic-rich massive intervals were deposited during interglacial periods (Cowan, 2000). The occurrence of calcareous nannoplankton in the Southern Ocean is used as a proxy for the southward oscillation of the Polar Front (e.g., Burckle et al., 1996; Bohaty and Harwood, 1998). However, the lack of subantarctic-subtropical warmer diatom species in those sample intervals in Hole 1095A (Iwai, 2000b) suggests that the increase in biocalcareous sedimentation was not the result of the southward migration of the Polar Front (warming) during the interglacial period. It may have resulted from the fluctuation of the carbonate compensation depth (CCD), which was affected by the deep-water circulation changes.

Shelf Sites

Holes 1097A and 1103A

Calcareous Nannofossils

Table T3 shows stratigraphic occurrences of calcareous nannofossils in Holes 1097A and 1103A. Samples from these two holes contain rare and/or barren nannofossils and reworked Cretaceous specimens. Sample 178-1097A-8R-CC contains only a poorly preserved *Gephyrocapsa* specimen, and it is likely to be correlated with the Pleistocene. Moreover, *Dictyococcites* specimens in Samples 178-1097A-28R-CC, 178-1103A-33R-CC, and 178-1103A-34R-CC are present in Unit S3. Specimens observed here are small (~3 µm in diameter) and are not the large *Dictyococcites* species usually found in the Paleogene. The presence of small *Dictyococcites* species also suggests that these horizons were deposited under comparatively open marine conditions.

Reworked Cretaceous foraminifers and radiolarians have also been observed in sediments from Units S1 and S2 at Site 1097 and Units S1 and S3 at Site 1103 (Barker, Camerlenghi, Acton, et al., 1999). The most abundant benthic foraminiferal assemblages and well-preserved specimens of *Cassidulinoides parkerianus* in Samples 178-1103A-31R-CC and 33R-CC suggest that those samples were deposited under the glaciomarine environment (Barker, Camerlenghi, Acton, et al., 1999). The results of calcareous nannofossil analysis are consistent with those of foraminifers and radiolarians (Barker, Camerlenghi, Acton, et al., 1999).

Pollen and Spores

A total of 31 pollen taxa and 17 spore taxa have been observed in the samples (Table T4). Pollen and spore assemblages are characterized by species of genus *Phyllocladidites, Podocarpidites, Nothofagidites, Proteacidites, Tricolpites* (pollens), *Psitriletes,* and *Foveotriletes* (spores). Total grains are, in general, <100 grains per 10 g of dry sediment (Fig. F2). The pollen and spore concentration maximum of 210 grains per 10 g of dry sediment occurs in Sample 178-1103A-13R-CC (113.2 mbsf) within the lower portion of Unit S1. Most of these grains, however, were decayed and considered to be recycled from older sediments. *Nothofagidites,* the genus for fossil pollen referred to as *Nothofagus,* occurred through seismic Units S1–S3. The occurrences of *Nothofagidites* spp. were generally rare and statistically meaningless in those samples. One exception occurred in Sample 178-1103A-34R-CC (319.60 mbsf), where four specimens of *Nothofagidites lachinae* were observed. This species was used to indicate the presence of a *Nothofagus* forest on the Antarctic continent (Fleming and Barron, 1996). Overall, at these sites the sparse occurrence of pollen and spores makes it difficult to assess the nature of the Antarctic terrestrial vegetation.

TAXONOMIC NOTES

Calcareous Nannofossils

Genus *Calcidiscus* Kamptner, 1950

Calcidiscus leptoporus (Murray and Blackman, 1898) Loeblich and Tappan, 1978

Genus *Chiastozygus* Gartner, 1968

Chiastozygus spp.

Genus *Dictyococcites* Black, 1967

Dictyococcites spp.
Remarks: In the present study, all reticulofenestrid specimens whose central opening cannot be idenitified under the light microscope are included in *Dictyococcites* specimens.

Genus *Emiliania* Hay and Mohler in Hay et al., 1967

Emiliania huxleyi (Lohmann, 1902) Hay and Mohler in Hay et al., 1967

Genus *Diffellithus* Reinhardt, 1965

Eiffellithus spp.

Genus *Gephyrocapsa* Kamptner, 1943

Gephyrocapsa spp. (large)
Remarks: Specimens of *Gephyrocapsa* >6 µm in length are included in *Gephyrocapsa* spp. (large).

Gephyrocapsa spp. (small)
Remarks: Specimens of *Gephyrocapsa* <4 µm corresponded to *Gephyrocapsa* spp. (small).

Gephyrocapsa? sp.
Remarks: A specimen, possibly considered to be *Gephyrocapsa,* was found in Sample 178-1097A-8R-CC. It is very difficult to assign it to species because of poor preservation. This specimen is ~5 µm in length.

