



Figure 3. Cuticle preparation of *D. odontopteroides* showing outlines of epidermal cells and stoma (center) flanked by guard cells and subsidiary cells. (X 400)

1987 and *D. cf. lancifolium*, *D. cf. elongata*, *D. cf. spinifolia*; Lacey and Lucas 1981). *Dicroidium odontopteroides* is the most common species, known from southern Victoria Land (Plumstead 1962; Rigby 1985), the Allan Hills (Townrow 1967), the Shackleton Glacier area (Townrow 1967), and northern Victoria Land (Tessensohn and Mädler 1987), as well as Mount Falla. *Dicroidium fremouwensis* was described from a permineralized peat deposit at Fremouw Peak (Middle Triassic) and is the only species based on anatomically preserved material (Pigg 1990). The remaining specimens are preserved as impression/compressions. The antarctic taxa are most similar to *Dicroidium* described from Australia, however, the Mount Falla material is noteworthy in that bipinnate frond types, such as *D. zuberi*, are not known.

This work was supported in part by National Science Foundation grant DPP 88-15976.

A glimpse of early Miocene antarctic forests: Palynomorphs from RISP diatomite

XINHE JIANG AND DAVID M. HARWOOD

Department of Geology
University of Nebraska-Lincoln
Lincoln, Nebraska 68588-0340

A clearer view of mid-Cenozoic antarctic terrestrial vegetation is available through the recovery of rich palynofloras in lower Miocene diatomite clasts from RISP Site J/9 sediment cores

References

- Banerji, J. and Y. Lemoigne. 1987. Significant additions to the Upper Triassic flora of Williams Point, Livingston Island, South Shetlands (Antarctica). *Géobios*, 20: 469-487.
- Barrett, P. J. 1969. Stratigraphy and petrology of the mainly fluvial Permian and Triassic Beacon rocks, Beardmore Glacier area, Antarctica. *Institute of Polar Studies Report*, 34:1-132.
- Barrett, P. J., D. H. Elliot, and J. F. Lindsay. 1986. The Beacon Supergroup (Devonian-Triassic) and Ferrar Group (Jurassic) in the Beardmore Glacier area, Antarctica. *Geology of the Central Transantarctic Mountains (Antarctic Research Series)*, 36(14):339-428.
- Bose, M. N., E. L. Taylor, and T. N. Taylor. 1990. Gondwana floras of India and Antarctica—A survey and appraisal. In T.N. Taylor and E.L. Taylor (Eds.), *Antarctic Paleobiology and its Role in the Reconstruction of Gondwana*. New York: Springer-Verlag, 118-148.
- Farabee, M. J., T. N. Taylor, and E. L. Taylor. 1989. Pollen and spore assemblages from the Falla Formation (Upper Triassic), central Transantarctic Mountains, Antarctica. *Review of Palaeobotany and Palynology*, 61: 101-138.
- Lacey, W. S. and R. C. Lucas. 1981. The Triassic flora of Livingston Island, South Shetland Islands. *British Antarctic Survey Bulletin*, 53:157-173.
- Pigg, K. B. 1990. Anatomically preserved *Dicroidium* foliage from the central Transantarctic Mountains. *Review of Palaeobotany and Palynology*, 66:129-145.
- Plumstead, E. P. 1962. Fossil floras of Antarctica. *Trans-Antarctic Expedition 1955-1958, Scientific Reports*, 9:1-154, pl. 1-28.
- Retallack, G. J. 1977. Reconstructing Triassic vegetation of eastern Australasia: A new approach for the biostratigraphy of Gondwanaland. *Alcheringa*, 1:247-277.
- Rigby, J. F. 1985. Some Triassic (Middle Gondwana) floras from South Victoria Land, Antarctica. *New Zealand Geological Survey; Hornibrook Symposium (Christchurch, New Zealand), Abstracts*: 78-79.
- Taylor, E. L., T. N. Taylor, B. Meyer-Berthaud, J. L. Isbell, and N. R. Cúneo. 1990. A Late Triassic flora from the Allan Hills, southern Victoria Land. *Antarctic Journal of the U.S.*, 25(5):20-21.
- Tessensohn, F., and K. Mädler. 1987. Triassic plant fossils from North Victoria Land, Antarctica. *Geologische Jahrbuch*, B66:187-201.
- Townrow, J. A. 1957. On *Dicroidium*, probably a pteridospermous leaf, and other leaves now removed from this genus. *Transactions of the Geological Society of South Africa*, 60:21-60.
- Townrow, J. A. 1967. Fossil plants from the Allan and Carapace Nunataks, and from the Upper Mill and Shackleton Glaciers, Antarctica. *New Zealand Journal of Geology and Geophysics*, 10:456-473.

