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Antarctic Neogene Landscapes—In the Refrigerator or in the Deep Freeze?

Introduction

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The present Antarctic landscape undergoes very slow environmental change because it is almost entirely covered by a thick, slow-moving ice sheet and thus effectively locked in a deep freeze. The ice sheet–landscape system is essentially stable,

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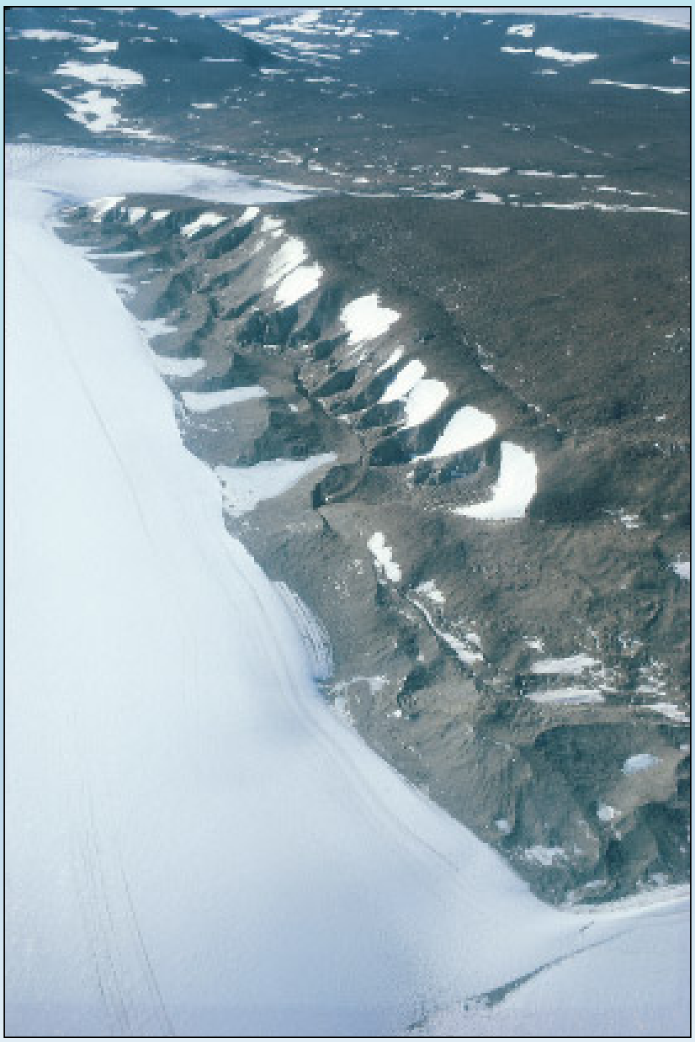

Figure 1. Oliver Bluffs in the Dominion Range at lat 85°S and 1760 m above sea level. The outcrop of the Meyer Desert Formation is fresh, trimmed by the most recent advance of the Beardmore Glacier (Denton et al., 1989), and is eroding. The sequence of the Meyer Desert Formation at Oliver Bluffs comprises ~80 m of interbedded diamictite and laminated mudstone, with minor peat and marl, which represent glacial, fluvial, lacustrine, and marsh or swamp environments that accumulated near sea level and were subsequently uplifted at least 1300 m (Webb et al., 1996). Photo by P.-N. Webb.

Atmospheric Transport of Diatoms in the Antarctic Sirius Group: Pliocene Deep Freeze

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INTRODUCTION

How did young diatoms (including some with ranges from the Pliocene to the Pleistocene) get into the Sirius Group on the slopes of the Transantarctic Mountains? Dynamicists argue for emplacement by a wet-based ice sheet that advanced across East Antarctica and the Transantarctic Mountains after flooding of interior basins by relatively warm marine waters [2 to 5 °C according to Webb and Harwood (1991)]. However, those calling for relative ice-sheet stability since the Miocene have interpreted these diatoms as wind transported (e.g., Denton et al., 1991).

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Glacial Transport of Diatoms in the Antarctic Sirius Group: Pliocene Refrigerator

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INTRODUCTION

The use of marine diatoms to date the Sirius Group (Fig. 1) is a focal point of the debate on Neogene Antarctic glacial history. The Pliocene age of the diatoms is not disputed, as diatom biostratigraphy is well established for this region (Harwood and