Genus *Pseudoemiliania* Gartner, 1969

Pseudoemiliania lacunosa (Kamptner, 1963) Gartner, 1969

Genus *Reticulofenestra* Hay et al., 1966

Reticulofenestra pseudoumbilicus (Gartner, 1967) Gartner, 1969

Genus *Watznaueria* Reinhardt, 1964

Watznaueria barnesae (Black, 1959) Perch-Nielsen, 1968

Spores

Trilete Spores

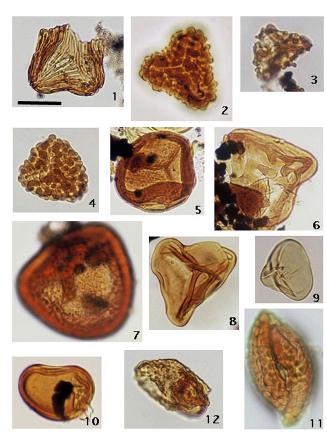
Cicatricosisporites australiensis (Cookson) Potonié, 1956 (Plate P1, fig. 1)

Foveotriletes sp. (Plate P1, fig. 5)
Dimensions: Equatorial diameter = 28–38 µm; lumina diameter = 0.6–1 µm (13 specimens).

Rugulatisporites sp. 1 (Plate P1, fig. 2)
Dimensions: Equatorial diameter = 30–42 µm; verrucae diameter = ~3–4 µm; exine thickness = ~3 µm (seven specimens).

Rugulatisporites sp. 2 (Plate P1, fig. 3)

P1. Light photomicrographs of fossil spores, p. 19.



Dimensions: Equatorial diameter = 24–28 µm; verrucae diameter = 2–4 µm (two specimens).

Rugulatisporites sp. 3 (Plate P1, fig. 4)
Dimensions: Equatorial diameter = 26–36 µm; verrucae diameter = 2–4 µm (22 specimens).

Reticulate-type spore 1 (Plate P1, fig. 6)
Dimensions: Equatorial diameter = 36–50 µm; lumina diameter = 4–7 µm (24 specimens).

Reticulate-type spore 2 (Plate P1, fig. 7)
Dimensions: Equatorial diameter = 48, 56 µm; exine thickness = ~4 µm; lumina diameter = ~1 µm (two specimens).

Psilate-type spore 1 (Plate P1, fig. 8)
Dimensions: Polar length = 22–28 µm; equatorial diameter = 28–36 µm; exine thickness = ~4 µm (14 specimens).

Psilate-type spore 2 (Plate P1, fig. 9)
Dimensions: Polar length = 14–24 µm; equatorial diameter = 18–30 µm (55 specimens).

Monolete Spores

Laevigatosporites ovatus Wilson and Webster, 1946 (Plate P1, fig. 10)

Polypodiisporites radiatus Pocknall and Mildenhall, 1984 (Plate P1, fig. 11)

Polypodiisporites sp. (Plate P1, fig. 12)
Dimensions: Polar length = 36–38 µm; equatorial diameter = 20–22 µm; verrucae = ~2 µm high and 1–3 µm wide (three specimens).

Pollen

Chenopodipollis sp. (Plate P2, fig. 22)
Dimensions: Equatorial diameter = 20 µm; pore diameter = 0.8–1 µm (one specimen).

Dilwynites tuberculatus Harris, 1965

Haloragacidites? sp. (Plate P2, fig. 23)
Dimensions: Equatorial diameter = 24 µm; pore diameter = 2–3 µm; rugulate? (one specimen).

Ilexpollenites? sp. (Plate P2, fig. 19)
Dimensions: Polar length = 18 µm; equatorial diameter = 12 µm; clavae height = 1–2 µm (one specimen).

Genus *Nothofagidites* (Erdtman) Potonié, 1960

Remarks: The two major morphological groups (*fusca* and *brassi* groups) occurred in the samples. Because of the difficulty of separating extant species on the basis of pollen morphology, the fossil species erected by Cookson (1959) and Couper (1953, 1960), with the exception of two species (*N. flemingii* and *N. lachlanae*), have not been consistently identified in this study.

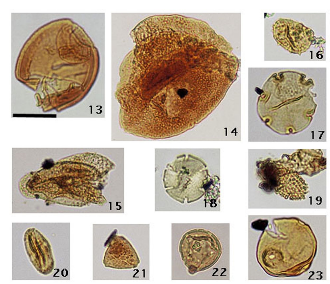
Nothofagidites flemingii (Couper) Potonié, 1960 (Plate P2, fig. 17)

Nothofagidites lachlanae (Couper) Truswell, 1983 (Plate P2, fig. 18)

Nothofagidites spp.
Remarks: This group includes degraded and broken pollen grains of *Nothofagidites* species and therefore could not been minutely identified in this study.

Nupharipollis? sp. (Plate P2, fig. 16)
Dimensions: Polar length = 20 µm; equatorial diameter = 12 µm; spine height = ~1 µm (one specimen).

P2. Light photomicrographs of fossil pollen grains, p. 21.



Phyllocladidites mawsonii Cookson ex Couper, 1953 (Plate **P2,** fig. 13)

Podocarpidites cf. *elliptica*
Remarks: The corpus diameter and the length and width of the sacci for the specimens observed are somewhat smaller than in the Australian *Podocarpidites elliptica* Martin (1973).
Dimensions: Corpus diameter = 22–34 µm; sacci = 10–26 µm long and 8–14 µm wide (three specimens).

Podocarpidites sp. 1 (Plate **P2,** fig. 14)
Dimensions: Corpus diameter = 24–34 µm; sacci = 10–30 µm long and 14–48 µm wide (12 specimens).