from beneath the Ross Ice Shelf (see figure 2 in Harwood et al. 1989). Problems associated with palynomorph mixing and reworking due to glacial processes limited the ability of palynologists to distinguish *in situ* grains from recycled grains, and prevented the unequivocal assessment of terrestrial fossil floras in Antarctica. In most studies of Antarctic Cenozoic palynology, recycled pollen dominate the assemblages (Truswell and Drewry 1984; Truswell 1986; Mildenhall 1989; Truswell 1990), and confuse paleo-floral reconstructions. These problems are greatly minimized in this study (Jiang and Harwood 1993), because we focus our attention on marine diatomaceous sediments that show little, if any, glacial influence, and lack reworked Paleozoic and Mesozoic palynomorphs.

We report on a palynomorph assemblage recovered from a lower Miocene diatomite that was deposited in the south central Ross Embayment at a time of minimal glaciation (Harwood et al. 1989). We believe that most, if not all, of the pollen was delivered

Palynomorphs recovered from RISP diatomite

Nothofagus type	Reported age range	Age ref.	
Angiosperms			
<i>Nothofagidites asperus*</i>	<i>menziesii</i>	Mid-Maastrichtian–Pliocene	1, 3, 4, 9, 11, 12
<i>N. brachy-spinulosus</i>	<i>fusca (a)</i>	Paleocene–Miocene	1, 4
<i>N. cranwelliae</i>	<i>brassii (a)</i>	Oligocene–Pliocene	1, 2, 3, 7
<i>N. suggestei</i>	? <i>brassii (b)</i>	mid-Miocene	1, 3
<i>N. emarcidus*</i>	<i>brassii (a)</i>	Eocene to Pleistocene	1, 3, 10
<i>N. flemingii*</i>	<i>fusca (b)</i>	mid-Paleocene to Miocene	1, 3, 7, 10, 13
<i>N. lachlaniae</i>	<i>fusca (b)</i>	Oligocene–Pliocene	1, 2, 3, 5, 6
<i>N. spinosus</i>	<i>brassii (c)</i>	Miocene–Pleistocene	1, 3
<i>N. vansteenisii*</i>	<i>brassii (c)</i>	Eocene–Miocene	1, 10, 11
<i>Illexpollenites? sp.</i>		Cretaceous–Miocene	3
<i>Myrtaceidites mesonesus</i>		Paleocene–Miocene	4
<i>Myrtaceidites sp.</i>		Paleocene–Miocene	3
<i>Triporopollenites ambiguus</i>		Eocene–Miocene	2
<i>Proteacidites destructoris</i>		early- to mid-Miocene	3
<i>Beaupreaidites sp.*</i>		Eocene–early Miocene	2, 3
<i>Nupharipollis sp.</i>			
<i>tricolpate sp.</i>			
<i>triporate sp.</i>			
Gymnosperms			
<i>Phyllocladites mawsonii*</i>		Turonian–Pleistocene	3, 4, 8
<i>Podocarpidites torquatus</i>		early- to mid- Miocene	3
<i>Podocarpidites sp.</i>			
Spores			
<i>Lycopodiumsporites sp.</i>			
<i>Lygodiumsporites sp.</i>			
<i>Cyathea sp.</i>			
<i>Dictyophyllidites sp.</i>			

Key to age reference:

1 - Dettmann et al. 1990	6 - Hill & Truswell 1993	11 - Cookson 1959
2 - Pocknall & Mildenhall 1984	7 - Haskell & Wilson 1975	12 - Couper 1960
3 - Mildenhall & Pocknall 1989	8 - Playford & Dettmann 1978	13 - Stover & Evans 1973
4 - Truswell 1983	9 - Romero 1973	14 - Truswell & Drewry
5 - Mildenhall 1989	10 - Stover & Partridge 1973	* Taxa reported by Brody & Martin (1979)

to the site of marine diatom deposition from temperate to cool temperate forests in the Transantarctic Mountains (200 kilometers to the west), or from island blocks of West Antarctica.

