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GLACIAL GEOLOGY

Diatoms in a South Pole ice core: Serious implications for the age of the Sirius Group

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One of the most controversial topics of the past decade for paleoclimatologists has been the hypothesized existence of a Pliocene warm interval in Antarctica around 3.0–2.5 million years ago (Webb and Harwood 1991). Resolution of this controversy has been linked to the validity of two competing explanations for the presence of marine diatoms in glacigenic Sirius Formation (now called *Sirius Group*; McKelvey et al. 1991) deposits sampled from high-elevation locations (mostly higher than 1,500 meters) along a 1,000-kilometer portion of the Transantarctic Mountains (figure 1).

- According to the "dynamic" hypothesis (Webb et al. 1984; Harwood 1986a,b; Harwood and Webb 1995), Sirius Group sediments contain reworked Pliocene marine diatoms that are thought to have been deposited originally west of the Transantarctic Mountains in the Wilkes and Pensacola subglacial basins during a Pliocene warm interval, when the east antarctic ice sheet retreated leaving a narrow ice-free seaway. Subsequent cooling and glacial expansion resulted in grounded ice overriding the basins, incorporating marine sediments and diatoms, and subsequently, emplacing them at Transantarctic Mountains locations as the Sirius Group. This may have occurred at a time when Transantarctic Mountains elevations were 1–3 kilometers lower than they are today (Webb and Harwood 1991).
- The contrasting "stable" hypothesis argues that the east antarctic ice sheet has remained relatively unchanged for millions of years (Denton, Prentice, and Burckle 1991). Supporting data include geomorphic analyses of dry valleys landforms (Marchant et al. 1993, 1994), the preservation of delicate argon-40/argon-39–dated features in the dry valleys (McIntosh and Wilch 1995), evidence for less than 300 meters of Transantarctic Mountains uplift since the early Pliocene (Wilch et al. 1993a,b), stable isotope records from deep-sea cores that show an absolute maximum of 25 meters of sea-level increase during and since the Pliocene (Kennett and Hodell 1993, 1995), and the nature of the antarctic marine biota which suggests a stable environment over millions of years (Kennett 1995).

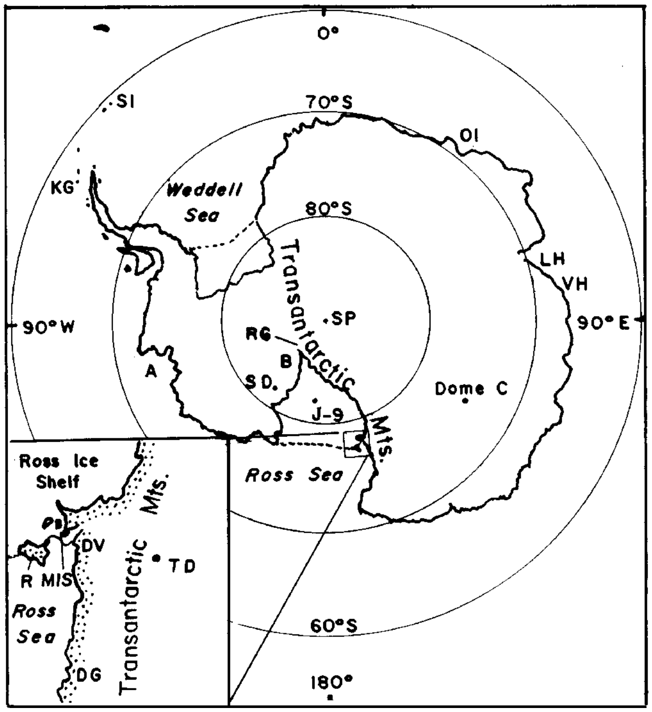

Figure 1. Map of Antarctica showing locations mentioned in text: B, ice stream B; DG, David Glacier; DV, dry valleys; J-9, Ross Ice Shelf Project site J-9; KG, King George Island; LH, Larsemann Hills; MIS, McMurdo Ice Shelf; OI, Ongul Islands; RG, Reedy Glacier; SD, Siple Dome; SI, Signy Island; TD, Taylor Dome; VH, Vestfold Hills. The Sirius Group outcrops at scattered locations in the Transantarctic Mountains from David Glacier southward to near Reedy Glacier. Wilkes and Pensacola subglacial basins are located west of the Transantarctic Mountains.

The diatoms in the Sirius Group represent the single key to resolving this controversy. Were these diatoms incorporated in the Sirius soon after they lived, hence providing maximum ages for Sirius emplacement, or do they represent aeolian contamination, possibly introduced long after the Sirius sediments were deposited? Here, we report on aerially transported diatoms in ice-core samples from the South Pole.

Methods and results

Material for this study comes from the 227-meter ice core drilled at the South Pole by the Polar Ice Coring Office during the 1980–1983 field seasons (Kuivinen et al. 1982). The core spans the last years between samples (stratigraphy based on information from Gow personal communication). We also sampled snow from pits at Siple and Taylor Domes.

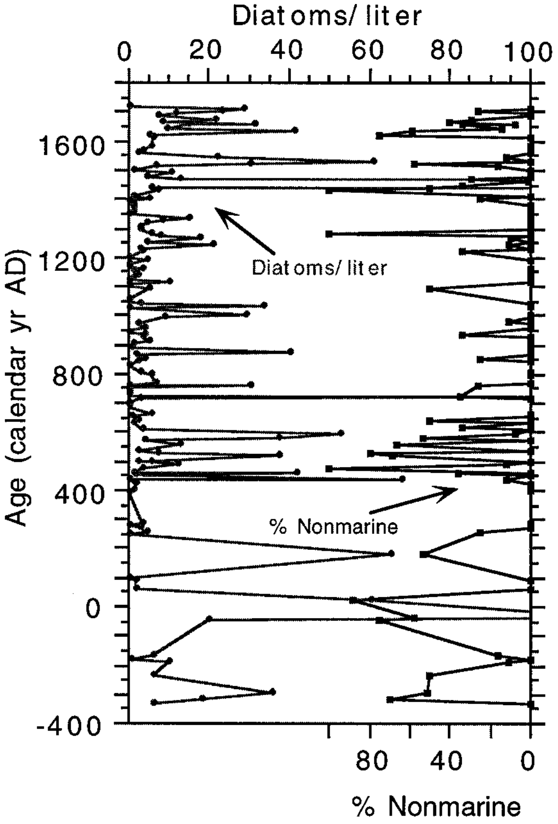

Figure 2. Diatom abundance fluctuations (specimens per liter) and percentage of nonmarine specimens in the South Pole core. Ages are calendar years based on correlation with the adjacent 1981 core at South Pole (Gow personal communication).

At the National Ice Core Facility (NICL) in Denver, Colorado, the melted ice samples, which ranged in volume from 250 to 2,000 milliliters, were filtered using a Millipore system having 1.2-millimeter perforated MF "Nuclepore" filters. Dried filters were cut into six wedges, two of which were kept for archive purposes. The remaining four were placed, sample side down, on glass cover slips and cleared (made transparent) with acetic acid. Cover slips were dried and mounted on standard glass slides. Each slide was examined in its entirety at 1,000 ×, and tallies from multiple slides for each sample were combined. In addition to recording diatoms, we also noted sponge spicules, silicoflagellates, pollen grains, opal phytoliths, inorganic particulates, plant fragments, and other organic fibers.

Some workers may wonder whether our samples are contaminated and, therefore, unreliable indicators of atmospheric diatom transport. We recognize three possible stages in the processing of our samples when contaminants might be introduced:

- during drilling or core packing in the field,
- during melting and filtering at NICL, and
- in our laboratory when filters were prepared for examination.

At the South Pole, no source for diatoms is near the drilling or core-packing site. If contamination occurred at the latter times, one would expect to see a significant extra-antarctic component in the diatom assemblage. Because our samples are all dominated by typical antarctic species, we conclude that contamination is not a problem for this study.

Diatoms are a small but pervasive constituent of snow falling at the South Pole (and at Siple and Taylor Domes), although in a patchy pattern through both space and time (figure 2). Over 40 marine and nonmarine taxa were recorded (table). Abundances are extremely variable, ranging from nil to over 260 specimens in individual samples. Of 136 samples

- 34 percent contain more than 75 percent marine specimens,
- 4 percent are more than 75 percent nonmarine,
- 35 percent have intermediate mixtures of marine and nonmarine taxa, and
- the remainder are barren or are dominated by species of uncertain provenance.

Most recorded species have been reported by us or other workers from a variety of antarctic sites (table). Not all taxa we report have yet been associated with antarctic source areas and may represent transport from remote locations such as the other southern continents. Census data for individual samples will be available in a separate publication (D. Kellogg in preparation).

Sources and atmospheric transport of diatoms

Diatoms are extremely light and easily transported by winds (e.g., the well-known diatom deposits in the equatorial Atlantic derived from Saharan Africa; Folger 1970), and winds in Antarctica are known to reach very high velocity. The antarctic surface windfield is dominated by katabatic flow, outward and down from high ice domes toward the sea (Parish and Bromwich 1987). Storms tend to track around the continent. Occasional large storms break through the circumflow and penetrate to the South Pole (Bromwich and Robasky 1993). Our diatoms were probably carried by these episodic events, which occur today at most a few times annually. An alternative transport mechanism, stratospheric return (poleward) flow, is unlikely because most of our diatoms are antarctic endemics whereas most stratospheric particles are entrained in tropical areas. Terrestrial sediments containing marine and nonmarine diatoms probably serve as the most important diatom sources. We envision diatom entrainment

Diatom taxa, abundance, assemblage and ecologic data

Taxon	Sample[a]	A[b]	Habitat[c]	Reported locations[d]	Notes
Achnanthes lanceolata	SP981 (2)	1	FR	EO, KG, SI	
Achnanthes sp.	SP 981 (2)	1	FR		
Actinochlus ehrenbergi	SP 440, 1460 (1)	1	MAR	A	
Actinoptychus senarius	SP 1460 (1)	1	MAR	R1, RP	
Chaetoceros diadema	TD pit D, 0 cm (1)	3	MAR		Polar waters
Chaetoceros sp.	TD pit K, 93 cm (1)	3	MAR	A, W	
Coscinodiscus marginatus	SP 1532 (10)	1	MAR	R1, RP	
Coscinodiscus radiatus	SP 1532 (6)	1	MAR	K (in red snow)	
Cyclotella comta	SP 1704 (3)	1,3	BR	A1, M, TV	
Cyclotella comta v. oligactis	SP 981 (24)	1	C	A, TV	
Cyclotella glomerata	SP 223 m(3)	1	FR	A, M	
Cyclotella pseudostelligera ?	SP 224.5 m(3)	1	BR		Often counted as *C. stelligera*
Cyclotella stelligera	SP 981 (184)	1,3	C	A1, LM, M	
Cyclotella striata ?	SP 223 m(11)	1	BR		
Cyclotella sp.	SP 726 (21)	1,3	C	A, M, R1	Probably *C. stelligera*
Cymbella lunata	SP 1265 (1)	1	FR	SO	As *Encyconema gracilis*
Denticulopsis hustedtii	SP 1449 (1)	1	MAR	A, R1, RP, W	Miocene
Diploneus smithii	SP 440 (1)	1	BR	LH	
Diploneus sp.	SP 182 (2)	1		A1	
Fragilaria pinnata	SP 981 (1)	1	FR	KG, LG, SI	
Fragilaria virescens	SP 981 (6)	1	FR	DV	
Grammatophora sp.	SP-37 (1)	1	MAR	A, RP	
Melosira distans	SP 223 m (17)	1,3	FR	A1, DV, M	
Melosira granulata	SP-37 (28)	1	FR	LG	=*Aulasoseira granulata*
Melosira sp.	SP 981, 458 (2)	1	FR	A, M, R1	Probably *M. granulata*
Navicula festiva	SP 223 m (2)	1	FR	KG	NZ (Harper, personal communication)
Navicula muticopsis	SD camp (2)	2	FR	DV, LM, M, RO, TV	
N. muticopsis v. evoluta	TD pit 50S, 84 cm (1)	3	FR	M, TV	
Navicula muticopsis n.v.	SD S50 W50 (15)	2	FR		Possible new variety?
Navicula sp.	SP 1637 (2)	1,2	FR?	A1, M, TV	
Nitschia aricularis ?	SD S50 W50 (3)	2	FR	EO	
Nitschia amphibia	TD pit E, 120 cm (1)	3	FR		Arctic
Nitschia closterium	TD pit I, 0 cm (1)	3	BR	M	
Nitschia curta	SD S50 W50 (1)	2	MAR	A, M, R, R1, R2, RP, TV	
Nitschia cylindra	TD pit 50S, 0 cm (11)	3	MAR	A, R1, R2	
Nitschia gracilis	SD S50 W50 (1)	2	FR	SI	
Nitschia microcephala ?	SD S50 W50 (3)	2	FR		Europe
Nitschia obliquecostata	TD pit 50S, 84 cm (1)	3	MAR	A, M, R1	
Nitschia sublineata	TD pit D, 0 cm (1)	3	MAR	A, M, R1	
Nitschia sp.	SP 1460, 213 m (4)	1,2	MAR/FR	A, M, R1, RP, TV	
Paralia sulcata	SP (5 samples) (1)	1	MAR	M, RP	=*Melosira sulcata*
Pinnularia nodosa	SP 1677 (1)	1	FR		NZ (Cassie 1984)
Pinnularia maior	SP 981 (2)	1	FR		Tierra del Fuego (Frenguelli 1923) (as *Navicula maior*); NZ (Cassie 1984)
Pinnularia sp.	SP 1637 (8)	1	FR?	M	
Pseudoneunotia doliolus	SP 1449, 1460 (1)	1	MAR		Subtropics, Pleistocene
Rhabdonema sp.	SP 1440 (1)	1	MAR	M, RP	
Stephanodiscus astraea	SP (6 samples) (1)	1	FR/BR		W. Europe
Stephanopyxis turris	TD pit 50S, 0 cm (1)	3	MAR	M, R1, RP	
Synedra fasciculata	SP 981 (5)	1	FR/BR		
Tabellaria flocculosa	SP 981 (2)	1	FR	A1, TV	
T. fenestrata/quadriseptata	SP 223 m (2)	1,2	FR	A1, DV	
Thalassionema nitzschiodes	SP 458, 1532 (4)	1	MAR	A, M, R1, RP, TV, W	See *T. longissima*
Thalassiosira eccentrica	TD pits B&D (1)	3	MAR	A, R1	
Thalassiosira occulus-iridis	TD pits D&G (1)	3	MAR	A	