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and the preserved terrestrial record of Quaternary glaciations suggests a cold polar ice sheet that expanded and contracted only modestly compared to the much more spectacular comings and goings of the great Northern Hemisphere ice sheets. Over the past 15 years, glacial geologists and others have focused attention on older pre-Quaternary glacial deposits (Sirius Group) in the Transantarctic Mountains that give tantalizing glimpses of a much more dynamic Antarctic ice sheet that existed before the present cold ice sheet. In this earlier much "warmer" ice system with wet-based ice sheets that moved rapidly compared to the cold, dry-based, stable ice sheet of today, the continent was in the refrigerator rather than in the deep freeze. So the Neogene history of the Antarctic contains a remarkable event—the switch from warm-based glaciations to cold-based glaciations as though the ice sheet were taken from the refrigerator and put into the freezer. But controversy rages over when the earlier dynamic "warm" ice sheet was replaced by the present stable "cold" ice sheet. The stabilists say that this occurred before the middle Miocene, while the dynamicists claim that the warm glacial regime persisted until late Pliocene time. The arguments range over many aspects of sedimentology, stratigraphy, geomorphology, biostratigraphy, micropaleontology, paleoecology, glacial geology, geochronology, and marine geology. The resolution of this debate has important ramifications for our understanding of how the present global ocean-earth-atmosphere-cryosphere system became established. Ice in Antarctica plays an important role in this system now and will continue to in the future. Understanding how the ice behaves and its role in the global system requires knowledge of its past behavior. We review here the broad evidence in this debate, and give some of the protagonists the opportunity to discuss one of the central issues in the debate—how to interpret evidence for the age of these dynamic glacial deposits based on interpretation of the apparently age-diagnostic diatoms that they contain.

STABILIST VIEW

Strong evidence supporting the stabilist interpretation of a Miocene switch from warm, dynamic ice sheet to cold, stable ice sheet comes from features at high elevations in the Dry Valleys. There, unconsolidated, unweathered, and uneroded ash beds within a few centimeters from the ground surface and as old as 4 to 15 Ma have been found; their pristine condition apparently precludes the warmer, moister climate implied by a dynamic East Antarctic Ice Sheet (Marchant et al., 1993a, 1993b, 1993c, 1996; Marchant and Denton, 1996). Other convincing glacial, geomorphic, and paleoclimate data from the Dry Valleys suggest that cold polar desert conditions have prevailed there for a very long time (since at least the middle Miocene), and the extent of these conditions has been interpreted to rule out the possibility of a Pliocene dynamic Antarctic ice sheet (Denton et al., 1991, 1993; Sugden et al., 1995).

Supporting evidence for the stabilist interpretation primarily from the marine record of the Southern Ocean was summarized by Kennett and Hodell (1995). On the basis of oxygen isotope data, they concluded that Pliocene sea-surface temperatures were not significantly higher than today and noted that no change in ice-sheet volume was recorded by the distribution of ice-rafted detritus. Since then, cosmogenic exposure-age analyses of clasts suggest long exposure (> 4 m.y.) of the Sirius Group (Kurz and Ackert, 1997; Ivy-Ochs et al., 1995), and ice-sheet modeling supports the stabilist interpretation (Huybrechts, 1993).

Stabilists interpret diatoms of Pliocene age in the Sirius Group as wind-transported, thus obviating the need for a Pliocene age for this deposit and permitting it to be significantly older (Burckle and Potter, 1996; Stroeven et al., 1996).

DYNAMICIST VIEW

Dynamicists have been amassing a large stratigraphic data base and convincing evidence for a wet-based ice sheet (and a warmer Antarctic climate) during their 20+ years of study of the glacigenic deposits and enclosed flora and fauna of the Sirius Group (e.g., McKelvey et al., 1991; Webb et al., 1984; Wilson et al., 1998). Best exposed in the southern Transantarctic Mountains, but also found in the Dry Valleys and the Prince Charles Mountains (Fig. 1; the correlative Pagodroma Group; McKelvey et al., 1995; but note that some question the correlation, but not the age), the Sirius Group is a hodgepodge of diamicts (neither well sorted nor well lithified) and stratified semilithified deposits that record deposition in a variety of glacial, fluvioglacial, glacial-marine, fiord, and lacustrine environments. The reworked marine diatoms in the Sirius Group are thought to have originated in marine seaways in interior East Antarctica; in this scenario, an ice sheet built up in East Antarctica during the Pliocene and transported the diatoms to the Transantarctic Mountains, where they were deposited in the Sirius Group. Unlike deposits of cold-based ice sheets, these deposits occur in packages many meters thick. This and the widespread occurrence of the Sirius Group throughout most of the Transantarctic Mountains and of the correlative Pagodroma Group (which contains in situ bivalves and Pliocene diatoms) in the Prince Charles Mountains in East Antarctica support the existence of an extensive wet-based ice sheet during the Pliocene (Webb et al., 1984; Barrett et al., 1992). As supporting evidence, dynamicists point to data from drillholes on the Antarctic continental margin (Hambrey and Barrett, 1993) and from seismic stratigraphic studies (Anderson and Bartek, 1992; Bartek et al., 1997), to the known Pliocene warming event (Cronin and Dowsett, 1991; Dowsett et al., 1996), and to ice-sheet modeling (Huybrechts, 1993), all of which are consistent with their interpretation of a dynamic, warm, wet-based ice sheet in the Pliocene.