Podocarpidites sp. 2 (Plate **P2,** fig. 15)
Dimensions: Corpus diameter = 22–26 µm; sacci 8–14 µm long and 26–42 µm wide (six specimens).

Proteacidites sp. 1
Dimensions: Equatorial diameter = 34 µm; lumina diameter = ~0.6 µm; reticulate (one specimen).

Proteacidites sp. 2 (Plate **P2,** fig. 21)
Dimensions: Equatorial diameter = 16–18 µm; lumina diameter = 0.2–0.4 µm; reticulate (two specimens).

Psilastephanocolporites? sp.
Dimensions: Equatorial diameter = 14 µm; pores = 3 µm long and 1.5 µm in diameter (one specimen).

Tricolpites spp.
Dimensions: Polar length = 28–42 µm; equatorial diameter = 18–26 µm (seven specimens).

Tricolporopollenites sp. (Plate **P2,** fig. 20)
Dimensions: Polar length = 22 µm; equatorial diameter = 10 µm; pore diameter = ~2 µm; scabrate? (one specimen).

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APPENDIX

Sample list for calcareous nannofossil analysis, Site 1095.

Core, section, interval (cm)	Event	Depth (mbsf)	Age (Ma)
178-1095A-			
Core top		0.00	0.000
1H-1, 2.5			
1H-2, 70		2.16	
1H-2, 131.5			
1H-3, 65			
1H-3, 117			
1H-3, 142.5			
1H-3, 150			
1H-4, 7			
1H-4, 100			
2H-1, 13			
2H-1, 72			
2H-1, 111			
2H-1, 139.5			
2H-2, 30			
2H-2, 93			
2H-3, 90			
2H-4, 14			
3H-1, 14			
3H-1, 18			
3H-2, 31.5			
3H-4, 70			
3H-4, 144			
3H-5, 18.5		16.64	
	C1n (o)	17.01	0.780
3H-6, 39.5			
3H-6, 52			
3H-6, 94			
3H-7, 70			
	C1r.1n (t)	23.20	0.990
4H-4, 10			
4H-4, 54			
4H-4, 114		26.44	
4H-5, 29.5		27.10	
4H-5, 78.5		27.58	
4H-6, 14		27.94	
4H-6, 64.5			
5H-1, 90		31.25	
5H-1, 140			
5H-2, 120			
5H-3, 80			
5H-4, 6			
5H-4, 108			
5H-5, 7			
5H-5, 88			
5H-6, 46			
6H-2, 70			
6H-4, 2			
6H-5, 2			
6H-6, 50			
178-1095B-			
	C2An.1n (o)	83.41	3.040
1H-2, 46		85.00	
1H-3, 95			
1H-5, 78			
1H-6, 111			
2H-1, 94			
2H-2, 46			
2H-3, 136			
2H-4, 110			
2H-6, 5		100.05	
	C2An.1n (o)	100.99	3.580
3H-2, 23			
3H-4, 59.5			
3H-6, 32			
4H-2, 40		120.80	
4H-4, 70			
4H-5, 11			
4H-5, 83			
4H-7, 44			
	C3n.1n (t)	126.20	4.180
5H-4, 48			
5H-4, 72			
7H-3, 90			
7H-5, 90			
7H-6, 90			
8H-2, 120			
8H-3, 20			
8H-5, 100			
9H-4, 30			
9H-4, 100			
9H-5, 5			
10H-2, 10			
10H-5, 89			
11H-1, 110			
11H-3, 70			
12H-4, 41			
12H-5, 10			
13H-2, 115.5			
13H-4, 73			
13H-5, 67			
14X-1, 49			
14X-3, 137.5			
15X-1, 33			
15X-2, 126			
16X-1, 12			
16X-3, 23			
17X-4, 78.5			
17X-6, 65			
18X-1, 50			
	C3An.2n (o)	257.80	6.567

Notes: Bold type = samples containing calcareous nannofossils. o = onset, t = termination. Onboard magnetostratigraphy (Barker, Camerlenghi, Acton, et al., 1999) was used for age control.

Figure F1. Site locations with bathymetric contours.