Diatom taxa, abundance, assemblage and ecologic data

Taxon	Sample[a]	A[b]	Habitat[c]	Reported locations[d]	Notes
Thalassiosira sp.	SP 1662 (14)	1,2	MAR	A, M, R1, RP	
T*halassiothrix longissima*	SD N50 W50 (119)	2,3	MAR	A, M, R1, RP, W	Includes T. nitzschiodes fragments
Trachyneis aspera	TD pit E, 120 cm (1)	3	MAR	A	
Trachyneis sp.	TD pit D, 80 cm (1)	3	MAR		
Centric diatom fragments	SP 1460 (53)	1,2,3		A, M, R1, RP, TV	Probably mostly marine taxa
Pennate diatom fragments	SP 981 (7)	1			
Unidentified	SP 1704 (3)	1,3			

[a] SP=South Pole; numbers are calendar age in years A.D. or depth in meters if older than 37 B.C.; TD=Taylor Dome, pit number and depth; SD=Siple Dome pit number; numbers in parentheses are maximum value recorded for the taxon in the sample listed.

[b] Assemblage: 1=South Pole; 2=Siple Dome; 3=Taylor Dome.

[c] MAR=Marine; FR=nonmarine; BR=brackish; C=possibly nonmarine but common in antarctic marine samples.

[d] A=Amundsen Sea marine sediments (Kellogg and Kellogg 1987a), A1=sediments and/or water on Amundsen Sea islands (Kellogg and Kellogg 1987a), DV=lakes and ponds in dry valleys (Seaburg et al. 1979), EO=East Ongul Islands (Karaswa and Fukushima 1977), K=Kerguelen Island, red snow (Fritsch 1912b), KG=King George Island (Schmidt et al. 1990), M=McMurdo Ice Shelf (Kellogg and Kellogg 1987b), LG=Lake Glubokoye (Lavrenko 1966), LH=Larsemann Hills (L. Heidi) (Gillieson 1991), LM=Lake Miers, Dry Valleys (Baker 1967), R=Ponds and sediments on Ross Island (Fritsch 1912a, and/or West and West 1911), R1=Ross Sea sediments (Truesdale and Kellogg 1979), R2=Ross Sea sediments (Barron and Burckle 1987), RP=Ross Ice Shelf Project site J-9 (Kellogg and Kellogg 1986), SI=Signy Island (Oppenheim 1990), SO=South Orkney Islands (Frenguelli 1923), TV=Taylor Valley deltas (Kellogg et al. 1980), W=west antarctic ice sheet beneath ice stream B (Scherer 1991).

as episodic, perhaps occurring only a few times in a decade, and responsible for the low background level of less than 20 diatoms per liter of melted ice typical for approximately 70 percent of our samples. Samples with higher diatom concentrations may represent short periods during which higher than normal surface winds occurred in a particular source area, or in more than one area of the coastal zone.

Specific provenances for our diatoms cannot be identified because most individual species have been reported from a number of locations (table). Marine diatom-bearing sediments are widespread in the dry valleys area of the Transantarctic Mountains, especially where Late Wisconsin Ross Sea Drift (Stuiver et al. 1981; Denton et al. 1989) is exposed. The marine species reported here are present in virtually every sample of this drift that we have examined. Similar diatom-bearing sediments are probably widespread elsewhere around the continent. That most marine specimens have been reworked from subaerially exposed sediments is further suggested by the high degree of dissolution and breakage exhibited by the marine specimens. Nonmarine diatoms are also widespread in the dry valleys, in subaerially exposed deposits, and in virtually every lake, pond, or seasonal melt pool. Many of these water bodies are ephemeral or display fluctuating water levels. Complete or partial desiccation exposes fossil material for transport by winds as described above.

Diatom deposition: Implications for the Sirius Group

Diatoms settling on the polar plateau are buried and trapped in the snow. As the snow compresses to ice and flows gradually down and outward toward the ice sheet margin, the diatoms are carried along until they reach either the glacial bed or come to the surface in an area with surface ablation (where flowlines outcrop). In the former case, diatoms from many years of deposition may become concentrated at the ice bed in morainal material. Thus, atmospherically transported diatoms have the potential to result in reworked assemblages containing diatoms of different ages.

Not all diatoms carried through the atmosphere end up in the ice. If they land on an ice- or snow-free area, they may be retransported unless they fall in cracks or crevices protected from the wind. Evidence for this diatom-trapping mechanism was presented by Burckle (1995, in preparation) who found Pliocene/Pleistocene diatoms in cracks and crevices of antarctic sedimentary rocks. Most atmospherically transported diatoms trapped in cracks and crevices of glacigenic sedimentary deposits should remain near the surface (Stroeven and Prentice 1995), but penetration is also possible, even in compact sediments such as the Sirius Group. A thin layer of snow falling on such a sediment often melts because of heat retention by the relatively dark surface, carrying small amounts of meltwater deep into the sediment by capillary action, entraining the tiny (mostly less than 100 micrometers), delicate diatoms. Penetration should be enhanced by the presence of frost cracks in the compact Sirius sediments. We have no data suggesting how deep such penetration may go but a meter or more seems possible. We conclude that atmospheric transport routinely distributes marine and nonmarine diatoms across the antarctic ice sheet. Our data demonstrate that Sirius Group contamination by younger diatoms is unavoidable because of the pervasive and widespread effects of this atmospheric transport.

Together with our work, studies by Burckle (1995, in preparation) and Burckle and Potter (1996) of diatoms in sedimentary and igneous antarctic rocks cast serious doubts on the validity of presumed *in situ* Pliocene marine diatoms in the Sirius Group because the Pliocene diatoms are not demonstrably associated with the glacial sediments in which they occur. Hence, the entire construct of a warm Pliocene event in Antarctica is in doubt. A more complete presentation of ideas and data presented in this paper may be found in Kellogg and Kellogg (1996).

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References

Baker, A.N. 1967. Algae from Lake Miers, a solar-heated antarctic lake. *New Zealand Journal of Botany*, 5(4), 453–468.

Barron, J.A., and L.H. Burckle. 1987. Diatoms from the 1984 USGS antarctic cruise in the Ross Sea. In A.K. Cooper and F.J. Davey (Eds.), *The antarctic continental margin: Geology and geophysics of the western Ross Sea* (CPCEMR Earth Science Series, Volume 5B). Houston: Circum-Pacific Council for Energy and Mineral Resources.

Benninghoff, W.S., and A.S. Benninghoff. 1978. Airborne particles and electric fields near the ground in Antarctica. *Antarctic Journal of the U.S.*, 13(4), 163–164.

Bourelly, P., and E. Manguin. 1954. Contribution of the freshwater algae from Kerguelen. *Memoires de l'Institut Scientifique de Madagascar*, 5, 7–58. [In French]

Brady, H.T., and H. Martin. 1979. Ross Sea region in the middle Miocene: A glimpse into the past. *Science*, 203, 437–438.

Bromwich, D.H., and F.M. Robasky. 1983. Recent precipitation trends over the polar ice sheets. *Meteorology and Atmospheric Physics*, 51, 259–274.

Burckle, L.H. 1995. Upper Neogene diatoms in Beacon Supergroup (Devonian to Jurassic) sedimentary rocks: The collapse of the collapse hypothesis. Abstracts, Pliocene Antarctic Glaciation Workshop, 19–21 April 1995, Woods Hole, Massachusetts, Woods Hole Oceanographic Institution.

Burckle, L.H. In preparation. Pliocene-Pleistocene diatoms in Paleozoic and Mesozoic igneous rocks from Antarctica cast considerable doubt upon the ice sheet collapse hypothesis. *Nature*.

Burckle, L.H., R.I. Gayley, M. Ram, and J.-R. Petit. 1988. Diatoms in antarctic ice cores: Some implications for the glacial history of Antarctica. *Geology,* 16(4), 326–329.

Burckle, L.H., and N. Potter, Jr. 1996. Pliocene-Pleistocene diatoms in Paleozoic and Mesozoic sedimentary and igneous rocks from Antarctica: A Sirius problem resolved. *Geology,* 24(3) 235–238.

Cassie, V. 1984. Checklist of the freshwater diatoms of New Zealand. *Bibliotheca Diatomologica*, 4, 1–129.

De Angelis, M., N.I. Barkov, and V.N. Petrov. 1987. Aerosol concentrations over the last climate cycle (160 kyr) from an antarctic core. *Nature*, 325, 318–321.

Denton, G.H., J.G. Bockheim, S.C. Wilson, and M. Stuiver. 1989. Late Wisconsin and early Holocene glacial history, inner Ross embayment, Antarctica. *Quaternary Research*, 31(2), 151–182.

Denton, G.H., M.L. Prentice, and L.H. Burckle. 1991. Cainozoic history of the antarctic ice sheet. In R.J. Tingey (Ed.), *The geology of Antarctica*. Oxford: Clarendon University Press.

Denton, G.H., M.L. Prentice, D.E. Kellogg, and T.B. Kellogg. 1984. Late Tertiary history of the antarctic ice sheet: Evidence from the Dry Valleys. *Geology,* 12(5), 263–267.

Drebes, G. 1974. *Marine phytoplankton*. Stuttgart: Georg Thieme Verlag.

Fitzgerald, P.G. 1992. Transantarctic Mountains of southern Victoria Land: The application of apatite fission track analysis to a rift shoulder uplift. *Tectonics*, 11(3), 634–662.

Folger, D.W. 1970. Wind transport of land-derived mineral, biogenic, and industrial matter over the North Atlantic. *Deep-Sea Research*, 17, 337–352.

Frenguelli, J. 1923. Diatoms of Tierra del Fuego, part 1. *Annals of the Scientific Society of Argentina*, 96, 14–263. [In Spanish]

Frenguelli, J., and H.A. Orlando. 1958. *Diatoms and silicoflagellates of the antarctic sector of South America.* Buenos Aires: Instituto Antartico Argentino.

Fritsch, F.E. 1912a. Freshwater algae in National Antarctic Expedition 1901–1904. *Natural History* (Zoology and Botany, London), 6, 1–60.

Fritsch, F.E. 1912b. Freshwater algae of the South Orkneys, *Report on the scientific results of the voyage of S.Y. "Scotia"* (Vol. 3). Edinburgh: Publisher not given.

Germain, H. 1981. *Diatom flora*. Paris: Editions Boubee. [In French]

Gillieson, D. 1991. Diatom stratigraphy in antarctic freshwater lakes. In D. Gillieson and S. Fitzsimmons (Eds.), *Quaternary Research in Australian Antarctic* (special publication 3). Canberra: Australian Defense Force Academy, Department of Geography and Oceanography, University College.

Gow, A.J. 1995. Personal communication.

Harper, M. 1995. Personal communication.

Harwood, D.M. 1986a. Diatom biostratigraphy and paleoecology and a Cenozoic history of antarctic ice sheets. (Ph.D Thesis, Ohio State University, Columbus.)

Harwood, D.M. 1986b. Recycled siliceous microfossils from the Sirius Formation. *Antarctic Journal of the U.S.*, 21(5), 101–103.

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.

Harwood, D.M., and P.-N. Webb. 1995. The case for dynamic Cenozoic ice sheets in Antarctica. Abstracts, Pliocene Antarctic Glaciation Workshop, 19–21 April 1995, Woods Hole, Massachusetts, Woods Hole Oceanographic Institution.

Hogan, A., S. Barnard, J. Samson, and W. Winters. 1982. The transport of heat, water vapor and particulate material to the south polar plateau. *Journal of Geophysical Research*, 87, 4287–4292.

Hustedt, G. 1959. The diatoms of Germany, Austria, and Switzerland. Leipzig: Akademische Verlagsgesellschaft Geest and Portig K.-G. (New York: Johnson Reprint Corporation). [In German]

Karaswa, S., and H. Fukushima. 1977. Diatom flora and environmental factors in some freshwater ponds of East Ongul Island. *Antarctic Record* (Japan), 59, 46–54.