Dynamicists' case for a warm-based ice sheet is bolstered by their recovery of many components of terrestrial ecosystems within the Sirius Group. Their findings include twigs, leaves, moss, pollen, seeds, and insects; much of the material is in excellent condition (Hill et al., 1996; Ashworth et al., 1997); unfortunately, these are not good biostratigraphic indicators. At issue is not the existence of such a biota, but its age: When did temperate conditions last exist in Antarctica?

However, at the same time the warm-based Sirius ice was overwhelming the terrestrial biota, it appears to have been carrying with it recycled marine microfossils, including foraminifera, radiolaria, sponge spicules, and diatoms. Of these, only diatoms are age diagnostic, giving diverse (Tertiary) ages, the youngest of which is Pliocene.

So when did the switch from wet-warm ice sheet to cold-dry ice sheet occur? It is difficult to reconcile the stabilist evidence of cold, polar desert conditions in the Dry Valleys since the Miocene with the specter during the Pliocene of a warm-based ice sheet "next door" to the Dry Valleys in the southern Transantarctic Mountains. Not surprisingly, stabilists favor the interpretation that the Pliocene age for the warm-based ice sheet deposits is erroneously young, citing the well-known proclivity of diatoms for being blown around by wind (Kellogg and Kellogg, 1996). Yet the dynamicists have good reasons for interpreting the diatoms as glacially deposited and thus indicating a Pliocene or younger age for the Sirius Group. They question whether the evidence for polar desert conditions in the Dry Valleys region can be used to interpret the ice-sheet behavior of the entire continent.

The two articles here concern one aspect of this debate: using diatoms to determine the age of the Sirius Group. Stroeven and co-workers (stabilists) summarize work in support of atmospheric transport of diatoms (rendering them useless as age indicators). Harwood and Webb discuss their evidence for glacial transport and a Pliocene age.

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WINDBLOWN DIATOMS IN ANTARCTICA

The discovery of marine diatoms in ice samples from the South Pole demonstrated conclusively that in Antarctica marine diatoms could be transported long distances by eolian processes (Kellogg and Kellogg, 1996). Previously, the contrast between the freshwater diatoms recovered from Last Glacial Maximum ice from East Antarctica and the predominately planktonic marine diatoms of the Sirius Group was used as evidence against eolian transport of Sirius diatoms (Burckle et al., 1988), but recovery of marine, brackish water, and freshwater diatoms in the South Pole ice removed that impediment from the eolian hypothesis.

If diatoms were transported to the Sirius Group by eolian processes, they should also be transported to other surfaces, regardless of age (e.g., Stroeven and Prentice, 1994). In a test of this hypothesis, Paleozoic and Mesozoic sedimentary, metamorphic, and igneous rocks from the Dry Valleys and the Beardmore Glacier area (Transantarctic Mountains) were examined, and diatoms and aggregates of diatoms common in the late Cenozoic Southern Ocean were recovered (Burckle, 1995; Burckle and Potter, 1996). The diatoms must have been introduced into these rocks by eolian processes.

TABLE 1. IDENTIFIABLE DIATOMS RECOVERED FROM SURFACE LAYER AND UNDERLYING SIRIUS GROUP TILLS AT MT. FLEMING, DRY VALLEYS, ANTARCTICA

Diatom species	Surface unit (10 cm)	Till units (10–95 cm)
Actinocyclus actinochilus	3	--
Actinocyclus ingens	1	--
Actinocyclus senarius	1	--
Coscinodiscus marginatus	1	--
Coscinodiscus oculu-iridis	1	--
Eucampia antarctica	5	--
Odontella weisflogii	1	1
Stellarima microtrias	5	--
Thalassiosira inura	2	--
Thalassiosira kolbeii	1	--
Thalassiosira lentiginosa	2	--
Thalassiosira oliverana	2	--
Thalassiosira torokina	4	--
Thalassiosira vulnifica	1	--

Note: Sirius Group till units were mostly barren, but some contained unidentifiable diatom fragments. Compilation includes six samples (2.9 kg) of the surface unit, and 17 samples (>7.4 kg) of the till units. Particles >25 µm were analyzed.