The palynofloras reported here and in Jiang and Harwood (1993) reflect a primary assemblage of pollen and spores produced during the early Miocene, at the time of diatomite deposition. This allows us to reconstruct a clearer picture of the Antarctic vegetation for the middle Tertiary (approximately 20 million years ago).

The timing of the progressive loss of higher plants from Antarctica is a topic of considerable interest (Truswell 1990; Webb and Harwood 1992). The recovery of *in situ* leaves, twigs, roots, and pollen of *Nothofagus* in upper Pliocene sediments of the Sirius Group near the head of the Beardmore Glacier in the Transantarctic Mountains suggests a continued presence of higher plants in Antarctica until the late Pliocene (Askin and Markgra 1986; Harwood 1986; Prentice et al. 1986; Carlquist 1987; Webb and Harwood 1987, 1991, 1992; Hill et al. 1991; Hill and Truswell 1993).

Burckle and Pokras (1991) speculate on an older age for the Sirius Group vegetation, believing it to be "... a relict assemblage which is probably no younger than Oligocene but which may have persisted into the early Miocene." Given this suggested age,

one might expect similar palynofloras in RISP diatomite and the Sirius Group. However, the lower Miocene pollen assemblage documented here and in Jiang and Harwood (in press) is different from the Sirius Group palynofloras. Askin and Markgraf (1986) and Hill and Truswell (1993) note that the Sirius Group assemblages are sparse and of extreme low diversity.

Brady and Martin (1979) reported the presence of palynomorph assemblages in the RISP sediment matrix, which they believed were of mid-Miocene age (an asterisk next to species names in table 1 indicates taxa reported in their study). The sediment matrix contains a mixture of at least three distinct ages of marine sediment and microfossils. These include distinct lower Miocene, middle Miocene, and upper Miocene components that were identified by examining the diatom composition within the sediment clasts and sediment matrix (Harwood et al. 1989; Scherer 1992). An early Miocene age of the diatomite sample used in this study is established by diatom biostratigraphy reported in Scherer (1992). Brady and Martin (1979) describe palynomorph assemblages from the matrix sediments that are dominated by *Nothofagidites*, occur in moderate state of preservation, did not contain Paleozoic to lower Tertiary recycled pollen but appeared to be from an assemblage of one age, and are similar to late Oligocene assemblages from the Ross Sea. The poor

representation of *Proteacidites* suggested an early to middle Miocene age. Brady and Martin were uncertain whether the pollen and spores were derived from local vegetation or were recycled in the glacial matrix of the RISP cores.

Our study of pollen in the marine diatomite clasts from RISP cores significantly reduces, and perhaps eliminates, the problem of glacial-induced fossil recycling and palynofloral assemblage mixing evident in RISP matrix. We report (in the table) a higher diversity palynomorph assemblage than Brady and Martin (1979) but obtained similar overall results (Jiang and Harwood 1993). This is to be expected, since the matrix sediments are derived largely from the degraded lower Miocene diatomite clasts, with lesser contribution from middle and upper Miocene sources (Harwood et al. 1989). Preservation is moderate to good, with some of the grains occurring in tetrads. The pollen assemblage is similar to early Miocene palynofloras of New Zealand (Pocknall and Mildenhall 1984; Mildenhall and Pocknall 1989), but of lower diversity. *Nothofagidites* is a common element, with approximately equal numbers of the *N. fusca* and *N. brassii* groups. The assemblage is dominated by *Nothofagidites cranwelliae*, *N. lachlaniae*, *N. brachyspinulosus*, *N. emarcidus*, *N. spinosus* (table). The significance of the RISP pollen record was hidden when Kellogg and Kellogg (1981, 1986) suggested the palynomorphs were all reworked from older Cenozoic deposits. We believe the palynoflora as described by Brady and Martin (1979) does represent a significant window into early Miocene Antarctic vegetation. The value of this assemblage is enhanced by our palynological study because: the age of the deposit is more clearly defined by diatom biostratigraphy (Scherer 1992); we minimize, and perhaps remove, the problem of mixed assemblages by studying the diatomite clasts; and the palynoflora was produced at a time of minimal glaciation and perhaps climatic optimum in Antarctica.