Kellogg, D.E. In preparation. Diatom evidence for high-frequency changes in high-elevation atmospheric circulation patterns above Antarctica.

Kellogg, D.E., and T.B. Kellogg. 1984. Nonmarine diatoms in the Sirius Formation. *Antarctic Journal of the U.S.*, 19(5), 44–45.

Kellogg, D.E., and T.B. Kellogg. 1986. Diatom biostratigraphy of sediment cores from beneath the Ross Ice Shelf. *Micropaleontology,* 32(1), 74–94.

Kellogg, D.E., and T.B. Kellogg. 1987a. Diatoms of the McMurdo Ice Shelf, Antarctica: Implications for sediment and biotic reworking. *Palaeogeography, Palaeoclimatology, Palaeoecology,* 60, 77–96.

Kellogg, D.E., and T.B. Kellogg. 1987b. Microfossil distributions in modern Amundsen Sea sediments. *Marine Micropaleontology,* 12, 203–222.

Kellogg, D.E., and T.B. Kellogg. 1996. Diatoms in South Pole ice: Implications for eolian contamination of Sirius Group deposits. *Geology,* 24(2), 115–118.

Kellogg, D.E., M. Stuiver, T.B. Kellogg, and G.H. Denton. 1980. Nonmarine diatoms from Late Wisconsin perched deltas in Taylor Valley, Antarctica. *Palaeogeography, Palaeoclimatology, Palaeoecology,* 30, 157–189.

Kellogg, T.B., and D.E. Kellogg. 1981. Pleistocene sediments beneath the Ross ice shelf. *Nature*, 293, 130–133.

Kennett, J.P. 1995. Modern shallow marine faunas of the Antarctic: Long-term evolutionary consequences of a relatively stable, isolated, cold-water ecosystem. Abstracts, Pliocene Antarctic Glaciation Workshop, 19–21 April 1995, Woods Hole, Massachusetts, Woods Hole Oceanographic Institution.

Kennett, J.P., and D.A. Hodell. 1993. Evidence for relative climatic stability of Antarctica during the early Pliocene: A marine perspective. *Geografiska Annaler*, 75A, 205–220.

Kennett, J.P., and D.A. Hodell. 1995. Stability or instability of antarctic ice sheets during warm climates of the Pliocene? *GSA Today*, 5, 1, 10–13, 22.

Kuivinen, K.C., B.R. Koci, G.W. Holdsworth, and A.J. Gow. 1982. South Pole ice core drilling, 1981–1982. *Antarctic Journal of the U.S.*, 17(5), 89–91.

Lavrenko, G.Y. 1966. Algae of a lake near Novolazareveskaya Station. Soviet Antarctic Expedition Information Bulletin 55/56, 6, 53–66.

Marchant, D.R., G.H. Denton, J.G. Bockheim, S.C. Wilson, and A.R. Kerr. 1994. Quaternary changes in level of the upper Taylor Glacier, Antarctica: Implications for paleoclimate and east antarctic ice sheet dynamics. *Quaternary Research*, 23(1), 29–43.

Marchant, D.R., G.H. Denton, D.E. Sugden, and C.C. Swisher, III. 1993. Miocene glacial stratigraphy and landscape evolution of the western Asgard Range, Antarctica. *Geografiska Annaler*, 75A, 303–330.

McIntosh, W.C., and T. Wilch. 1995. Applications of ^{40}Ar/^{39}Ar dating of volcanic ash to antarctic Neogene climate and glacial history: A review of some published and ongoing studies. Abstracts, Pliocene Antarctic Glaciation Workshop, 19–21 April 1995, Woods Hole, Massachusetts, Woods Hole Oceanographic Institution.

McKelvey, B.C., P.-N. Webb, D.M. Harwood, and M.C.G. Mabin. 1991. The Dominion Range Sirius Group: A record of the late Pliocene–early Pleistocene Beardmore Glacier. In M.R.A. Thomson, J.A. Crame, and J.W. Thomson (Eds.), *Geological evolution of Antarctica.* Cambridge: Cambridge University Press.

Oppenheim, D.R. 1990. A preliminary study of benthic diatoms in contrasting lake environments. In K.R. Kerry and G. Hempel (Eds.), *Antarctic ecosystems: Ecological change and conservation* (Proceedings of the 5th SCAR Symposium on Antarctic Biology). Berlin: Springer-Verlag.

Parish, T.R., and D.H. Bromwich. 1987. The surface windfield over the antarctic ice sheets. *Nature*, 328, 51–54.

Patrick, R., and C. Reimer. 1966. *Diatoms of the United States.* Philadelphia: Academy of Natural Sciences.

Scherer, R.P. 1991. Quaternary and Tertiary microfossils from beneath ice stream B: Evidence for a dynamic west antarctic ice sheet history. *Palaeogeography, Palaeoclimatology, Palaeoecology* (Global and Planetary Change Section), 90(4), 395–412.

Schmidt, R., R. Maeusbacher, and J. Mueller. 1990. Holocene diatom flora and stratigraphy from sediment cores of two antarctic lakes (King George Island). *Journal of Paleolimnology*, 3(1), 55–74.

Seaburg, K.G., B.C. Parker, G.W. Prescott, and L.A. Whitford. 1979. The algae of southern Victoria Land, Antarctica. Vaduz: J. Cramer.

Shaw, G.E. 1978. Particles in the air at the South Pole. *Antarctic Journal of the U.S.*, 13(5), 194–196.

Stroeven, A.P., and M.L. Prentice. 1995. Marine diatoms in antarctic Tertiary tills: A new dataset from Mount Fleming, south Victoria Land, indicates possible transport mechanisms. Abstracts, Pliocene Antarctic Glaciation Workshop, 19–21 April 1995, Woods Hole, Massachusetts, Woods Hole Oceanographic Institution.

Stuiver, M., G.H. Denton, T.J. Hughes, and J.L. Fastook. 1981. History of the marine ice sheet in West Antarctica during the last glaciation: A working hypothesis. In G.H. Denton and T.J. Hughes (Eds.), *The last great ice sheets.* New York: Wiley-Interscience.

Truesdale, R.S., and T.B. Kellogg. 1979. Ross Sea diatoms: Modern assemblage distributions and their relationship to ecologic, oceanographic, and sedimentary conditions. *Marine Micropaleontology*, 4(1), 13–31.

van Heurck, H. 1896. A treatise on the diatomaceae. London: William Wesley and Son.

Webb, P.-N., and D.M. Harwood. 1991. Late Cenozoic glacial history of the Ross embayment, Antarctica. *Quaternary Science Reviews*, 10(2/3), 215–223.

Webb, P.-N., D.M. Harwood, B.C. McKelvey, J.H. Mercer, and L.D. Stott. 1984. Cenozoic marine sedimentation and ice-volume variation on the east antarctic craton. *Geology*, 12(5), 287–291.

West, W., and G.S. West. 1911. Freshwater algae. *British Antarctic Expedition (1907-1909)*, 7, 263–298.

Wilch, T.L., G.H. Denton, D.R. Lux, and W.C. McIntosh. 1993a. Limited Pliocene glacier extent and surface uplift in middle Taylor Valley, Antarctica. *Geografiska Annaler*, 75A, 331–351.

Wilch, T.I., D.R. Lux, G.H. Denton, and W.C. McIntosh. 1993b. Minimal Pliocene–Pleistocene uplift of the dry valleys sector of the Transantarctic Mountains: A key parameter in ice-sheet reconstructions. *Geology*, 21(9), 841–844.

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GLACIAL GEOLOGY

Recycled marine microfossils in glacial tills of the Sirius Group at Mount Fleming: Transport mechanisms and pathways

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The documentation of marine microfossils in consolidated glacial sediments of the Sirius Group (McKelvey et al. 1991), radically altered the range of glacial and climatic interpretations of this deposit (e.g., Mercer 1968; Brady and McKelvey 1979; Barrett and Powell 1982; Harwood 1983; Webb and Harwood 1991; Stroeven et al. 1994; Stroeven, Prentice, and Kleman in press). A resolution of these disparate viewpoints depends critically on the inferred transport mechanism of marine microfossils from their source areas to these glacial sediments (Sugden 1992; Stroeven and Prentice 1994).

We tested marine diatom transport to the Sirius Group by considering the microfossil distribution within one key glacial deposit in the dry valleys reported to contain Neogene marine diatoms: the Sirius Group at Mount Fleming (Harwood 1986a) (figure 1). We assumed that the microfossils were recycled by the ice depositing the till and expected to find a random occurrence of diatoms in samples from the investigated deposits.

The lithostratigraphic subdivision was threefold: consolidated, unweathered dark gray sediments overlain by moderately consolidated, weathered light gray sediments, and capped by yellow-reddish unconsolidated sediments (figure 2). We interpret the bottom two units as lodgement till emplaced by alpine ice and consider them Sirius Group equivalents (Stroeven, Prentice, and Borns 1992; Stroeven et al. 1994; Stroeven and Prentice in preparation). Because hallmark characteristics of lodgement till are absent for the surface unit, however, it could be a lag deposit from the underlying lodgement till or a glacial or nonglacial deposit unrelated to the underlying Sirius Group till. At excavations 91-001 and 91-002, dark-gray unweathered till cropped out (figure 2). At least one microfossil sample was collected from all lithostratigraphic units present in each excavation.

Diatom extraction followed improved standard procedures (Harwood 1986b; Harwood, Grant, and Karrer 1986; Stroeven 1994). The diatom extraction technique relies on the specific size and hydrodynamic properties of diatoms for extraction. Samples averaging 0.5 kilogram were dispersed in Calgon solution for 48 hours and introduced in a 1.2-meter settling tube. Deionized water that was filtered at 0.45 micron entered at the base of this settling tube through a plastic rod and agitated the sediment. We calculated that a water column having an upward velocity of 0.04 meter per second will float most common diatoms (i.e., diatoms that have a specific gravity less than 2.25 and a diameter less than 100 microns). The suspended material was siphoned off near the top of the tube and sieved at 25 microns. Further separation of the fraction larger than 25 microns occurred through heavy-liquid separation and centrifuging at 500 and 2,000 revolutions per minute.

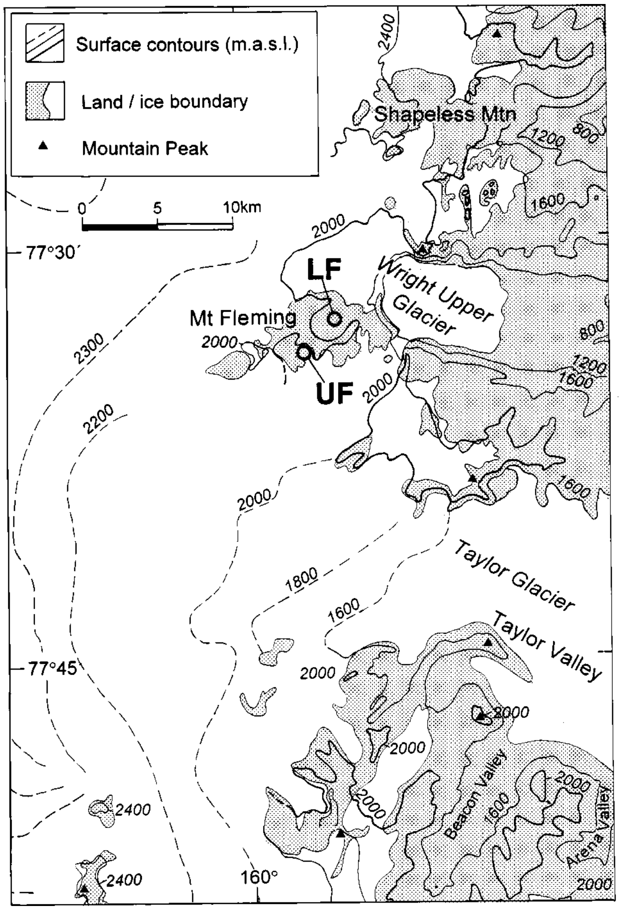

Figure 1. Index map of the dry valleys in the McMurdo Sound region with surface elevation contours. Mount Fleming is situated at the head of Wright Valley, southwest of Wright Upper Glacier. UF and LF refer to the locations of the upper and lower Fleming tills of the Sirius Group at Mount Fleming (Stroeven 1994; Stroeven and Prentice in preparation).