TESTS OF THE EOLIAN HYPOTHESIS WITHIN THE SIRIUS GROUP

If diatoms were wind transported to the Sirius Group, they should be most abundant at or near the surface. As a test, samples were collected at intervals beneath the surface of the Sirius Group (Mt. Fleming, Dry Valleys). The best preserved and most abundant diatoms are in the top 10 cm, and rare, unidentifiable diatoms occur below that to a depth of 95 cm (Table 1; Stroeven, 1994, 1996; Stroeven et al., 1996; Stroeven and Prentice, 1997). The near-surface concentration is consistent with the eolian hypothesis.

Additionally, if Sirius Group sediments recorded drawdown and renewal of the East Antarctic Ice Sheet, one would expect to find diatoms in it that reflect habitats found on a deglaciated Antarctic landscape. Burckle et al. (1996) explored this question through a comparison with the micropaleontology of Scandinavian tills. They found that two persistent features characterized the Scandinavian tills: (1) diatoms found in the tills reflected a wide variety of habitats over which the ice sheet advanced and (2) the diatoms occurred in varying abundances throughout the till. Such is not the case for the Mt. Fleming Sirius Group tills where the diatoms are predominantly of planktic marine origin and occur preferentially in surface layers.

SOURCE OF DIATOMS AND TRANSPORT MECHANISMS

Where did the wind-transported diatoms come from? Stroeven et al. (1996) suggested sea spray and/or uplifted marine sediments. The following scenario is consistent with the diverse substrates (till, ice, and igneous, sedimentary, and metamorphic rocks) ranging widely in age (Paleozoic to Holocene) that have yielded diatoms. Onshore winds pick up nearshore marine and brackish water diatoms as well

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Pliocene Refrigerator *continued from p. 1*

Maruyama, 1992; Winter and Harwood, 1997). The question centers on when and how the diatoms were incorporated into Sirius Group deposits. Webb et al. (1984) suggested that diatoms were eroded by ice from marine strata in subglacial basins of East Antarctica (Fig. 2) and transported to the Transantarctic Mountains, where they were deposited *within* the Sirius Group during the late Pliocene. It was recently proposed that diatoms were deposited by wind *onto* the surface of the Sirius Group as a contaminant, or, that they were associated with the Sirius Group as a result of a Pliocene meteorite impact (2.15 Ma) in the Southern Ocean (Gersonde et al., 1997). In this paper we contrast the characteristics predicted for each of these transport mechanisms (Table 1).

Diatoms on the surface of a Sirius Group deposit probably originate from multiple sources, and care must be taken to distinguish those derived from eolian, glacial, and other processes, on the basis of diatom factors including age, ecology, size, and preservation. In spite of the well-documented wind transport of diatoms and the known ability of strong Antarctic winds to carry gravel-size particles near the ground, we assert that surface contamination via eolian deposition or meteorite ejecta cannot explain the occurrence of Pliocene and older microfossils in the steep and eroding cliffs of the Meyer Desert Formation at Oliver Bluffs, Dominion Range (Figs. 1, 2). Glacial transport provides the simplest and most parsimo-

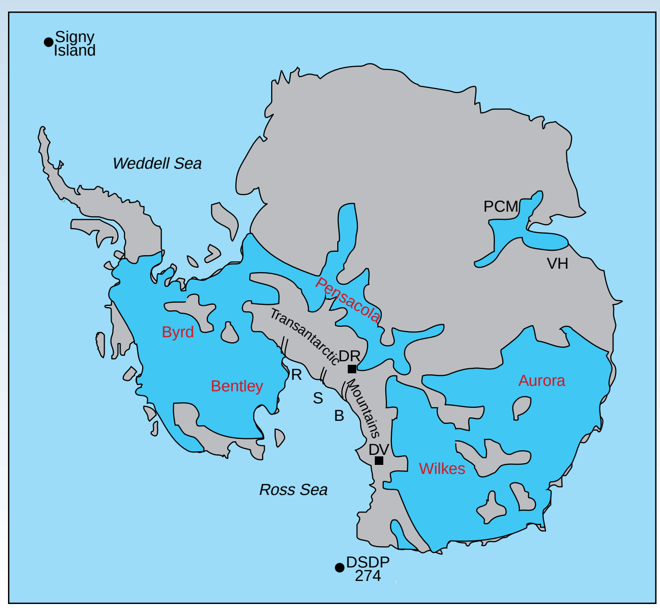

Figure 2. Location map of Antarctica showing locations cited in the text. PCM = Prince Charles Mountains; VH = Vestfold Hills; DV = Dry Valley region; B = Beardmore Glacier; S = Shackleton Glacier; DR = Dominion Range; R = Reedy Glacier; names in red are of subglacial basins shown by the outline, which reflects contour for 1000 m below sea level.

as coastal freshwater forms and carry them inland where they are deposited on various substrates in areas such as the Dry Valleys and elsewhere in the Transantarctic Mountains and in West Antarctic. Occasionally, winds may succeed in airlifting open-ocean marine diatoms as well and transporting them inland to areas such as West Antarctica, the Dry Valleys, and the Beardmore Glacier area. If such winds were the only transporting agent of diatoms in Antarctic rocks, we believe that the diverse occurrences would have immediately been recognized as the product of eolian transport.