The terrestrial vegetation represented by the palynoflora reported herein survived in Antarctica through several glaciations of the Oligocene (Barrett et al. 1989; Wise et al. 1991). Similar conclusions about the survival of Antarctic floras through these glacial events were reached by Mildenhall (1989) from the study of the Oligocene to earliest Miocene CIROS-1 drillcore. Mildenhall's study, however, could only refer to "presumed *in situ* Oligocene taxa," due to the high level of pollen recycling evident in the glacial sediments of CIROS-1. Even though the sample examined here was reworked from a diatomite deposit, the pollen assemblage recovered from within the diatomite was produced from plants that were growing at the time the diatomite was deposited.

We now have a clear view from which we will be able to start to trace the progressive removal of higher plants from Antarctica due to climate cooling and increasing ice cover through the Cenozoic.

This project was supported by National Science Foundation grant DPP 91-58075. E.M. Truswell and D.C. Mildenhall provided valuable comments.

References

- Askin, R. A. and V. Markgraf. 1986. Palynomorphs from the Sirius Formation, Dominion Range, Antarctica. *Antarctic Journal of the U.S.*, 21(5):34-35.
- Barrett, P. J., M. J. Hambrey, D. M. Harwood, A. R. Pyne, P. N. Webb. 1989. Synthesis. In P. J. Barrett editor, Antarctic Cenozoic history from the CIROS-1 drillhole, McMurdo Sound. *Bulletin in the Miscellaneous Series of the New Zealand Department of Scientific and Industrial Research*. 245:241-251.
- Brady, H. T. and H. Martin. 1979. Ross Sea Region in the Miocene: a glimpse of the past. *Science*, 203:437-438.
- Burckle, L. H. and E. M. Pokras. 1991. Implications of a Pliocene stand of *Nothofagus* (Southern Beech) within 500 kilometers of the South Pole. *Antarctic Science*, 3(4):389-403.
- Carlquist, S. 1987. Upper Pliocene-lower Pleistocene *Nothofagus* wood from the Transantarctic Mountains. *Aliso*, 11:571-583.
- Cookson, I. C. 1959. Fossil pollen of *Nothofagus* from Australia. *Proceedings of the Royal Society, Victoria*, 71:25-30.
- Couper, R. A. 1960. *New Zealand Mesozoic and Cenozoic plant microfossils* (Bulletin 32). Wellington: New Zealand Geological Survey.
- Dettmann, M. E., D. T. Pocknall, E. J. Romero, and M. d. C. Zamaloa. 1990. *Nothofagidites* Erdtman ex Potonie, 1960; a catalogue of species with notes on the paleogeographic distribution of *Nothofagus* Bl. (Southern Beech). New Zealand Geological Survey Paleontological Bulletin. 60:1-79.
- Harwood, D. M. 1986. Diatom biostratigraphy and paleoecology with a Cenozoic history of antarctic ice sheets. Ph.D. dissertation, The Ohio State University, Columbus, Ohio; 592 pp.
- Harwood, D. M., R. P. Scherer, and P. N. Webb. 1989. Multiple Miocene marine productivity events in West Antarctica as recorded in upper Miocene sediments beneath the Ross Ice Shelf (Site J-9). *Marine Micropaleontology*, 15:91-115.
- Haskell, T. R. and G. J. Wilson. 1975. Palynology of sites 280-284. DSDP leg 29, off southeastern Australia and western New Zealand. *Initial Reports of the Deep Sea Drilling Project*, 29:723-741.
- Hill, R. S., D. M. Harwood, and P. N. Webb. 1991. Last remnant of Antarctica's Cenozoic flora: Pliocene *Nothofagus* of the Sirius Group, Transantarctic Mountains. *Eighth Gondwana Subcommission Symposium*, Hobart, Australia, June 1991, Abstracts.
- Hill, R. S. and E. M. Truswell. 1993. *Nothofagus* fossils in the Sirius Group, Transantarctic Mountains: Leaves and pollen and their climatic implications. In J. P. Kennett and D. Warnke (Eds.), *The Antarctic paleoenvironment: A perspective on global change*, Part 2. American Geophysical Union, Washington, D. C.
- Jiang, X. and D. M. Harwood. 1993. Palynomorphs from RISP site J-9 diatomite: A clear view of mid-Cenozoic antarctic vegetation. In J. P. Kennett and D. Warnke (Eds.), *The Antarctic Paleoenvironment: A perspective of global change*, Part 2. American Geophysical Union, Washington, D. C.
- Kellogg, T. B. and D. E. Kellogg. 1981. Pleistocene sediments beneath the Ross Ice Shelf. *Nature*, 293:130-133.
- Kellogg, D. E. and T. B. Kellogg. 1986. Diatom biostratigraphy of sediment cores beneath the Ross Ice Shelf. *Micropaleontology*, 32:74-79.
- Mildenhall, D. C. 1989. Terrestrial palynology. In P. J. Barrett (Ed.), Antarctic Cenozoic history from the CIROS-1 drillhole, McMurdo Sound. *New Zealand DSIR Bulletin*, 245:119-127.
- Mildenhall, D. C. and D. T. Pocknall. 1989. Miocene-Pleistocene spores and pollen from central Otago, New Zealand. *New Zealand Geological Survey Paleontological Bulletin*, 59:1-128.
- Playford, G. and M. E. Dettmann. 1978. Pollen of *Dacrydium franklinii* Hook F. and comparable early Tertiary microfossils. *Pollen et Spores*, 20(4):513-534.
- Pocknall, D. T. and D. C. Mildenhall. 1984. Late Oligocene-early Miocene spores and pollen from Southland, New Zealand. *New Zealand Geological Survey Paleontological Bulletin*, 51:1-66.
- Prentice, M. L., G. H. Denton, T. V. Lowell, H. C. Conway, and L. E. Heusser. 1986. Pre-late Quaternary glaciation of the Beardmore Glacier region, Antarctica. *Antarctic Journal of the U.S.*, 21(5):95-98.
- Romero, E. J. 1973. Polen fosil de "*Nothofagus*" ("*Nothofagidites*") del Cretacico y Paleoceno de Patagonia. *Revista del Museo de la Plata (Nueva Serie)*, Seccion Paleontologia, 7(74):291-303.
- Scherer, R. P. 1992. Diatom paleoproductivity and sediment transport in West Antarctic basins and the Neogene history of the West Antarctic Ice Sheet (WAIS). Ph.D. dissertation, The Ohio State University, Columbus, Ohio, 272 pp.
- Stover, L. E. and P. R. Evans. 1973. Upper Cretaceous-Eocene spore-pollen zonation, offshore Gippsland Basin, Australia. *Special Publication No. 4 of the Geological Society of Australia*, 55-72.