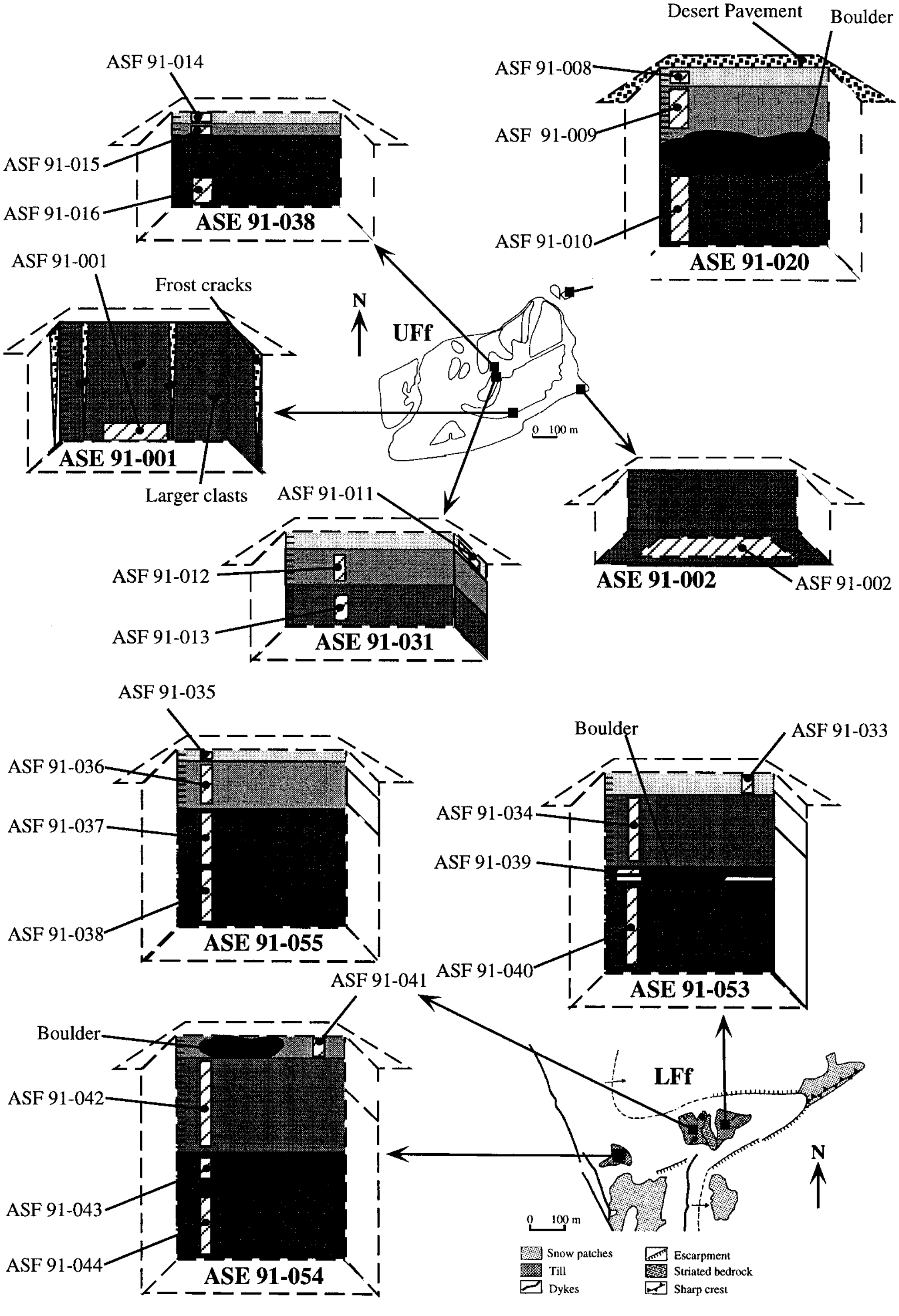

Figure 2. Pit stratigraphies for excavations 91-001, 91-002, 91-020, 91-031, and 91-038 pertain to site UF, whereas excavations 91-053, 91-054, and 91-055 pertain to site LF in figure 1. Given are the location of the excavations; the approximate depth of the excavations (depth scale is in 2.5-centimeter increments); the lithostratigraphy of the excavations; and sample location and number. In all but two excavations, three units could be distinguished: from the top-down, a loose yellow-reddish layer, capping a light-gray, massive, structureless, moderately consolidated layer, and a massive, structureless, consolidated dark-gray layer. Also given are the locations of sediment and microfossil samples (ASF 91-).

We ran all samples twice through the microfossil extraction unit. The first run was on a dissolved split of the raw sample. Following these preliminary results (Stroeven and Prentice 1994), we considered the possibility that diatoms remained "stuck-together" in diatomaceous sediment microclasts. To remove all lingering organic material that could bind these microclasts, we treated the coarse (i.e., larger than 100 microns) fraction of the first run with 30 percent hydrogen peroxide and repeated the improved standard procedure. Improvements in diatom-yield were negligible (table), however, indicating that diagenetic processes played no significant role in observed diatom abundance distributions.

In all, 23 samples from eight pits were examined for and yielded marine and nonmarine diatoms, diatomaceous sediment microclasts, radiolarian fragments, and one sponge spicule (figure 3, table). Our results indicate the existence of a marked microfossil abundance decline from the surface unit into the semiconsolidated till. This distribution is best illustrated in pits 91-031, 91-053, and 91-054 (figure 2, table). Moreover, microfossils are better preserved in the surface unit than in the till units, where they were only identified to the genus-level.

We regard it unlikely that better preserved marine diatoms at the surface were derived from the poorly preserved marine diatoms in the lodgement till units by lag processes. Instead, we suggest that the lodgement till was barren of biological material and that few diatom fragments at depth indicate a recycling-downward process in polar-desert conditions.

Critical evidence that has been used to support the subglacial reworking of diatoms into the Sirius Group till is the presence of diatomaceous sediment microclasts in the matrix of these tills (e.g., Harwood 1983, 1986a,c; Harwood, Grant, and Karrer 1986). Diatomaceous sediment microclasts were absent, however, in the matrix of the lodgement till units, except at pit 91-055 (figure 2, table). These diatomaceous sediment microclasts range in size from 25 to 40 microns, however, and do not preclude eolian transport. We suggest that the inverse stratigraphy observed in pit 91-055 is a function of either nonrepresentative surface sampling or the disintegration of fewer and larger diatomaceous sediment microclasts into a multitude of smaller ones by the extraction procedure, or both. Similarly, we suggest that the apparent abundance of microfossil fragments in sample 91-009 (pit 91-020; figure 2, table) signifies the breakdown of one or few intact diatoms into a number of unrecognizable fragments.

These results indicate that for one deposit on which the dynamicists built their viewpoint, the Sirius Group at Mount Fleming, the glacial conveyor mechanism appears erroneous. We suggest that if the microfossils in the surface unit arrived by glacial transport mechanisms, they ought to occur within a glacial deposit of younger age than the underlying lodgement tills. If the microfossils arrived by eolian processes, they should occur in surface deposits of disparate origin but of unknown age, both glacial and nonglacial, given the ability for the deposit to trap fine-grained, wind-blown material (McFadden, Wells, and Jercinovich 1987; Wells et al. 1995).

Denton, Prentice, and Burckle (1991) proposed scenarios by which airborne diatoms were incorporated into Sirius Group glacial sediments. For these diatoms to become airborne, however, at least two requirements must be met:

- Outcrops of Plio-Pleistocene marine sediments were available for subaerial wind-scouring.
- The atmospheric circulation system and the ice-sheet configuration were significantly different, so that *only* the observed Plio-Pleistocene *marine* diatom flora of the Sirius Group was elevated.

The latter is important because eolian transport at present recycles varying proportions of marine and nonmarine diatoms to east antarctic ice sheet plateau locations (Burckle et al. 1988; Kellogg and Kellogg 1996). In addition, the source area from which these marine diatoms were scoured by wind remained enigmatic, because the preponderance of planktic taxa over benthic taxa in Sirius Group sediments seemingly invalidates uplifted near-shore marine sediments (e.g., Webb and Harwood 1991) and because a stable cryosphere and marine diatom source areas appear to be conditions in contradiction. This contradiction arises because the stabilists meltdown mechanisms cannot account for the necessary ice recession (Denton et al. 1993). Finally, the absence in Sirius Group samples from Mount Fleming of marine diatom species such as *Nitzschia curta* that dominate today in circumantarctic waters (Burckle 1984) requires that the eolian microfossil conveyor operated before such species became dominant.

We advocate alternative mechanisms for deglaciation and outline one plausible scenario with marine diatom source areas and transport pathways. This scenario highlights eolian transport of Plio-Pleistocene diatoms to high-elevation deposits and is constrained by ice-volume fluctuation during the early and middle Pliocene. An, albeit short-lived, ice-volume reduction of between 10 and 40 percent of the present ice volume appears reasonable (Kennett and Hodell 1993). Denton et al. (1993) present argon-39/argon-40 constraints on the upper limit of glaciation in Taylor Valley during the last 2.97-million years. Therefore, ice is an unlikely transporting agent for diatoms in those deposits in the dry valleys situated above the last 2.97-million-year maximum ice limit and having early-middle Pliocene diatom assemblages reported in them (Stroeven et al. in press).

We regard Wilkes Basin as a prime candidate for partial deglaciation because at its margin facing the open ocean, the ice sheet is partly grounded at depths in excess of 1,000 meters below present-day sea level (Drewry 1983). During proposed periods of ice recession, with associated delayed isostatic recovery, marine sedimentation occurred in these basins. Upon emergence of basin floors, strong katabatic winds from the large but shrunken east antarctic ice sheet caused deflation of the exposed marine sediments, and airborne marine diatomaceous microclasts were blown to presently high-altitude Transantarctic Mountain sites (Stroeven et al. in press). The eolian source was closed when these basins were overrun by a reexpanded east antarctic ice sheet. For marine diatom transport by glaciers, the whole length of the Wilkes and

Occurrence of microfossils in samples from the Sirius Group at Mount Fleming. Samples in bold typeface have been taken in the loose surface unit, whereas others have been taken at depth, and refer to lodgement till samples. We ran all samples twice through the microfossil extraction unit. Improvements in diatom-yield during the second run were negligible (bottom line), indicating that diagenetic processes played no significant role in observed diatom abundance distributions. Refer to figures 1 and 2 for excavation locations (ASE) and sample locations (ASF) within each pit. Given are B=barren, B-R=barren-rare (1 diatom fragment/slide), R=rare (2–9 diatom fragments/slide), A=abundant (10 diatom fragments/slide), P=present, and HW=Harwood (1986a) samples from Mount Fleming.

ASE 91-#	**001**	**002**	<------020------>			<------031------>			<------038------>			<-----------053----------->				<-----------054----------->				<-----------055----------->				**HW**
ASF 91-#	**001**	**002**	**008**	009	010	**011**	012	013	**014**	015	016	**033**	034	039	040	**041**	042	043	044	**035**	036	037	038	
Depth in cm	**30-40**	**20-25**	**0-10**	15-25	50-75	**0-5**	10-20	25-35	**0-5**	5-10	30-40	**0-10**	15-35	40-45	50-80	**0-10**	15-45	55-65	70-95	**0-5**	10-20	25-45	60-75	
Region	<--------------- *upper Fleming till* ------------------>											<-------------------- *lower Fleming till* -------------------->												
Actinocyclus actinochilus						R			R			R												
Actinocyclus ingens																R								P
Actinoptychus senarius						R																		
Arachnoidiscus frg.												R												
Chaetoceros sp.	R															R					R			
Chaetoceros bristles																								P
Coscinodiscus sp. frg.			R			R										R								P
Coscinodiscus marginatus																R								
Coscinodiscus oculusiridis																R								
Denticulopsis hustedtii																								P
Eucampia sp. frg.																R								
Eucampia antarctica			R			R																		
Isthmia sp. frg.			R																					
Nitzschia sp.																								P
Odontella weisflogii	R					R																		
Rhizosolenia hebetata group																								P
Stephanopyxis sp.												R												
Stellarima microtrias			R			R										R								
Thalassionema sp.																					R		R	
Thalassiosira sp.			R			R										R							R	
Thalassiosira inura																R								
Thalassiosira kolbeii																R								
Thalassiosira lentiginosa												R				R				R				
Thalassiosira oliverana			R													R								
Thalassiosira torokina						R										R								
Thalassiosira vulnifica																R								
Thalassiothrix/Thalassionema frg.	R							R													R			P
Centric diatoms																R					R			
Centric diatom frg.							R								R	R					R	R		P
Diatomaceous sedim. microclasts																					A	R	R	P
Non-marine diatoms						R																		
Radiolarian frg.						R																		
Silicoflagellates																								P
Sponge spicule																R								
Second test	*B*	*B*	*B*	*A?*	*B*	*B*	*B*	*B*			*B*	*R?*	*B*	*B*	*B*	*B*	*B*	*B*	*B*	*B*	*B*	*B*	*B*	
Summary rating	R	B	R	A?	B	A	B-R	R	R	B	B	R	B	B	B-R	A	B	B	B	B-R	A	R	R	