We find another transport mechanism compelling. Gersonde et al. (1997) mapped an extensive and chaotic terrain in the southeast Pacific Ocean and found physical evidence for a bolide impact at ~2.3 Ma. Further, the micropaleontological ages of the disturbed sediment (Eocene to Pliocene) matched the ages of the microfossils found in the Sirius Group. They concluded that the bolide impact made airborne a cloud of sea-floor debris, which fell on Antarctica. This bolide impact could have changed both the rain rate and the source of airborne diatoms to the Antarctic continent. Instead of rare brackish and/or freshwater diatoms, it could have caused a marked increase in the rain rate of pelagic diatoms of various Cenozoic ages over the Antarctic continent. Although this bolide hypothesis awaits testing, it answers remaining questions unresolved by the eolian hypothesis.

CONCLUSIONS

On the basis of paleohabitats of diatoms found in Sirius Group sediments and on detailed stratigraphical observations of the Sirius Group on Mt. Fleming, we dismiss inferences that lead to the belief that there was a significant drawdown of the East Antarctic Ice Sheet during the Pliocene, and we conclude that if such deglacial events occurred, they must be Miocene or older.

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nious interpretation of our observations (Webb and Harwood, 1991). We focus on the Meyer Desert Formation at this locality because it is the prime repository of a wide variety of stratigraphic and paleontologic data that has bearing on Antarctic paleoclimate, tectonics, and glacial history (Webb et al., 1996; Ashworth et al., 1997).

SIRIUS GROUP DIATOM ASSEMBLAGES

Diatoms within the Sirius Group have been found at 12 of 14 localities sampled, in varying abundance (Harwood, 1986a, 1986b). They commonly are highly fragmented as both isolated clasts in the matrix and within clasts of diatomite up to 240 µm in diameter (Figs. 3, 4). Most of the recovered diatoms are open marine, planktonic forms, endemic to the Antarctic region; benthic taxa are rare. In the Meyer Desert Formation, 22 of the 60 diatom species recovered are Neogene; their combined ranges indicate a Pliocene age. Diatoms consistently are rare, with a patchy distribution, even within a single stratigraphic section.

CRITICAL ASSESSMENT OF THE EOLIAN HYPOTHESIS

Several lines of evidence indicate that the Meyer Desert Formation diatoms were not transported and deposited by eolian processes.

South Pole Diatoms Are from Patagonia. Diatoms in ice at the South Pole (Kellogg and Kellogg, 1996) led to the suggestion that marine pelagic diatoms in the Sirius Group were wind-borne contaminants (Barrett, 1996). The South Pole assemblages, however, are dominated by freshwater diatoms and small marine benthic taxa. In addition, geochemical analyses of Antarctic ice cores from Vostok and Dome C indicate that dust particles (including diatoms) originate from Patagonian loess and the Argentine continental shelf (Basile et al., 1997), but *not* from Antarctic sources. Diatoms reported by Barrett et al. (1997) in regolith on the surface of the Transantarctic Mountains have a similar non-Antarctic source; 50% of their specimens are of freshwater forms that are absent to rare in the modern and fossil flora of Antarctic lakes (Spaulding and McKnight, 1998).

Size limits of Antarctic Eolian Particles. Diatoms and marine diatomite clasts in the Meyer Desert Formation are too large (>100 µm) to be transported by eolian processes (Fig. 3). The size distribution of eolian particles in the Antarctic ice cores has a mode around 2 µm; maximum sizes (equivalent diameter) are between 10 and 24 µm (Basile et al., 1997). Material transported very long distances in Earth's atmosphere is mostly smaller than 10 µm, and much of it is smaller than 2 µm (Pye, 1987, p. 1). Empty valves of freshwater diatoms are common components in aerosol samples and can be transported around the globe, but these particles are typically <25 µm diameter or 60 µm long (Pye, 1987). These data from different environments indicate that the eolian hypothesis does not represent a suitable mechanism to transport 100 to 240 µm size particles (Figs. 3, 4) to Sirius Group sites high in the Transantarctic Mountains.

No Source Identified for Eolian Diatoms. The present ice sheet obscures most sources for fossil Antarctic diatoms.