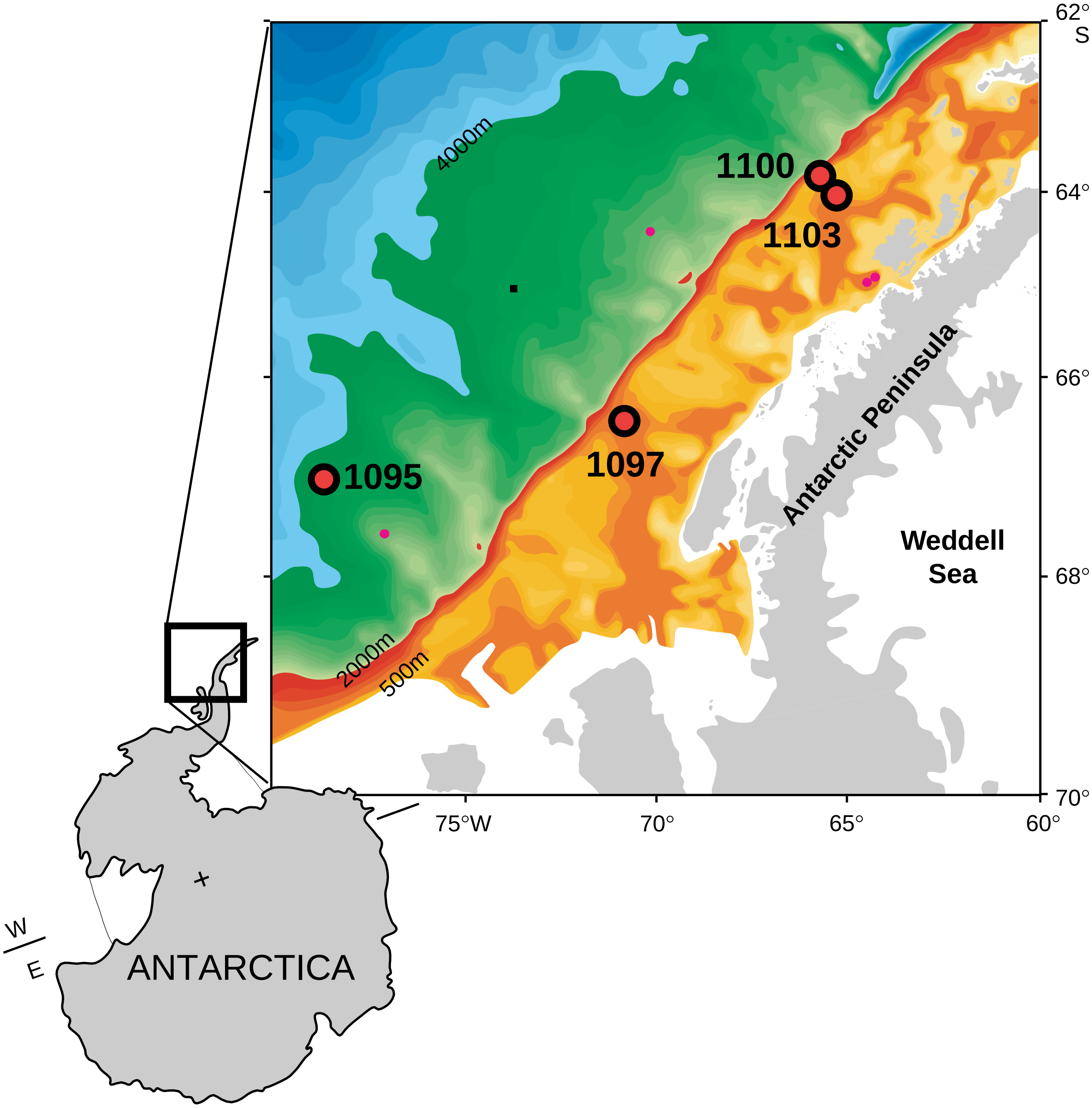

Figure F2. Stratigraphic distribution of total grains counted, decayed grains, pollen, spores, and charcoal and coal-chip preservation.