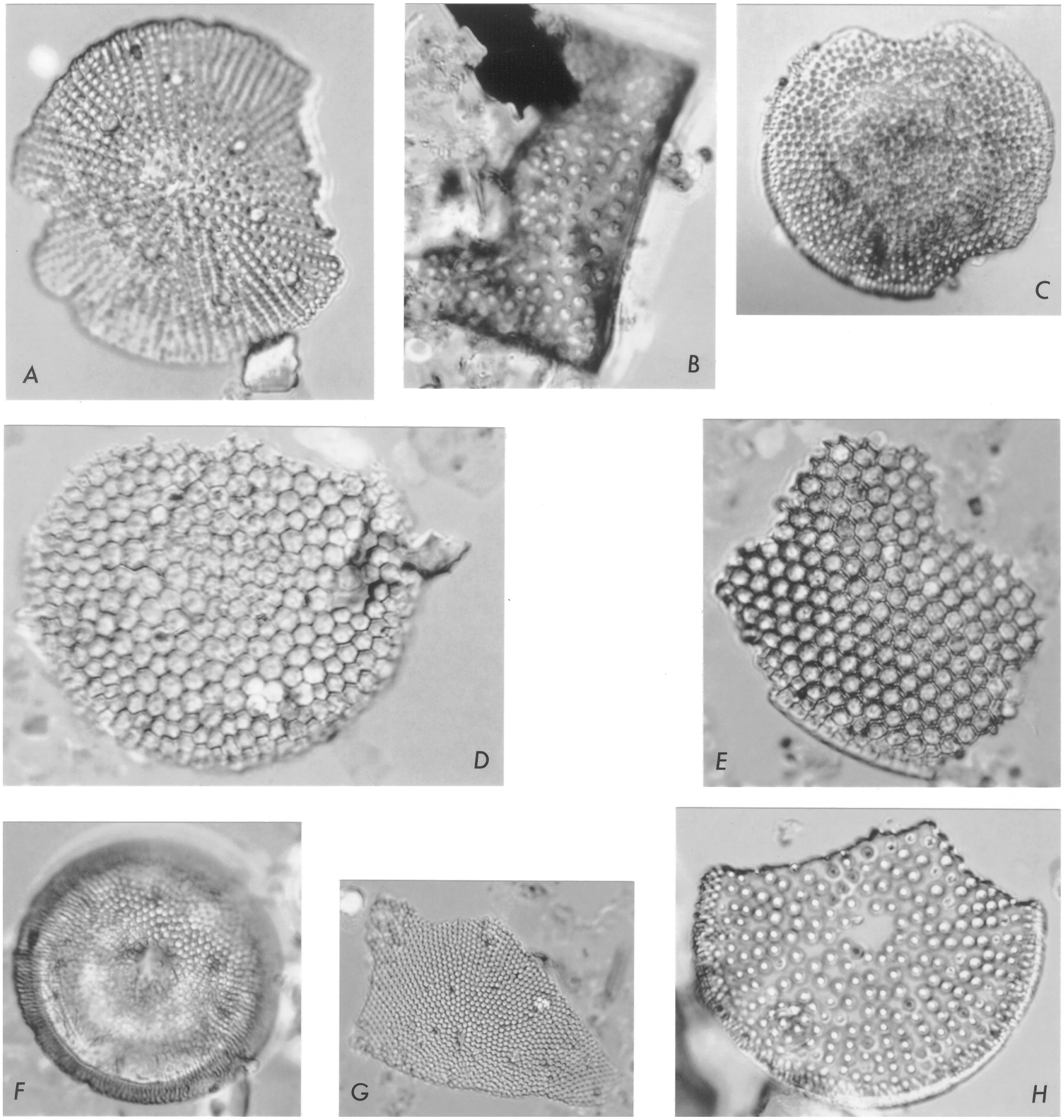

Figure 3. Diatoms recovered from surface sediments overlying the Sirius Group at Mount Fleming. Enlargement is 1,000 ×, and the diatoms were photographed from sample ASF 91-041 (figure 3), except where indicated otherwise. *A. Thalassiosira vulnifica. B. Eucampia antarctica,* sample ASF 91-011; *C. Thalassiosira vulnifica. D. Coscinodiscus marginatus. E. Thalassiosira kolbeii. F. Thalassiosira inura. G. Stellarima microtrias,* enlarged 750 ×. *H. Actinocyclus ingens*. Identifications as given by D. Harwood, University of Nebraska–Lincoln.

Pensacola basins has to be deglaciated to explain the spatial distribution of Pliocene marine diatom-bearing tills. For eolian diatom transport (which is directionally variable and turbulent), however, only partial deglaciation of these basins and subsequent uplift above contemporaneous sea-level, is required.

We are indebted to our co-investigators M. Helfer and C. Schlüchter and to G. Simonds, S. Dunbar, S. Iversen, and D. Rosenthal for fieldwork. D. Harwood supervised the diatom extraction procedures, identified recovered diatom species, and provided us with helpful student assistance. Helpful comments by L.H. Burckle, D. Goodwillie, and G.C. Rosqvist improved the manuscript. H. Drake drew some of the figures. We thank VXE-6 for excellent field support. This work is supported by National Science Foundation grant OPP 90-20975 to Michael L. Prentice and Harold W. Borns, Jr., by the Swedish Natural Science Research Council, and by the Swedish Society for Anthropology and Geography André grant to Arjen P. Stroeven.

References

Barrett, P.J., and R.D. Powell. 1982. Middle Cenozoic glacial beds at Table Mountain, southern Victoria Land. In C. Craddock (Ed.), *Antarctic geoscience*. Madison: University of Wisconsin Press.

Brady, H., and B. McKelvey. 1979. The interpretation of a Tertiary tillite at Mount Feather, southern Victoria Land, Antarctica. *Journal of Glaciology*, 22(86), 189–193.

Burckle, L.H. 1984. Diatom distribution and oceanographic reconstruction in the Southern Ocean—Present and last glacial maximum. *Marine Micropaleontology*, 9(3), 241–262.

Burckle, L.H., R.I. Gayley, M. Ram, and J.-R. Petit. 1988. Diatoms in antarctic ice cores: Some implications for the glacial history of Antarctica. *Geology*, 16(4), 326–329.

Denton, G.H., M.L. Prentice, and L.H. Burckle. 1991. Cainozoic history of the antarctic ice sheet. In R.J. Tingey (Ed.), *The geology of Antarctica*. Oxford: Clarendon Press.

Denton, G.H., D.E. Sugden, D.R. Marchant, B.L. Hall, and T.I. Wilch. 1993. East antarctic ice sheet sensitivity to Pliocene climatic change from a dry valleys perspective. *Geografiska Annaler*, 75A(4), 155–204.

Drewry, D.J. 1983. *Antarctica: Glaciological and geophysical folio.* Cambridge: Scott Polar Research Institute, University of Cambridge.

Harwood, D.M. 1983. Diatoms from the Sirius Formation, Transantarctic Mountains. *Antarctic Journal of the U.S.*, 18(5), 98–100.

Harwood, D.M. 1986a. Diatom biostratigraphy and paleoecology with a Cenozoic history of antarctic ice sheets. (Ph.D. dissertation, Ohio State University, Columbus, Ohio.)

Harwood, D.M. 1986b. Diatoms. In P.J. Barrett (Ed.), *Antarctic Cenozoic history from the MSSTS-1 drillhole, McMurdo Sound.* Wellington, New Zealand: Department of Scientific and Industrial Research Bulletin.

Harwood, D.M. 1986c. Recycled siliceous microfossils from the Sirius Formation. *Antarctic Journal of the U.S.,* 21(5), 101–103.

Harwood, D.M., M.W. Grant, and M.H. Karrer. 1986. Techniques to improve diatom recovery from glacial sediments. *Antarctic Journal of the U.S.*, 21(5), 107–108.

Kellogg, D.E., and T.B. Kellogg. 1996. Diatoms in South Pole ice: Implications for eolian contamination of Sirius Group deposits. *Geology*, 24(2), 115–118.

Kennett, J.P., and D.A. Hodell. 1993. Evidence for relative climatic stability of Antarctica during the early Pliocene: A marine perspective. *Geografiska Annaler*, 75A(4), 205–220.

McFadden, L.D., S.G. Wells, and M.J. Jercinovich. 1987. Influences of eolian and pedogenic processes on the origin and evolution of desert pavements. *Geology*, 15(6), 504–508.

McKelvey, B.C., P.-N. Webb, D.M. Harwood, and M.C.G. Mabin. 1991. The Dominion Range Sirius Group: A record of the late Pliocene–early Pleistocene Beardmore Glacier. In M.R.A. Thomson, J.A. Crame, and J.W. Thomson (Eds.), *Geological evolution of Antarctica*. Cambridge: Cambridge University Press.

Mercer, J.H. 1968. Glacial geology of the Reedy glacier area, Antarctica. *Geological Society of America Bulletin*, 79(4), 471–486.

Stroeven, A.P. 1994. Semi-consolidated glacial deposits on Mount Fleming, south Victoria Land, Antarctica: A test of the late Neogene east antarctic ice sheet collapse hypothesis. (M.S. Thesis, University of Maine, Orono, Maine.)

Stroeven, A.P., H.W. Borns, Jr., M.L. Prentice, J.L. Fastook, and R.J. Oglesby. 1994. Upper Fleming Sirius till: Evidence for local glaciation and warmer climates during the Neogene. In F.M. van der Wateren, A.L.L.M. Verbers, and F. Tessensohn (Eds.), *Landscape evolution in the Ross Sea Area, Antarctica.* Haarlem: Rijks Geologische Dienst.

Stroeven, A.P., and M.L. Prentice. 1994. Do marine diatoms in Sirius Group tills indicate ice sheet disintegration? *Geological Society of America Abstracts With Programs*, 26(7), A-143. [Abstract]

Stroeven, A.P., and M.L. Prentice. In preparation. A case for Sirius Group alpine glaciation at Mount Fleming, south Victoria Land, Antarctica: A case against Pliocene east antarctic ice sheet reduction. *Geological Society of America Bulletin.*

Stroeven, A.P., M.L. Prentice, and H.W. Borns, Jr. 1992. Mount Fleming upper valley drift: Evidence for Neogene glacial history of Antarctica. *Antarctic Journal of the U.S.*, 27(5), 51–54.

Stroeven, A.P., M.L. Prentice, and J. Kleman. In press. On marine microfossil transport and pathways in Antarctica during the late Neogene: Evidence from the Sirius Group at Mount Fleming. *Geology.*

Sugden, D. 1992. Antarctic ice sheets at risk? *Nature*, 359, 775–776.

Webb, P.-N., and D.M. Harwood. 1991. Late Cenozoic glacial history of the Ross embayment, Antarctica. *Quaternary Science Reviews*, 10(2/3), 215–223.

Wells, S.G., L.D. McFadden, J. Poths, and C.T. Olinger. 1995. Cosmogenic ^{3}He surface-exposure dating of stone pavements: Implications for landscape evolution in deserts. *Geology*, 23(7), 613–616.

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LAND-ICE STUDIES

Glaciological delineation of the dynamic coastline of Antarctica

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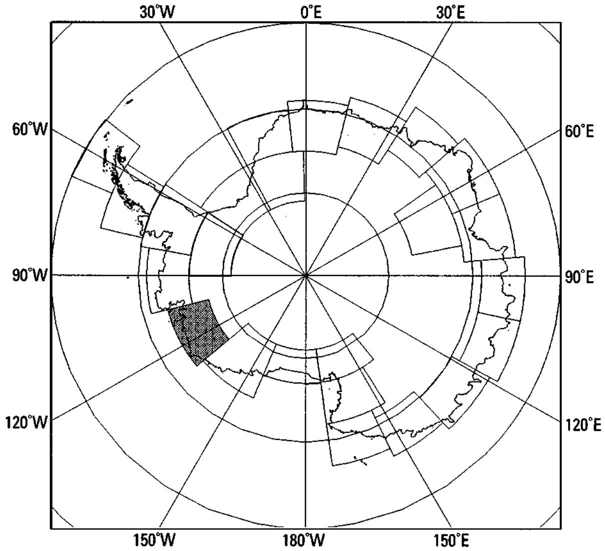
In spite of their importance to global climate and sea level, the mass balance of the antarctic ice sheet and the dynamics of the coast of Antarctica are largely unknown. In 1990, the U.S. Geological Survey, in cooperation with the Scott Polar Research Institute (SPRI), began a long-term coastal-mapping project in Antarctica that is based on analysis of Landsat images and ancillary sources (Williams et al. 1995). The project has five objectives:

- to determine coastline changes that have occurred between the mid-1970s and the late 1980s/early 1990s;
- to establish an accurate baseline series of 24 1:1,000,000-scale maps that defines, from analysis (at a scale of 1:500,000) of Landsat images, the glaciological characteristics (e.g., floating ice, grounded ice, and so forth) of the coastline of Antarctica during the two time periods (figure);
- to determine velocities of outlet glaciers, ice streams, and ice shelves from comparison of Landsat images of the same areas taken over time;
- to compile a comprehensive inventory of named (from published maps and Landsat images) and unnamed (from analysis of Landsat images) outlet glaciers and ice streams in Antarctica that are mappable from Landsat images or from ancillary sources (e.g., maps, gazetteers, CD-ROMs, and so forth) (Swithinbank 1980, 1985, 1988; Alberts 1981, 1995; NSF 1989; BAS, SPRI, and WCMC 1993); and
- to compile a 1:5,000,000-scale map of Antarctica derived from the 24 maps.

Changes in the area and volume of polar ice sheets are intricately linked to changes in global climate. It is not known whether the ice sheet is growing or shrinking (NRC 1985). As a result, measurement of changes in the antarctic ice sheet was given a very high priority in recommendations by the Polar Research Board of the National Research Council (1986) and the Scientific Committee on Antarctic Research (SCAR) (1989).



Index map to the planned 24 1:1,000,000-scale Coastal-Change and Glaciological Maps of Antarctica. Bakutis Coast map shown in gray.