Pliocene Refrigerator *continued on p. 6*

Pliocene Refrigerator *continued from p. 5*

If the margin of the East Antarctic Ice Sheet has been at its present position since the middle Miocene (stabilist view), then there has not been a source of Antarctic diatoms available to atmospheric scavenging for 15 m.y. or more. Sea spray is not a viable source; air-trap samples taken on sub-Antarctic islands yielded only very small diatoms and a paucity of planktonic marine taxa (Chalmers et al., 1996).

Diatoms in Paleozoic Rocks. In a search for diatoms on a limited number of pre-Cenozoic sedimentary and igneous rocks Burckle and Potter (1996) recovered well-preserved and abundant diatoms (about 700 *whole* specimens per gram) in sediment filling cracks. The recovered diatoms differ markedly from those of the Sirius Group in being much more abundant, better preserved, and derived from an open ocean setting rather than from a continental shelf. Barrett et al. (1997) reported between 0.2 and 7 diatom fragments per gram from the Sirius Group at Mt. Feather, which is more consistent with our observations of diatom abundance.

Proponents of the eolian hypothesis imply that marine diatom assemblages should be ubiquitous in Antarctic air, soil, and outcrops. Lakes are obvious sediment traps for eolian particles, yet marine diatoms (fossil and recent) are absent or rarely encountered in Antarctic lakes (S. Spaulding, 1997, personal communication). Furthermore, deltaic deposits <10 km inland from McMurdo Sound contain only severely broken marine diatoms with relatively unbroken nonmarine forms (Kellogg et al., 1980).

Limited and Contradictory Data from Mt. Fleming. Harwood (1986a) recovered a few poorly preserved specimens from the Sirius Group deposit at Mt. Fleming. Stroeven et al. (1996) prepared additional samples in Harwood's laboratory, producing more data, but again, diatoms were found to be unevenly distributed and very rare. Harwood identified and characterized the diatoms for this study. Stroeven et al. (1996) and Stroeven and Prentice (1997) interpreted the results to indicate a marked reduction in diatoms from the surface into the deposit. We disagree with this interpretation because of the small number of diatoms and lack of demonstrated statistically significant differences between the samples.

METEORITE EJECTA HYPOTHESIS

Another mechanism for diatom transport, proposed by Gersonde et al. (1997), is based on recognition of a late Pliocene meteorite impact event (~2.15 Ma) in the Southern Ocean. Gersonde et al. suggested that ejecta-borne diatoms may have contaminated the Sirius Group. If this was the source for Pliocene-Pleistocene marine diatoms on the surface of the deposit at Mt. Feather, Dry Valleys, it may allow a pre-Pliocene age for this deposit. However, since Pleistocene time, the Beardmore Glacier (Denton et al., 1989) has been eroding the Meyer Desert Formation in the Dominion Range, and any impact-derived sediment would have been eroded from our sampling sites.

We acknowledge the possibility that Pliocene diatoms in meteorite ejecta could have been incorporated in basal sediments of the Sirius Group deposited by subsequent glacial advance. In either scenario, glacial or ejecta, the youngest elements (Pliocene) of the recycled flora lead us to the conclusion that the Meyer Desert Formation is a post–middle Pliocene deposit. Detailed comparison of the diatom floras within impact debris in the Bellingshausen Sea with Sirius diatom floras is needed to look for agreement and to define the remaining discordance.