- Stover, L. E. and A. D. Partridge. 1973. Tertiary and Late Cretaceous spores and pollen from the Gippsland Basin, southeastern Australia. *Proceedings of the Royal Society, Victoria*, 85(2):237-286.
- Truswell, E. M. 1983. Recycled Cretaceous and Tertiary pollen and spores in antarctic marine sediments: a catalogue. *Palaeontographica*, Abt. B, 186:121-174.
- Truswell, E. M. 1986. Palynology. In P. J. Barrett (Ed.), Antarctic Cenozoic history from the MSSTS-1 drillhole, McMurdo Sound. *New Zealand DSIR Miscellaneous Bulletin*, 237:131-134.
- Truswell, E. M. 1990. Cretaceous and Tertiary vegetation of Antarctica: A palynological perspective. In T. N. Taylor and E. L. Taylor (Eds.), *Antarctic paleobiology—Its role in the reconstruction of Gondwana*. New York: Springer-Verlag, 71-88.
- Truswell, E. M. and D. J. Drewry. 1984. Distribution and provenance of recycled palynomorphs in surficial sediments of the Ross Sea, Antarctica. *Marine Geology*, 59:187-214.
- Webb, P. N. and D. M. Harwood. 1987. Late Neogene terrestrial flora of Antarctica: Its significance in interpreting Late Cenozoic glacial history. *Antarctic Journal of the U.S.*, 22(2): 7-11.
- Webb, P. N. and D. M. Harwood. 1992. Pliocene fossil *Nothofagus* (Southern Beech) from Antarctica: Phytogeography, dispersal strategies and survival in high southern latitude glacial-deglacial paleoenvironments. *Proceedings from NATO Science Advanced Institute Series*. In J. Alden (Ed.), *Forest Development in Cold Climates*, Plenum Press.
- Wise, S. W., Jr., J. Breza, D. M. Harwood, and W. Wei. 1991. Paleogene glacial history of Antarctica. In D. W. Muller, J. A. Mackenzie, and H. Weissert (Eds.), *Controversies in Modern Geology*. London: Academic Press, 133-171.