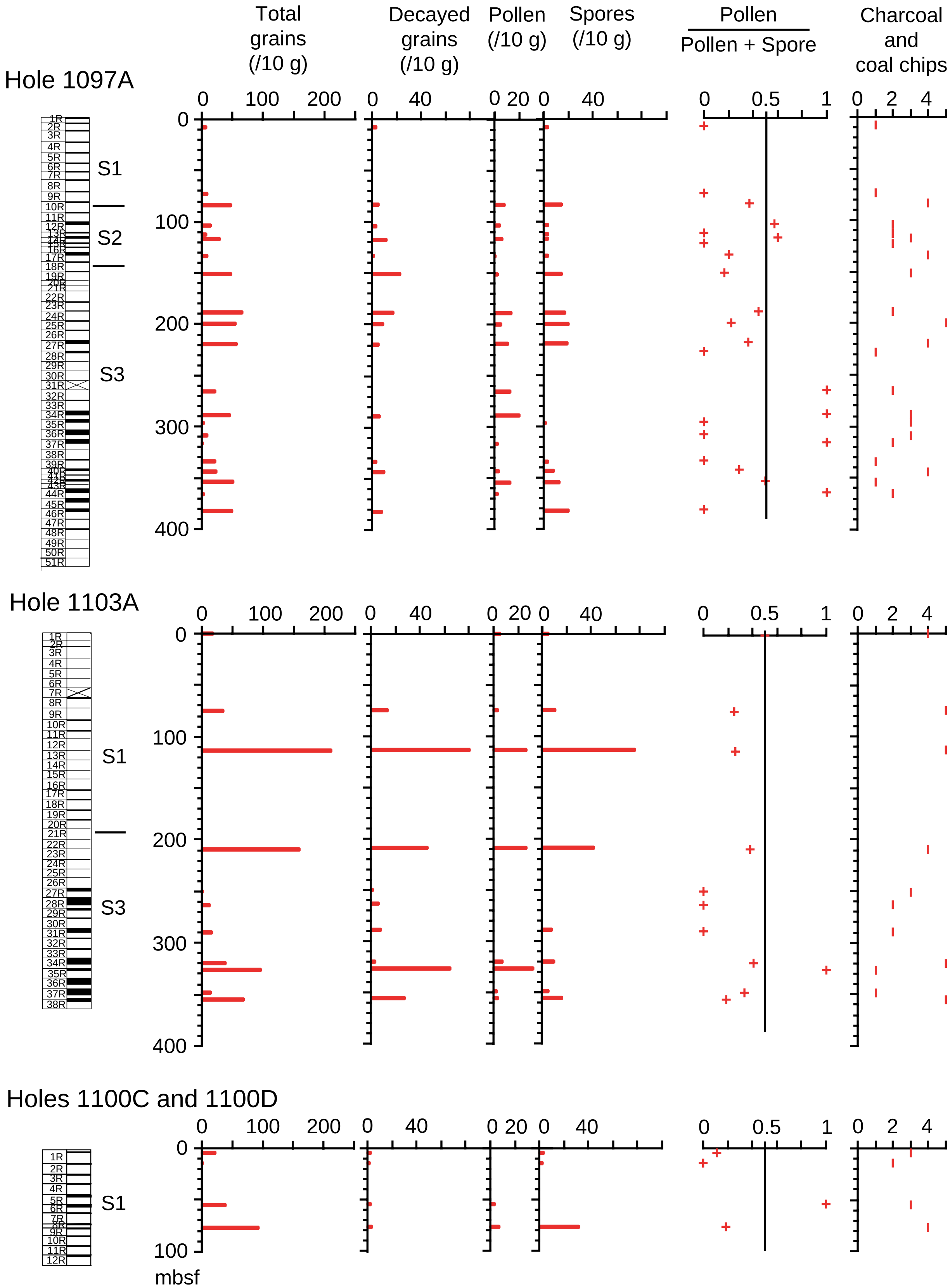

Table T1. Holes used in this study.

Hole	Latitude	Longitude	Water depth (m)	Number of cores	Recovery (%)	Interval drilled (mbsf)
178-						
1095A	66°59.126′S	78°29.238′W	3841.6	10	99.1	0-87.3
1095B	66°59.126′S	78°29.269′W	3841.6	52	79.2	83-570.2
1097A	66°23.568′S	70°45.384′W	551.7	51	13.6	0-436.6
1100C	63°52.998′S	65°42.363′W	458.6	1	81.0	0-5.0
1100D	63°53.005′S	65°42.352′W	458.6	12	4.8	0-110.5
1103A	63°59.970′S	65°27.919′W	493.5	38	12.3	0-362.7

Table T2. Occurrence of calcareous nannofossils with zonal assignments, Hole 1095A.

Core, section, interval (cm)	Depth (mbsf)	*Calcidiscus leptoporus*	*Coccolithus pelagicus*	*Emiliania huxleyi*	*Gephyrocapsa* spp. (large)	*Gephyrocapsa* spp. (small)	*Pseudoemiliania lacunosa*	*Reticulofenestra pseudoumbilicus*	Zone*
178-1095A-									
1H-2, 70	2.16	+	+	+					CN15
3H-5, 18.5	16.64	+	+			+	+		
4H-4, 114	26.44	+	+						
4H-5, 29.5	27.10	+	+				+		
4H-5, 78.5	27.58	+	+				+		CN13b
4H-6, 14	27.94	+	+			+	+		
5H-1, 90	31.25	+	+		+		+		
178-1095B-									
1H-2, 46	85.00		+					+	
2H-6, 5	100.05							+	CN11
4H-2, 40	120.80		+						

Notes: * = Zonal scheme is from Okada and Bukry (1980). + = present.

Table T3. Occurrence chart of calcareous nannofossils from Holes 1097A and 1103A with the Units S1–S3 of Barker, Camerlenghi, Acton, et al. (1999).

				Cretaceous specimens					
Unit	Core, section	Depth (mbsf)	Comments	*Dictyococcites* spp.	*Gephyrocapsa*? sp.	*Chiastozygus* spp.	*Eiffellithus* spp.	*Watznaueria barneae*	Other
	178-1097A-								
S1	2R-CC	7.5							+
	8R-CC	63.3			+			+	
S2	18R-CC	141.2						+	
S3	28R-CC	228.3		+					
	178-1103A-								
	1R-CC	0.2	Barren						
	3R-CC	16.8						+	
	4R-CC								+
	5R-CC	36.0						+	
	6R-CC	45.6				+		+	
	8R-CC	65.3	NO						
	9R-CC	74.7	Barren						
	10R-CC	83.4	NO						
S1	11R-CC	94.3						+	
	13R-CC	113.2				+	+	+	+
	14R-CC	122.8						+	+
	15R-CC	132.3						+	
	17R-CC	151.8	Barren						
	18R-CC	161.9							+
	20R-CC	180.8					+	+	+
	23R-CC	209.3	Barren						
	24R-CC	218.4						+	
	27R-CC	250.6	NO						
	28R-CC	263.4	Barren						
	29R-CC	269.1	NO						
	30R-CC	276.5	Barren						
	31R-CC	289.4	Barren						
S3	32R-CC	295.6	Barren						
	33R-CC	306.5		+					
	34R-CC	319.6		+					
	35R-CC	326.5	Barren						
	36R-CC	338.8	Barren						
	37R-CC	348.8	NO						
	38R-CC	355.3	NO						

Notes: NO = not observed. + = present.