Methodology

The primary steps in the compilation of the coastal-change and glaciological maps of Antarctica are as follows:

1. Identification of optimum Landsat multispectral scanner (MSS) or thematic mapper (TM) images for the two time periods (mid-1970s and late 1980s/early 1990s) and enlargement to a nominal scale of 1:500,000.
2. Identification and plotting of ground control points and pass points on Landsat images from geodetic field-survey information (e.g., field notebooks, tables, and vertical and trimetrogon aerial photographs and maps) archived in the U.S. Geological Survey's SCAR Library (Reston, Virginia 22092). Plotting of pass points on overlapping Landsat images and transfer of control points and pass points to transparent overlays to provide ties between images in areas where geodetic ground control does not yet exist.
3. Manual annotation of glaciological features by SCAR Code (SCAR 1980) or Antarctic Digital Database (ADD) Geocode (BAS et al. 1993) on 1:500,000-scale transparent overlays of Landsat images for both time periods. [The ADD project provides a digitized coastline and other cartographic information of Antarctica generalized to a scale of 1:1,000,000 that is available on a CD-ROM (BAS et al. 1993); the ADD CD-ROM provides the best existing coastline information for Antarctica.]

4. Manual transfer of the combined (MSS with TM) annotated overlays to 1:500,000-scale oblique Mercator maps of each map sheet. TM images provide the most geometrically accurate base for combining the annotations derived from analysis of the MSS and TM images.
5. Digitization, at 1:500,000-scale, using the U.S. Geological Survey's MAPGEN software (Evenden and Botbol 1985) and a digitizing program called "digin" written by G.I. Evenden (unpublished), of glaciological annotations and other related information on the oblique Mercator projections by SCAR Code or ADD Geocode.
6. Transformation of digitized annotations to a 1:1,000,000-scale polar stereographic map base (standard parallel at 71°S) using the U.S. Geological Survey's MAPGEN software (Evenden 1990).
7. Addition of glacier velocities, geographic place names, including codes for unnamed outlet glaciers and ice streams identified on Landsat images and modification of selected topographic form lines (BAS et al. 1993) and bathymetric contours using Adobe Illustrator software.
8. Analysis of coastal changes, glaciological features, and outlet-glacier, ice-stream, and ice-shelf velocities.

The following discussion of the recently completed Bakutis Coast map (currently being readied for printing) is used as an example of the types of coastal-change and glaciological information that can be derived from analysis of Landsat MSS and TM images.

Glaciological features

The Bakutis Coast (Swithinbank et al. in preparation) shows two dominant glaciological features: relatively narrow fringing ice shelves (Getz, Dotson, and Crosson Ice Shelves) and the Thwaites Glacier system (Thwaites Glacier, Thwaites Glacier Tongue, and Thwaites Iceberg Tongue). The Bakutis Coast map is divided into five ice-front segments by four islands (Dean, Siple, Carney, and Wright) located between DeVicq Glacier and Martin Peninsula. Siple Island, Carney Island, Martin Peninsula, and Bear Peninsula also contain small ice shelves separated by ice walls. Twenty-seven named and 14 unnamed outlet glaciers and ice streams flow into the ice shelves or directly into the Amundsen Sea; three other named glaciers are located in interior mountain ranges.

Coastal change

As would be expected, the ice fronts, iceberg tongues, and glacier tongues are the most dynamic and changeable features in the coastal regions of Antarctica. Seaward of the grounding line of outlet glaciers, ice streams, and ice shelves, the floating ice margin is subject to frequent and large calving events or rapid flow. Both of these situations lead to annual and decadal changes in the position of ice fronts on the order of several kilometers, even tens of kilometers in extreme cases of major calving events. Although calving does occur along ice walls, the magnitude of change on an annual to decadal basis is generally not discernible on Landsat images; therefore, ice walls can be used as relatively stable reference features against which to measure other changes along the coast; only a single observation date is given for the position of ice walls.

An analysis of changes from Wrigley Gulf on the western part of the Bakutis Coast map to the western part of Pine Island Bay on the east (130–104°W) indicates the following. West and north of Dean Island, the Getz Ice Shelf advanced from 3 to 12 kilometers (km) between 11 January 1973 and 25 February 1988 across a 51-km-wide ice front. The eastern part of the tongue of DeVicq Glacier (mostly on the Saunders Coast map) receded 6 km. West and east of Carney Island small parts of the Getz Ice Shelf receded from 1 to 5 km between 22 December 1972 and 25 February 1988 and between 23 November 1973 and 25 December 1986, respectively. The 46-km-wide ice front of Dotson Ice Shelf also receded 1 to 5 km between 16 January 1973 and 23 January 1990. The largest changes, however, occurred in the Thwaites Glacier Tongue and in the adjacent Crosson Ice Shelf. From the southeastern end of the ice wall of Hamilton Ice Piedmont (about 110°W) to the ice wall west of Pine Island Glacier (about 104°W) is a distance of 186 km. Along a 62-km-wide front of Crosson Ice Shelf that includes the confluence of Smith, Pope, and Vane Glaciers, the ice front receded from 5 to 13 km between 27 December 1972 and 22 January 1988. The irregular 83-km-wide terminus of Thwaites Glacier Tongue advanced about 10 km between 27 December 1972 and 22 January 1988; between 22 January 1988 and 9 February 1989, it advanced another 2 km.

Outlet-glacier, ice-stream, and ice-shelf velocities

Velocities of floating glaciers (e.g., glacier tongues, ice streams, and ice shelves) were determined by two methods: an interactive one in which crevassed patterns are traced visually on images (Lucchitta et al. 1993) and an auto-correlation program developed by Bindschadler and Scambos (1991) and Scambos et al. (1992). Under optimum conditions, errors can be as small as ±0.02 km per year, but for most Landsat image pairs, where registration of features is accurate to only two or three pixels, the accuracy of velocity vectors is ±0.1 km per year. The larger glacier tongues and ice shelves have well-developed rift patterns that can be used for velocity measurements. From 10 to 50 measurement points were made for each glacier tongue or ice shelf. Thwaites Glacier Tongue has an average velocity of 2.8 km per year, on the basis of Landsat images acquired on 2 December 1984 (50276-14524) and 9 January 1990 (42734-14552) (Ferrigno et al. 1993). On the basis of Landsat images acquired on 13 January 1973 (1174-14325) and 22 January 1988 (42016-14343), the floating tongue of Smith Glacier moved at an average rate of 0.6 km per year, although the velocity decreased to 0.5 km per year near the grounding line. The Smith Glacier tongue increased in velocity to an average of 0.7 km per year between 19 January 1988 and 23 January 1990. Dotson Ice Shelf, into which several named (Singer, McClinton, Dorchuk, Keys, Kohler, Boschert, True, Zuniga, Brush, and Sorenson Glaciers) and other unnamed glaciers flow, has an average velocity of 0.4 km per year (Lucchitta et al. 1993, 1994).

Glacier inventory

Producing a sophisticated glacier inventory of Antarctica according to the requirements of the World Glacier Monitoring Service, as part of their ongoing "World Glacier Inventory" program, is impossible with the present state of glaciological knowledge about Antarctica (Swithinbank 1980). It is, however, possible to use Landsat images, supplemented by other satellite images and photographs south of 81.5°S (e.g., recently declassified Corona photographs, Systeme Probatoire d'Observation de la Terre images, Soyuzkarta images and photographs, National Oceanic and Atmospheric Administration Advanced Very-High-Resolution Radar images, and so forth), and available maps to produce a reasonably complete preliminary inventory of named and unnamed outlet glaciers and ice streams and also to define more accurately related glaciological features, such as ice domes, ice piedmonts, ice shelves, ice rises, ice rumples, glacier tongues, iceberg tongues, and so forth. Satellite images and photographs also permit a better distinction to be made of islands and peninsulas, physical features that were often incorrectly identified and defined on earlier maps because of the lack of appropriate data.

References

Alberts, F.G. (Compiler and editor). 1981. *Geographic names of the Antarctic.* (National Science Foundation Publication NSF 81-5.) Arlington, Virginia: U.S. Board on Geographic Names, Defense Mapping Agency, U.S. Geological Survey, and National Science Foundation.

Alberts, F.G. (Compiler and editor). 1995. *Geographic names of the Antarctic* (2nd edition). (National Science Foundation publication NSF 95-157.) Arlington, Virginia: U.S. Board on Geographic Names, Defense Mapping Agency, U.S. Geological Survey, and National Science Foundation.

Bindschadler, R.A., and T.A. Scambos. 1991. Satellite-derived-velocity field of an antarctic icestream. *Science*, 252(5003), 242–246.

British Antarctic Survey (BAS), Scott Polar Research Institute (SPRI), and World Conservation Monitoring Centre (WCMC). 1993. *Antarctic digital database user's guide and reference manual.* Cambridge: Scientific Committee on Antarctic Research. [This manual accompanies a CD-ROM.]

Evenden, G.I. 1990. *Cartographic projection procedures for the UNIX environment—A user's manual* (U.S. Geological Survey Open-File Report 90-284). Denver: U.S. Geological Survey, Earth Science Information, Box 25046, Denver Federal Center. [With later supplements, *Cartographic projection procedures* (Release 4; interim report and second interim report) 25 February 1994. Woods Hole, Massachusetts: U.S. Geological Survey, Woods Hole Field Center, Quissett Campus.]

Evenden, G.I., and J.M. Botbol. 1985. *User's manual for MAPGEN (UNIX version)—A method of transforming digital cartographic data to a map* (U.S. Geological Survey Open-File Report 85-706). Denver: U.S. Geological Survey, Earth Science Information, Box 25046, Denver Federal Center.

Ferrigno, J.G., B.K. Lucchitta, K.F. Mullins, A.L. Allison, R.J. Allen, and W.G. Gould. 1993. Velocity measurements and changes in the position of Thwaites Glacier/iceberg tongue from aerial photography, Landsat images and NOAA AVHRR data. *Annals of Glaciology*, 17, 239–244.

Lucchitta, B.K., K.F. Mullins, A.L. Allison, and J.G. Ferrigno. 1993. Antarctic glacier-tongue velocities from Landsat images: First results. *Annals of Glaciology*, 17, 356–366.

Lucchitta, B.K., K.F. Mullins, H.M. Ferguson, C.E. Smith, and J.G. Ferrigno. 1994. Velocity of the Smith ice tongue and Dotson Ice Shelf, Walgreen Coast, Marie Byrd Land, West Antarctica. *Annals of Glaciology*, 20, 407–412.

National Research Council (NRC). 1985. Glaciers, ice sheets, and sea level: Effects of a CO_2-induced climatic change. Report of a workshop held in Seattle, Washington, 13–15 September 1984, Polar Research Board. Washington, D.C.: National Academy Press.

National Research Council (NRC). 1986. *U.S. research in Antarctica in 2000 A.D. and beyond. A preliminary assessment.* Polar Research Board. Washington, D.C.: National Academy Press.

National Science Foundation (NSF). 1989. *Gazetteer of the Antarctic* (4th ed.) (National Science Foundation Publication NSF 89-98). Fairfax, Virginia: U.S. Board on Geographic Names, Defense Mapping Agency. Arlington, Virginia: National Science Foundation.

Scambos, T.A., M.J. Dutkiewicz, J.C. Wilson, and R.A. Bindschadler. 1992. Application of image cross-correlation to the measurement of glacial velocity using satellite image data. *Remote Sensing of Environment*, 42, 177–186.

Scientific Committee on Antarctic Research (SCAR). 1980. *Standard symbols for use on maps of Antarctica* (2d ed.). Canberra: SCAR Working Group on Geodesy and Cartography.

Scientific Committee on Antarctic Research (SCAR). 1989. *The role of Antarctica in global change.* Scientific priorities for the International Geosphere-Biosphere Programme (IGBP). (Prepared by the SCAR Committee for the IGBP, April, Cambridge, England, United Kingdom.) Cambridge: ICSU Press/SCAR.

Swithinbank, C. 1980. The problem of a glacier inventory in Antarctica. In *World glacier inventory*, proceedings of the workshop at Riederalp, Switzerland, 17–22 September 1978. (Publication number 126.) Wallingford, Oxfordshire, United Kingdom: International Association of Hydrological Sciences Press.

Swithinbank, C. 1985. A distant look at the cryosphere. *Advances in Space Research*, 5(6), 263–274.

Swithinbank, C. 1988. Antarctica (with sections on the "Dry Valleys" of Victoria Land by T.J. Chinn and Landsat images of Antarctica by R.S. Williams, Jr., and J.G. Ferrigno). In R.S. Williams, Jr., and J.G. Ferrigno (Eds.), *Satellite image atlas of glaciers of the world* (U.S. Geological Survey Professional Paper 1386-B). Denver: U.S. Geological Survey, Earth Science Information, Box 25046, Denver Federal Center.

Swithinbank, C., R.S. Williams, Jr., J.G. Ferrigno, B.K. Lucchitta, B.A. Seekins, and C.E. Rosanova. In preparation. *Coastal-change and glaciological map of the Bakutis Coast, Antarctica: 1972–1990* (U.S. Geological Survey Miscellaneous Investigations Series Map, I-XXXX-F. Scale. 1:1,000,000).

Williams, R.S., Jr., J.G. Ferrigno, C. Swithinbank, B.K. Lucchitta, and B.A. Seekins. 1995. Coastal-change and glaciological maps of Antarctica. *Annals of Glaciology*, 21, 284–290.

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LAND-ICE STUDIES

Antarctica and sea-level change

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Does the Antarctic pose a potential danger to humanity through sea-level rise (e.g., Mercer 1978)? Or, as argued by the Intergovernmental Panel on Climate Change (IPCC 1990, pp. 257–281), will Antarctica actually mitigate anthropogenic sea-level rise?