Brittle fault arrays in the Royal Society Range, southern Victoria Land

TERRY J. WILSON

Byrd Polar Research Center
and
Department of Geological Sciences
Ohio State University
Columbus, Ohio 43210

The Transantarctic Mountains form the uplifted margin of the west antarctic rift system (Fitzgerald et al. 1986; Stern and ten Brink 1989; Behrendt and Cooper 1991), which developed during the breakup of the Gondwana supercontinent in the Mesozoic and Cenozoic. Compared to other rift-flank uplifts, the Transantarctic Mountains have more dramatic vertical relief and a greater length, comparable to mountain belts formed at convergent plate boundaries. The structural architecture of the Transantarctic Mountains differs from other rift margins in having a uniform tilt direction and a range-parallel segmentation into blocks separated by transverse physiographic troughs, rather than the typical along-axis segmentation into blocks with alternating tilt direction bounded by morphologically high transverse structures. My previous structural studies in southern Victoria Land have shown that Cenozoic fault arrays define a regional extension direction that is oriented obliquely to the trend of the Transantarctic Mountains, possibly resulting in reactivation and opening of the transverse structures as pull-apart basins and explaining their unusual morphology (Wilson 1990, 1992).

The most prominent transverse break in the Transantarctic Mountains occurs along the southern end of the Royal Society Range, where the mountain chain steps westward toward the Byrd Glacier. During Mesozoic-Cenozoic rifting, this transverse zone was the site of voluminous magmatism in the Jurassic, now represented by extensive outcrops of Ferrar dolerite around the

Skelton Névé, and in the Cenozoic from about 30 million years ago to the present within the McMurdo Volcanic province. Systematic mapping of the distribution, geometry, and displacement patterns of brittle fault arrays within the Royal Society Range is being carried out in the present study in order to investigate the structural development of this major transverse step in the Transantarctic Mountains.

During the 1991-1992 season, field studies were carried out in the foothills of the Royal Society Range between Ferrar Glacier and Radian Glacier, and in exposures around the margins of the Blue Glacier (figure 1). The initial field party, including Peter Braddock, Robert Janosy, Timothy Stepp, and Terry Wilson, was deployed to the ridge north of Garwood Valley on 4 November 1991. Field work was carried out on foot from helicopter-deployed base camps at Garwood, Marshall Ridge, Shangri-la, Lake Keyhole, Rücker Ridge, and Bettle Peak. Helicopter-supported day trips were made to the ridge north of Marshall Valley, Holiday Peak, Herbertson Glacier, Cathedral Rocks, the Walcott Glacier area, Hobbs Peak, and Salmon Hill. In mid-December, the party, with mountaineer Mike Roberts, transversed the northern and eastern portions of Blue Glacier by skidoo to investigate localities throughout that region. Field work was completed on 21 December.

Multiple brittle fault sets are present at all of the field sites visited; representative data from several localities are presented in figure 1. The combined data from the five localities show considerable scatter in fault plane orientation, but the statistical contour plot of poles to the fault planes defines five distinct fault sets within the region (figure 1B). The parallelism between the dominant fault sets at each locality and prominent local physiographic features is of particular interest. At Cathedral Rocks and Herbertson Glacier, the fault sets parallel the Ferrar Glacier trend (figure 1), where a major transverse fault has been inferred (Gunn and Warren 1962; Findlay et al. 1984; Fitzgerald 1987). At Marshall Ridge and the locality along the western Blue Glacier, fault sets parallel the ridge trends. Faults developed on the ridge east of Lake Penny (figure 2) have a west-northwest trend parallel to the major linear trough occupied by Radian Glacier (figure 1A). These relations demonstrate a fundamental structural control on the morphology of the Royal Society Range, particularly the transverse structures that segment the Transantarctic Mountains along their length.