Table T4. Occurrence chart of pollen and spores, Holes 1097A, 1100C, 1100D, and 1103A. (See table note. Continued on next page.)

Seismic unit*	Core, section	Depth (mbsf)	Trilete spores	*Cicatricosisporites australiensis*	*Foveotriletes* sp.	*Rugulatisporites* sp. 1	*Rugulatisporites* sp. 2	*Rugulatisporites* sp. 3	Reticulate-type spore 1	Reticulate-type spore 2	Psilate-type spore 1	Psilate-type spore 2	Other trilete types	Monolete spores	*Laevigatosporites ovatus*	*Polypodiisporites radiatus*	*Polypodiisporites* sp.	Other monolete types	Pollen	*Chenopodipollis* sp.	*Dilwynites tuberculatus*	*Haloragacidites*? sp.	*Ilexpollenites*? sp.	*Nothofagidites*, *brassi* pollen type	*Nothofagidites*, *fusca* pollen type	*Nothofagidites flemingii*	*Nothofagidites lachlanae*	*Nothofagidites* spp.	*Nuphariipollis*? sp.	*Phyllocladidites mawsonii*	*Podocarpidites* cf. *elliptica*	*Podocarpidites* sp. 1	*Podocarpidites* sp. 2	*Proteacidites* sp. 1	*Proteacidites* sp. 2	*Psilastephanocolporites*? sp.	*Tricolpites* spp.	*Tricolporopollenites* sp.	Indeterminable	Decayed grains	Concealed	Total grains counted	Charcoal and coal chips (grade 1–5)	Sample weight (g)	Total grains (/10g)	Charcoal and coal chips (grade 1–5)
	178-1097A-																																													
S1	2R-CC	7.5							1			1																												2		4	1	5.22	7.7	1
	9R-CC	73.28																																					2			2	1	2.12	9.4	1
	10R-CC	83.36		1							1	3															2										1		7	2		17	4	3.47	49.0	4
	12R-CC	103.90							2			1	1							1										1							1		2	3		12	2	7.92	15.2	2
S2	13R-CC	112.60			1							1	1		1																								2			6	2	8.04	7.5	2
	14R-CC	117.20										2	2												1		1					1							2	6		15	3	4.91	30.5	3
	15R-CC	122.80																																								0	2	4.56	0.0	2
	17R-CC	133.30							1			2	2					1													1									2	1	10	4	10.64	9.4	4
	19R-CC	151.10			1						1	2	2																			1							2	8		17	3	3.46	49.1	3
	24R-CC	188.70			1				3			1	3								2		1									1							2	5		19	2	2.84	66.9	2
	25X-CC	199.60			2				1		1	3	3																		1						1		1	3	3	19	5	3.36	56.5	5
	27R-CC	219.30			1				3			3	4																		1		1						1	2	3	19	4	3.63	52.3	4
	28R-CC	228.30																																								0	1	10.88	0.0	1
	32R-CC	265.60																								1		1									1		2			5	2	2.29	21.8	2
	34R-CC	288.80																			1					1											1		2	1	1	7	3	1.49	47.0	3
	35R-CC	296.20				1					1		2																													4	3	10.5	3.8	3
S3	36R-CC	308.80																																					2		1	3	3	3.02	9.9	3
	37R-CC	316.20																																				1				1	2	3.71	2.7	2
	39R-CC	334.02							1				3																										1	1		6	1	2.6	23.1	1
	40R-CC	343.80							2		2		1			1									1			1											1	6		15	4	6.07	24.7	4
	42R-CC	354.00																1														1							2			4	1	0.76	52.6	1
	44R-CC	365.40																							1																	1	2	3.15	3.2	2
	46R-CC	382.70					1		5			4	1				2																						5	5	6	29	4	5.78	50.2	4
	48R-CC	401.20										1	2																													3	1	2.37	12.7	1
	50R-CC	419.80									2		1				1									1										1			1	2		9	3	4.36	20.6	3
	178-1100C-																																													
	1R-CC	4.00			1			3	1		1	2	14																			1							3	13	5	44	3	19.5	22.6	3
	178-1100D-																																													
	2R-CC	14.66										1																														1	2	4.18	2.4	2
S1	6R-CC	54.61											2																				1						2	3	2	10	3	2.54	39.4	3
	9R-CC	76.91			1			8	2		2		6																			3							1	10	4	37	4	3.96	93.4	4
	178-1103A-																																									0				
	1R-CC	0.20			1							1	3												1							1										7	4	3.67	19.1	4
S1	9R-CC	74.74						1				1	1			1									1														1	4		10	5	2.8	35.7	5
	13R-CC	113.20			1		1	7		1		7	3											1								1	3				1		3	18		47	5	2.23	210.8	5
	23R-CC	209.30							1		1	11	6												1		1			1	1	1	1				1		6	14	2	48	4	3.02	158.9	4

Table T4 (continued).