The IPCC Scientific Assessment suggested (1990, p. 276) that

- the contribution of the antarctic ice sheets to sea-level change between 1985 and 2030 is most likely to be a sea-level fall of 6 millimeters (mm) and that the extreme values range from no change to a fall of 8 mm and
- for each degree of global warming, the antarctic ice sheets will cause sea-level fall of 0.3±0.3 mm per year.

Revision of the IPCC assessment is ongoing, but this argument might lead one to believe that the antarctic ice sheets provide protection against sea-level rise during greenhouse warming, at least for the short planning horizon used.

This "optimistic" assessment of the role of Antarctica in sea-level change is ultimately based on two assumptions: that warming brings more snowfall to Antarctica and that rapid changes in ice flow "can effectively be ignored" (IPCC 1990, p. 276) for the time scales considered. Recent research raises serious questions about both of these assumptions and leaves the Antarctic as a potentially major factor in future sea-level rise.

Looking first at the snowfall-temperature link, there is no question that warming increases the moisture-holding ability, and thus the precipitation potential, of saturated air. It is equally clear that this is not the entire story or the Sahara would be the wettest place on Earth. This absurd argument emphasizes that precipitation must depend on atmospheric circulation as well as on temperature.

Arguments in favor of a temperature/snow-accumulation link in Antarctica often are based on spatial correlations—as one moves inland, the temperature falls and the rate of snow accumulation falls (reviewed in IPCC 1990, pp. 257–281). There are exceptions, of course; for example, the Siple Coast of West Antarctica has snow accumulation similar to South Pole despite being roughly 25°C warmer than South Pole (e.g., Giovinetto and Bentley 1985). Nonetheless, the spatial correlations are often quite strong.

It is worth noting, however, that there is no physical reason why spatial and temporal gradients must be the same. Indeed, in a possibly analogous case, recent studies of the dependence of stable-isotopic compositions on temperature show that the spatial and temporal gradients can differ significantly (Peel, Mulvaney, and Davison 1988; Cuffey et al. 1994).

Some data, such as dilution of beryllium-10, do indicate a temporal correlation between accumulation and temperature over glacial-interglacial times (e.g., Lorius et al. 1985). Such a correlation could arise from thermodynamic control of snowfall but also might reflect changes in synoptic activity coincident with glacial/interglacial temperature changes.

Atmospheric studies cast serious doubt on simple temperature control of snowfall. In East Antarctica, for example, most of the snow falls in the cold winter rather than in the warm summer (Bromwich 1988). For Greenland, synoptic-scale activity is at least as important as temperature in controlling snowfall (Bromwich et al. 1993).

Recent work by Kapsner et al. (1995) on the Greenland Ice Sheet Project 2 long ice-core record sought to assess dependence of snow accumulation on temperature through correlation analysis. Temperature was estimated from stable-isotopic composition of ice, after borehole-temperature tests showed that the stable isotopes do contain much temperature information over time at that site (Cuffey et al. 1994). Accumulation was estimated from distances between summer layers in the ice core, corrected for ice-flow and compaction effects.

The result was that for central Greenland, temperature has not exerted strong control on snow accumulation. Over the most recent millennium, warming increased snow accumulation less than expected from thermodynamic relations. During changes between glacial and interglacial climate states, accumulation changed more than can be explained thermodynamically, demonstrating dynamic changes such as storm-track shifts.

Greenland ordinarily is considered more sensitive to storm-track shifts than Antarctica. Nonetheless, the demonstration of such effects in Greenland raises questions about the wisdom of using temperature alone to predict snow accumulation in Antarctica. The need is clear for a better understanding of antarctic meteorology in global-scale atmospheric circulation models, to allow reliable model-based predictions of snowfall.

In addition, annually resolved deep ice cores from the Antarctic should allow assessment of past relations of snowfall and temperature.

Shifting now to ice dynamics, modern data from West Antarctica, paleo-data from the North Atlantic, and our understanding of ice-dynamical processes all argue that ice flow can change rapidly in response to climatic forcing or to internal instabilities.

The stagnation of ice stream C, the thickening of the ice plain of ice stream B, the thinning and speed-up of the head of ice stream B, and various other changes on the Siple Coast of West Antarctica are well-documented (*see*, for example, Shabtaie et al. 1988; Whillans and Bindschadler 1988; Bindschadler 1993). These changes occurred at rates that, if general over the ice sheet, would have significant implications for projections of sea-level change. These changes are not now general, and when summed have little effect on sea level (Shabtaie and Bentley 1987), but they show that ice flow can change rapidly.

The tremendous nonlinearity of ice-dynamical processes makes it relatively easy to create models with large instabilities and rapid changes. For a given gravitational driving stress, observed velocities in modern ice sheets vary by orders of magnitude, and time-evolution from one velocity regime to another is allowed and even expected based on our understanding of the physics. The models of MacAyeal for West Antarctica (1992) and for the Laurentide ice sheet in Hudson Bay (1993a; 1993b) provide excellent examples.

The Heinrich events in the North Atlantic (Broecker 1994) record rapid ice-sheet changes. These were events of greatly enhanced (by more than an order of magnitude) rates of ice-rafted-debris sedimentation (Higgins et al. 1995), correlated with times of cold oceanic conditions, meltwater-diluted surface waters in the north Atlantic (Bond et al. 1992), and widespread climate changes (Broecker 1994). At least most of the events are dominated by debris from Hudson Strait (Grousset et al. 1993; Gwiazda, Hemming, and Broecker 1994).

One might consider that changes in ice shelves contributed to changes in ice-rafted debris reaching the ocean. The role of the ice pump and other processes in promoting rapid melting beneath ice shelves causes ice shelves to serve as filters that remove debris from ice before freely floating bergs are calved (e.g., Jenkins and Doake 1991; Jacobs et al. 1992).

However, the rate of sediment delivery during Heinrich events appears too large for any steady-state delivery by grounded ice (e.g., Alley and MacAyeal 1994), indicating that the Heinrich events are sudden surges of the Laurentide ice sheet from Hudson Bay.

Of course, demonstrating that sudden changes in ice flow are possible and have occurred in the past is far from accurately predicting if, and when, a sudden change will occur in the future. The time scales involved (Heinrich events were spaced a few thousand years apart; the west antarctic ice sheet has survived for at least tens of thousands of years) suggest that West Antarctic collapse is a low-probability event over times on the order of a century or shorter. But this certainly is not the same as a zero-probability event, and the potentially high impact commands special attention.

We thus see that

- changes in atmospheric circulation are important in controlling snow accumulation and its response to climate change, so that warming is not guaranteed to increase snow accumulation greatly and
- rapid changes in ice flow, especially toward thinning, are to be expected from at least some ice sheets.

Taken together, these suggest great uncertainty regarding the role of Antarctica in future sea-level change and present the possibility of significant or catastrophic sea-level rise.

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References

Alley, R.B., and D.R. MacAyeal. 1994. Ice-rafted debris associated with binge/purge oscillations of the Laurentide Ice Sheet. *Paleoceanography*, 9, 503–511.

Bindschadler, R.A. 1993. Siple Coast Project research of Crary Ice Rise and the mouths of ice streams B and C, West Antarctica: Review and new perspectives. *Journal of Glaciology*, 39, 538–552.

Bond, G., H. Heinrich, W. Broecker, L. Labeyrie, J. McManus, J. Andrews, S. Huon, R. Jantschik, S. Clasen, C. Simet, K. Tedesco, M. Klas, G. Bonani, and S. Ivy. 1992. Evidence for massive discharges of icebergs into the North Atlantic ocean during the last glacial period. *Nature*, 360, 245–249.

Broecker, W.S. 1994. Massive iceberg discharges as triggers for global climate change. *Nature*, 372, 421–424.

Bromwich, D.H. 1988. Snowfall in high southern latitudes. *Reviews of Geophysics*, 26, 149–168.

Bromwich, D.H., F.M. Robasky, R.A. Keen, and J.F. Bolzan. 1993. Modeled variations of precipitation over the Greenland Ice Sheet. *Journal of Climate*, 6, 1253–1268.

Cuffey, K.M., R.B. Alley, P.M. Grootes, J.F. Bolzan, and S. Anandakrishnan. 1994. Calibration of the delta ^{18}O isotopic paleothermometer for central Greenland, using borehole temperatures. *Journal of Glaciology*, 40, 341–349.

Giovinetto, M.B., and C.R. Bentley. 1985. Surface balance in ice drainage systems of Antarctica. *Antarctic Journal of the U.S.*, 20(4), 6–13.

Grousset, F.E., L. Labeyrie, J.A. Sinko, M. Cremer, G. Bond, J. Duprat, E. Cortijo, and S. Huon. 1993. Patterns of ice-rafted detritus in the glacial North Atlantic (40-55)\(deN). *Paleoceanography*, 8, 175–192.

Gwiazda, R.H., S. Hemming, and W. Broecker. 1994. Continental provenance of Heinrich layer grains determined with Pb isotopes. *EOS, Transactions of the American Geophysical Union*, 75(44), 349. [Abstract]

Higgins, S.M., R.F. Anderson, J.F. McManus and M.Q. Fleisher. 1995. A high-resolution ^{10}Be/^{230}Th study of Heinrich events over the last 30 kyr in a North Atlantic deep sea core. *EOS, Transactions of the American Geophysical Union*, 76(17), 170. [Abstract]

IPCC (Intergovernmental Panel on Climate Change). 1990. Sea level rise. In J.T. Houghton, G.J. Jenkins, and J.J. Ephraums (Eds.), *Climate change: The IPCC assessment.* Cambridge: Cambridge University Press.

Jacobs, S.S., H.H. Helmer, C.S.M. Doake, A. Jenkins, and R.M. Frolich. 1992. Melting of ice shelves and the mass balance of Antarctica. *Journal of Glaciology*, 38, 375–387.

Jenkins, A., and C.S.M. Doake. 1991. Ice-ocean interaction on the Ronne Ice Shelf. *Journal of Geophysical Research*, 96, 791–813.

Kapsner, W.R., R.B. Alley, C.A. Shuman, S. Anandakrishnan, and P.M. Grootes. 1995. Dominant control of atmospheric circulation on snow accumulation in central Greenland. *Nature*, 373, 52–54.

Lorius, C., J. Jouzel, C. Ritz, L. Merlivat, N.I. Barkov, Y.S. Korotkevich, and V.M. Kotlyakov. 1985. A 150,000-year climatic record from antarctic ice. *Nature*, 316, 591–596.

MacAyeal, D.R. 1992. Irregular oscillations of the west antarctic ice sheet. *Nature*, 359, 29–32.

MacAyeal, D.R. 1993a. A low-order model of growth/purge oscillations of the Laurentide ice sheet. *Paleoceanography*, 8, 767–773.

MacAyeal, D.R. 1993b. Binge/purge oscillations of the Laurentide ice sheet as a cause of the North Atlantic's Heinrich events. *Paleoceanography*, 8, 775-784.

Mercer, J.H. 1978. West antarctic ice sheet and CO_2 greenhouse effect: A threat of disaster. *Nature,* 271, 321–325.

Peel, D.A., R. Mulvaney, and B.M. Davison. 1988. Stable-isotope/air-temperature relationships in ice cores from Dolleman Island and the Palmer Land plateau, Antarctic Peninsula. *Annals of Glaciology,* 10, 130–136.

Shabtaie, S., and C.R. Bentley. 1987. West antarctic ice streams draining into the Ross Ice Shelf: Configuration and mass balance. *Journal of Geophysical Research,* 92, 1311–1336.

Shabtaie, S., C.R. Bentley, R.A. Bindschadler, and D.R. MacAyeal. 1988. Mass-balance studies of ice streams A, B, and C, West Antarctica, and possible surging behavior of ice stream B. *Annals of Glaciology,* 11, 137–149.

Whillans, I.M., and R.A. Bindschadler. 1988. Mass balance of ice stream B, West Antarctica. *Annals of Glaciology,* 11, 187–193

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SUPPORT AND SERVICES

The National Museum of Natural History

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The Smithsonian Institution's National Museum of Natural History (NMNH) shares a 34-year history of cooperative studies in the natural history of polar environments with the National Science Foundation (NSF). Collaboration began in 1963 when the then recently formed Smithsonian Oceanographic Sorting Center (SOSC) received a grant from the NSF Office of Polar Programs to serve as a national archiving and distribution center for natural history specimens and associated data collected by researchers working in Antarctica under the United States Antarctic Research Program [USARP (now USAP, United States Antarctic Program)] (Landrum and Sandved 1969). Beginning in 1973, specimens and data from the Arctic were included as well (Landrum 1975). In May, 1992, the SOSC was abolished as a separate unit and administrative oversight of SOSC activities was delegated to NMNH Department of Invertebrate Zoology. Under a new cooperative agreement with NSF in August 1995, the NMNH will continue the original SOSC polar mission.