PLIOCENE WARMTH FROM ANTARCTIC DATA

A wealth of information on Antarctic Pliocene warming can be found in recent

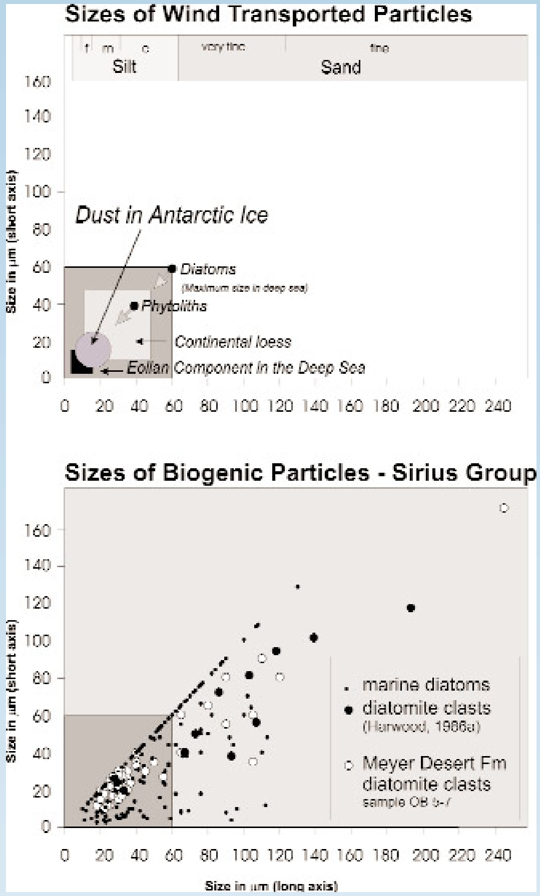

Figure 3. Comparison of the size range (silt) of particles commonly carried by the wind and fossil diatoms and diatomaceous sediment clasts present in the Sirius Group. The largest diatomaceous sediment clast from Oliver Bluffs is 240 × 170 µm in size; a field of similar grains is between 60 and 120 µm. Individual diatom valves recovered from many Sirius Group deposits in the Transantarctic Mountains reach near the normal upper size range for pelagic diatoms—100 to 140 µm—suggesting a mechanism of transport without significant loss of the larger specimens. Wind is unlikely to produce this spectrum, because it would sort for size, leaving the larger particles behind, whereas ice would not discriminate. Size data for eolian particles are from Basile et al. (1997), Pye (1987), and Rea and Hovan (1995).

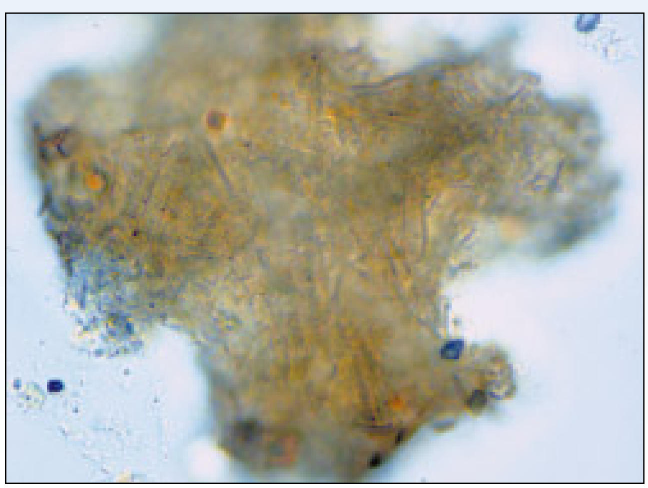

Figure 4. Example of a diatomaceous sediment clast from the Meyer Desert Formation, Dominion Range, sample OB 5-7. Visible through this clast of diatom ooze are abundant fragments of diatoms, as well as high numbers of *Thalassionema* sp. and *Thalassiothrix* sp. This clast is 90 x 80 µm. Assemblages dominated by *Thalassionema* and *Thalassiothrix* are typical of Sirius Group microfloras, reflecting the high productivity of East Antarctic interior basins during times of deglaciation.

TABLE 1. TRANSPORT MECHANISMS FOR DIATOMS IN SIRIUS GROUP, ANTARCTICA

Characteristic	Predicted for Antarctic Eolian Pathway	Predicted for Meteorite Ejecta Pathway	Predicted for Glacial Pathway	Observed in Sirius Group
Largest size of diatoms and diatomite clasts	Small, generally <60 μm (Fig. 3)	Large sizes possible	Large sizes possible	Large diatoms up to 100 μm; clasts of diatomite up to 240 μm
Presence or absence of larger marine microfossils	Absent	Present	Present	Present: foraminifera, sponge spicules, radiolarians, ostracods
Ecology of diatoms recovered	Freshwater and shallow marine predominate	Open marine from Southern Ocean	Mixture*	Mixture†
Source of Antarctic diatoms	Unclear—ice sheet covers landscape (requires deglaciation to expose beds)	Bellingshausen Sea; >3600 km from Transantarctic Mountains	Subglacial basins, possibly from local fjords in some cases	Presumed recycled from subglacial basins (Fig. 2)
Age range of Antarctic microfossils	Narrow §	Wide potentially; late Pliocene and older	Wide #	Wide**
Relation between diatom and diatomite clasts	Not applicable; sediment clasts are too large for distant wind transport	Identical diatoms	Identical; diatoms derived from clasts upon disaggregation in transport and lab preparation	Identical; diatom assemblage composition is similar in diatomite clasts and the till matrix
Presence or absence of volcanic ash	Present; southern Victoria Land ash should be incorporated with diatoms	Absent	Absent? No ash in source basin	Absent
Presence or absence of pollen from outside Antarctica	Present rare	Absent	Absent; no source in Antarctica	Absent
Distribution of diatoms in a stratigraphic section	Surficial; uniform on outcrop surfaces and across diverse landforms	Surficial; uniform on outcrop surfaces and across diverse landforms††	Nonuniform; depends on distribution of diatomite clasts	Nonuniform; productive samples from specific horizons
Presence or absence of diatoms on steep eroding cliffs	Absent	Absent	Present	Present