Seismic unit*	Core, section	Depth (mbsf)	Trilete spores	*Cicatricosisporites australiensis*	*Foveotriletes* sp.	*Rugulatisporites* sp. 1	*Rugulatisporites* sp. 2	*Rugulatisporites* sp. 3	Reticulate-type spore 1	Reticulate-type spore 2	Psilate-type spore 1	Psilate-type spore 2	Other trilete types	Monolete spores	*Laevigatosporites ovatus*	*Polypodiisporites radiatus*	*Polypodiisporites* sp.	Other monolete types	Pollen	*Chenopodipollis* sp.	*Dilwynites tuberculatus*	*Haloragacidites*? sp.	*Ilexpollenites*? sp.	*Nothofagidites, brassi* pollen type	*Nothofagidites, fusca* pollen type	*Nothofagidites flemingii*	*Nothofagidites lachlanae*	*Nothofagidites* spp.	*Nupharipollis*? sp.	*Phyllocladidites mawsonii*	*Podocarpidites* cf. *elliptica*	*Podocarpidites* sp. 1	*Podocarpidites* sp. 2	*Proteacidites* sp. 1	*Proteacidites* sp. 2	*Psilastephanocolporites*? sp.	*Tricolpites* spp.	*Tricolporopollenites* sp.	Indeterminable	Decayed grains	Concealed	Total grains counted	Charcoal and coal chips (grade 1–5)	Sample weight (g)	Total grains (/10g)	Charcoal and coal chips (grade 1–5)
	27R-CC	250.60																																						1		1	3	6.56	1.5	3
	28R-CC	263.40											2																											2		4	2	3.13	12.8	2
S3	31R-CC	289.40						2																																2		4	2	2.43	16.5	2
	34R-CC	319.60			3			1	1		1	8	17					2							1		4			1		3		1	1				10	6		60	5	15.34	39.1	5
	35R-CC	326.50																				1									1									2		4	1	0.31	129.0	1
	37R-CC	348.80											1		1			1								1													2			6	1	3.88	15.5	1
	38R-CC	355.30				6				1	1		4		1									1											1				3	15	4	37	5	5.4	68.5	5

Note: * = Seismic unit defined in Barker, Camerlenghi, Acton, et al., 1999.

Plate P1. Light photomicrographs of fossil spores from Leg 178 sites, western Antarctic Peninsula. Scale bar = 20 µm. **1.** *Cicatricosisporites australiensis* (Cookson) Potonié (Sample 178-1097A-10R-CC [83.36 mbsf]); slide 1097-10/1, coordinates 35.4/101.6. **2.** *Rugulatisporites* sp. 1 (Sample 178-1103A-38R-CC [355.3 mbsf]); slide 1103-38/1, coordinates 27.2/82.7. **3.** *Rugulatisporites* sp. 2 (Sample 178-1097A-46R-CC [382.7 mbsf]); slide 1097-46/1, coordinates 44.2/99.6. **4.** *Rugulatisporites* sp. 3 (Sample 178-1103A-31R-CC [289.4 mbsf]); slide 1103-31/1, coordinates 39.6/86.9. **5.** *Foveotriletes* sp. (Sample 178-1097A-13R-CC [112.6 mbsf]); slide 1097-13/1, coordinates 29.3/85.4. **6.** Reticulate-type spore 1 (Sample 178-1097A-24R-CC [188.7 mbsf]); slide 1097-24/1, coordinates 33.8/97.7. **7.** Reticulate-type spore 2 (Sample 178-1103A-13R-CC [113.2 mbsf]); slide 1103-13/1, coordinates 29.4/87.4. **8.** Psilate-type spore 1 (Sample 178-1100D-9R-CC [76.91 mbsf]); slide 1100-9/1, coordinates 47.3/91.4. **9.** Psilate-type spore 2 (Sample 178-1103A-23R-CC [209.3 mbsf]); slide 1103-23/1, coordinates 38.6/98.7. **10.** *Laevigatosporites ovatus* Wilson and Webster (Sample 178-1097A-13R-CC [112.6 mbsf]); slide 1097-13/1, coordinates, 31.9/92.6. **11.** *Polypodiisporites radiatus* Pocknall and Mildenhall (Sample-1097A-40R-CC [343.8 mbsf]); slide 1097-40/1, coordinates 46.0/98.9. **12.** *Polypodiisporites* sp. (Sample 178-1097A-46R-CC [382.7 mbsf]); slide 1097-46/1, coordinates 26.2/99.2. (**Plate shown on next page.**)

Plate P1 (continued). (Caption shown on previous page.)

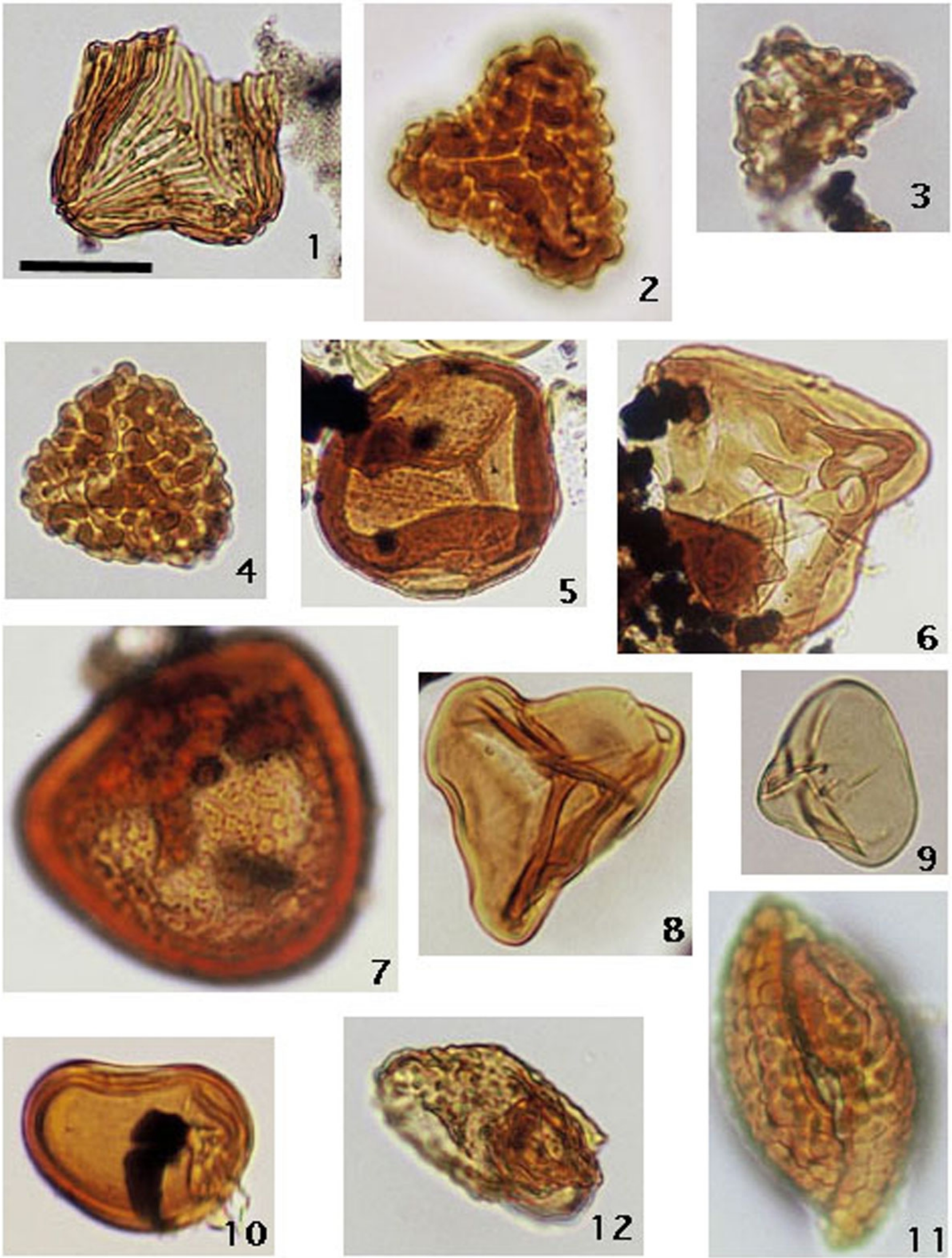

Plate P2. Light photomicrographs of fossil pollen grains from Leg 178 sites, western Antarctic Peninsula. Scale bar = 20 µm. **13.** *Phyllocladidites mawsonii* Cookson ex Couper (Sample 178-1103A-23R-CC [209.3 mbsf]); slide 1103-23/1, coordinates 40.6/98.8. 2. **14.** *Podocarpidites* sp. 1 (Sample 178-1103A-34R-CC [319.6 mbsf]); slide 1103-34/1, coordinates 44.5/85.7. 3. **15.** *Podocarpidites* sp. 2 (Sample 178-1103A-13R-CC [113.2 mbsf]); slide 1103-13/1, coordinates 36.1/100.7. 4. **16.** *Nupharipollis*? sp. (Sample 178-1103A-23R-CC [209.3 mbsf]); slide 1103-23/1, coordinates 38.6/100.8. 5. **17.** *Nothofagidites flemingii* (Couper) Potonié (Sample 178-1097A-32R-CC [265.6 mbsf]); slide 1097-32/1, coordinates 46.1/81.9. 6. **18.** *Nothofagidites lachlanae* (Couper) Truswell (Sample 178-1103A-23R-CC [209.3 mbsf]); slide 1103-23/1, coordinates 43.2/82.2. 7. **19.** *Ilexpollenites*? sp. (Sample 178-1097A-24R-CC [188.7 mbsf]); slide 1097-24/1, coordinates 45.5/88.7. 8. **20.** *Tricolporopollenites* sp. (Sample 178-1097A-37R-CC [316.2 mbsf]); slide 1097-37/1, coordinates 45.1/87.2. 9. **21.** *Proteacidites* sp. 2 (Sample 178-1103A-38R-CC [103.9 mbsf]); slide 1103-38/1, coordinates 41.1/93.2. 10. **22.** *Chenopodipollis* sp. (Sample 178-1097A-12R-CC [103.9 mbsf]); slide 1097-12/1, coordinates 36.7/99.6. 11. **23.** *Haloragacidites*? sp. (Sample 178-1103A-35R-CC [326.5 mbsf]); slide 1103-35/1, coordinates 47.0/82.2. (**Plate shown on next page.**)

Plate P2 (continued). (Caption shown on previous page.)