* All diatoms present in basinal sediments; nonmarine, benthic marine, planktonic marine.
† Predominantly planktonic marine; rare benthic marine and rare freshwater.
§ Unless there are extensive exposures of Paleogene and Neogene marine sediments in Antarctica (now covered by ice sheet).
\# Glacial erosion, not age, selectively favors erosion and transportation of youngest sediment on top of basin fill.
** Cretaceous, Paleocene, late Eocene, late Oligocene, middle Miocene, late Miocene, early Pliocene, mid-Pliocene, Pliocene-Pleistocene.
†† Alternatively, distribution may be within the deposit if ejecta blanketed landscape and was incorporated during subsequent deposition of glacial deposits.

reports and summaries (Abelmann et al., 1990; Wilson, 1995; Quilty, 1996; Dowsett et al., 1996; Gazdzicki and Webb, 1996; Bohaty and Harwood, 1998). The absence of calcareous nannofossils and *Nothofagus* (southern beech) pollen in deep-sea deposits was cited as evidence against warmer Antarctic conditions during the Pliocene (Burckle and Pokras, 1991; Kennett and Hodell, 1995; Prentice et al., 1993); both of these fossil groups subsequently were identified in Deep Sea Drilling Project and Ocean Drilling Program cores. They indicate brief yet significant warming events in the Southern Ocean (Bohaty and Harwood, 1998) and the expansion of mid-Pliocene *Nothofagus* vegetation in the Transantarctic Mountains (Fleming and Barron, 1996). The Antarctic records are consistent with evidence of *global* Pliocene warmth and higher sea level (Cronin and Dowsett, 1991; PRISM Project Members, 1995; Poore and Sloan, 1996). The diverse terrestrial biota of the Meyer Desert Formation suggests that Pliocene mean annual temperatures were ~15 °C warmer than those of today [–16 °C in Francis and Hill (1996) and –9 to –5 °C in Ashworth et al. (1997)]. From these data, it appears that there were brief intervals during the Pliocene when the refrigerator door was left open.

CONCLUSIONS

For the eolian hypothesis to remain viable, the following key questions related to the Meyer Desert Formation must be addressed. How can particles >200 μm in diameter be carried to high elevation, against prevailing wind? How do these biogenic particles penetrate laminated strata in vertical faces without disturbing the stratigraphy? How do diatoms adhere to a near-vertical face of a compact diamicton and penetrate faster than the rate of bluff erosion? And the most important question: Where are the exposures of Pliocene, Miocene, Oligocene, and Eocene strata that provided the source of pelagic Antarctic diatoms?

We feel there is no compelling need to look to the atmosphere to interpret the data from the Meyer Desert Formation. A direct interpretation is grounded in geologic simplicity: Diatoms within glacigenic deposits were deposited by ice. Unless relevant evidence is presented that explains the data from the Meyer Desert Formation more convincingly, the glacially transported origin of diatoms in the Sirius Group, in our view, remains a viable mechanism.

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Pliocene Refrigerator *continued on p. 8*

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Summary

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Reconstructing the history of the Antarctic ice sheet during the Neogene is the ultimate geological puzzle, requiring integration of vast arrays of disparate data that relate to only a small part of a large continent. When did the Antarctic ice sheet switch from its wet-based and dynamic “refrigerator” mode to its dry-based and stable “freezer” mode? Whether seen from the stabilist or dynamicist viewpoint, key pieces of the “Neogene Antarctica: refrigerator or deep freeze?” puzzle are missing. Stabilists need to answer questions such as: (1) Is evidence for a Neogene cold polar desert in the Dry Valleys indicative of continent-wide conditions? (2) How can clear evidence of warm Pliocene conditions from elsewhere in Antarctica (e.g., Prince Charles Mountains) be reconciled with evidence for a polar desert in the Dry Valleys since the Miocene? (3) How could landscapes in the Dry Valleys remain unchanged for millions of years during which weathering, periglacial, and eolian processes must have been operating?

Similarly, questions the dynamicists need to answer include: (1) How can a dynamic warm ice sheet have existed at the same time as polar desert conditions in the nearby Dry Valleys? (2) Can the amount of uplift implied by the presence of Pliocene fiordlike deposits within the Sirius Group at an elevation of 1700 m in the Transantarctic Mountains be explained? (3) Can the long exposures indicated by the cosmogenic exposure dating analyses be explained within the context of a dynamic ice sheet in the Pliocene?

Could both the stabilists and the dynamicists be correct? Perhaps pieces of the puzzle are missing. Might one of those pieces fill a gap in understanding by linking the dynamicists’ and the stabilists’ data and interpretations? Antarctica exerts a major influence on global climate and sea level. If we are to predict future climate change and its effects in Antarctica, we need an unambiguous interpretation of its geologically recent past.

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