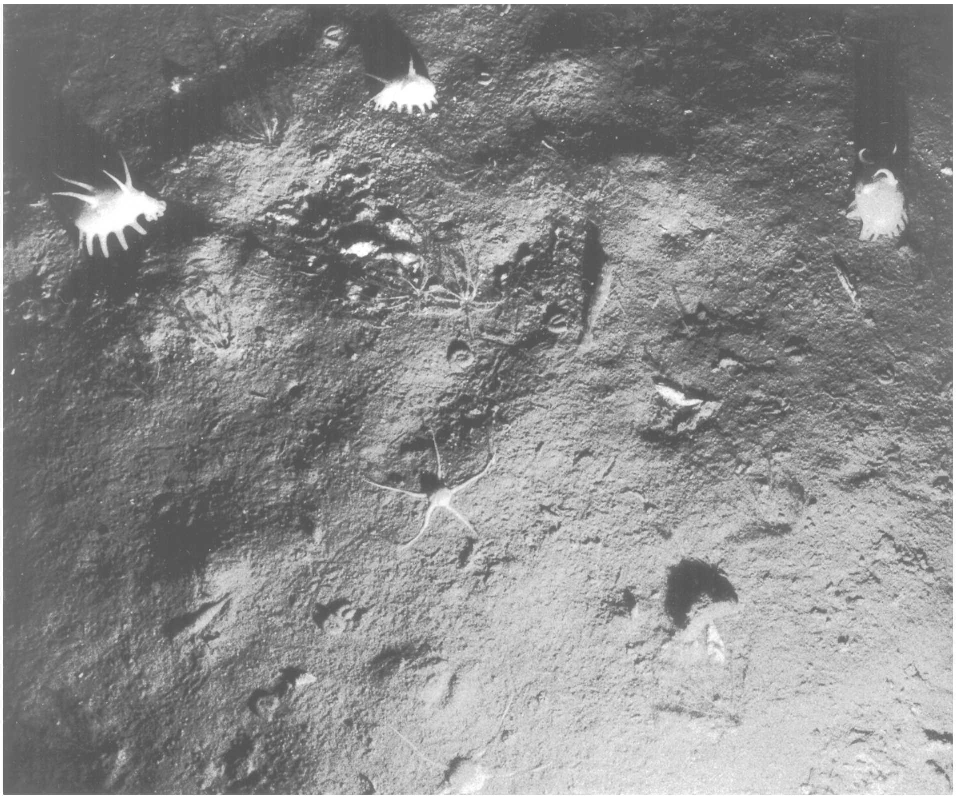

Figure 1. Photograph from a depth of 594 meters, half-square-meter area of fine grain sediment of the Ross Sea floor from cruise 32 of the USNS *Eltanin* (camera station 21, 78°29′S 164°57′W to 78°31′S 164°24′W), showing a diversity of invertebrate life.

To encourage cooperation and dissemination of information, NSF-sponsored investigators working in polar regions are expected by NSF to deposit natural history specimens and associated data at the NMNH at the conclusion of their studies.

Early cataloging activities of the SOSC

The SOSC sorted, identified, and curated bulk polar specimen collections. Arriving in crates, drums, and barrels, the specimens had been collected during antarctic cruises of the USNS *Eltanin*, R/V *Hero*, *Polar Duke*, *Islas Orcadas*, USCGC *Glacier*, and others and from island stations in the Arctic Ocean. Since 1963, more than 40 million specimens have been processed by SOSC or NMNH staff. Initial rough sorting of specimens to phylum or group at the SOSC was followed by careful fine sorting to the lowest practical taxonomical level (usually order or family). Some groups such as the Copepoda and macroscopic Algae were classified to the genus level.

The contributions SOSC's taxonomic work made to the scientific community were broad and far-reaching:

- During the early years of the SOSC's participation in USAP, SOSC staff developed a variety of innovative collection processing and sorting techniques, particularly those needed for efficient processing of enormous volumes of microorganisms.
- The SOSC staff prepared numerous taxonomic keys for specialists and identification guides for general use.
- The NSF Office of Summer Education Programs funds were awarded to the SOSC to provide basic taxonomic training to high-school and university students (Wallen, Fehlmann, and Stoertz 1968; Anonymous 1969).
- Research in collection-management procedures such as archival glassware, relaxing agents, fixatives/post-fixatives, and preservatives (including those that maintained color, as well as fungal- and bacterial-inhibiting compounds) also was conducted (Anonymous 1969).
- The SOSC staff frequently participated in field studies in polar regions and were often consulted for their expertise in specimen collection and fixation/preservation techniques.
- After demonstrating success using a centralized location to process large numbers of specimens and associated data from large collection expeditions, the SOSC was used as a model to establish several oceanographic sorting centers throughout the world (Wallen et al. 1968).

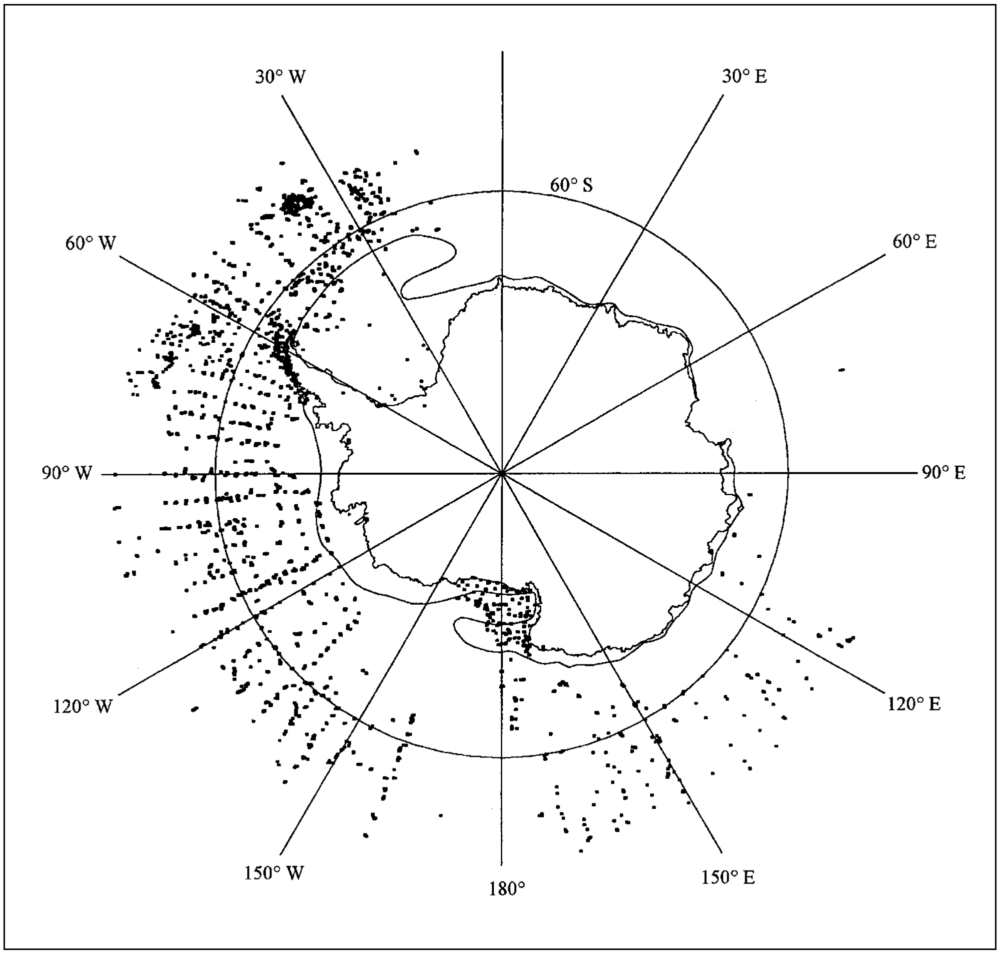

Figure 2. GIS map of the USAP marine collection sites, including and below 50°S.

A readily accessible storehouse of antarctic records

The SOSC also functioned as a data-management center and data clearinghouse for information related to the natural history of polar marine environments. In 1963, with funds from the NSF Office of Polar Programs, the SOSC created the Antarctic Records Program (SOSC-ARP) (Fehlmann 1966). The SOSC-ARP summarized and recorded collection data that accompanied the bulk natural history specimens sent to SOSC and maintained a file of antarctic collecting permits. Unified data standards were established by the SOSC-ARP to institute consistent documentation of data.

Initially, data were recorded on standardized specimen labels and taxonomic cards. In 1967, SOSC-ARP record keeping was automated and consolidated using two SCM Typetronic units (Wallen et al. 1968). These machines could print multiple copies of specimen labels and taxonomic cards and store information that could be fed into a mainframe database, which served as a record of all material processed at the SOSC. Using a Cal-Comp plotter, geographic plots of certain taxa and station data were prepared from this database (Landrum 1980). Vessel and cruise logs also were entered into the computer and summary logs were printed for general use. Relatively rapid storage and retrieval of data were possible.

To speed processing and to ensure standardization of collected data, SOSC staff frequently participated in ship-based antarctic expeditions. Initially, data collection was recorded manually, but later, shipboard computers were used for field entry of collection data (Landrum 1972). Recently, specific information about collection sites—information that could be easily incorporated into NMNH data standards—has been derived by shipboard data technicians using computerized navigational systems.

Specimen distribution

Another vital function of the SOSC was to ensure that natural history specimens were readily and widely available for study by qualified researchers. To guarantee the dissemination of material, the SOSC formed eight advisory committees (Landrum and Sandved 1969) covering the following disciplines:

- algae,
- arthropods,
- higher invertebrates,
- lower invertebrates,
- meiobenthos,
- mollusks,
- vertebrates, and
- worms.

Each committee was composed of five scientists, each having recognized expertise in his or her discipline. The committees advised the SOSC on the most appropriate distribution of material in their assigned taxa.

To encourage research in "orphan" polar taxa, the SOSC offered the Cooperative Systematics Program, which provided NSF subcontracts to researchers interested in the systematics of lesser known organisms (Landrum 1975, 1981). The results of these studies were published in the *Antarctic Research Series* and scientific journals.

Figure 3. Partial specimen holdings of uncataloged and unidentified polar invertebrates.

An archive for photos and slides

In accordance with its NSF polar archiving and distribution initiative, the SOSC managed a collection of 20,300 black-and-white frames of bottom photographs from the southern oceans and subantarctic ocean regions (figure 1) from 1,064 camera stations taken on the USNS *Eltanin*, R/V *Hero*, and USCGC *Glacier* cruises that circumscribed three-fourths of the antarctic continent (Simmons and Landrum 1973). The actual area observed from the stations is approximately equivalent to 12 football fields (Simmons and Landrum 1973). Color transparencies from 143 camera stations were also archived. Accompanying data (e.g., direction, position, and station) were stored in a computer mainframe database to allow for relatively rapid retrieval of information.

These photographs of relatively unexplored areas of polar seafloor are invaluable to marine geologists, biologists, and physical oceanographers. Over 60,000 copies of photographs and their accompanying data have been shipped to researchers for use in more than 30 publications (Simmons and Landrum 1973).

Present-day activities: Building on past accomplishments

The NMNH maintains a large collection of polar natural history specimens, including 200,000 lots of unidentified and uncataloged invertebrates and approximately 31,115 lots of identified, cataloged invertebrates of which 2,049 lots are types. Approximately 19,763 lots of polar specimens are currently on loan to scientists in 191 institutions. Acquisition and collection data for the specimens are readily accessible in several computerized databases and files. Polar station data, a shelf inventory of all uncataloged material, and records of all loaned material are also accessible in computerized databases.

The NSF provides funding for three full-time collection/data technicians and one part-time data manager. Current project activities include curating and archiving collections of

- antarctic bryozoans (approximately 10,000 lots identified by Judith Winston, Virginia Museum of Natural History),
- sponges (approximately 4,800 lots and spicule preparations identified by Vladimir Koltun, Russia Zoological Institute), and
- mollusks (approximately 2,000 lots identified by Richard Dell, Dominion Museum, New Zealand) for permanent deposition at NMNH.

Polar material of various taxa, such as octocorals (identified by Ted Bayer, NMNH), and polychaetes also are being curated and retrospectively cataloged into the main NMNH collections computer database. Additional projects include the development of a database of all types of polar invertebrates archived at NMNH and various Geographic Information System (GIS) maps from the database of USAP program stations (figure 2).

A World Wide Web page with links to a searchable polar station data file, images, and other related data, scheduled to be loaded on the Smithsonian Institutions's gopher server, is currently under construction. The address is

http://www.nmnh.si.edu/iz/usap.html

Other services provided by the staff include lending polar specimens for study by qualified researchers, providing access to polar station data, and preparing of custom GIS maps showing the ecological distribution of polar taxa.

Borrowing unstudied polar specimens

The NMNH has extensive archived unidentified holdings of plankton and a variety of invertebrate groups (figure 3). At present, the most numerous unstudied holdings include the amphipods, polychaetes, and bivalves. Upon request, the NMNH polar specimen holdings may be lent to qualified researchers in the United States and abroad. Loans are not made to graduate students, but permanent university faculty may borrow specimens for graduate student use. Written or e-mail requests for loans should be directed to either the Chairman of the Department of Invertebrate Zoology or the USAP program manager. To protect the integrity of the specimens, loans are typically made with the following conditions:

- The loan is granted to the researcher's institution and not directly to the researcher.
- The initial loan period may not exceed 6 months for type specimens and 12 months for nontypes. On written request, most loans may be renewed for an additional 6- or 12-month period.
- Permission to dissect; to make scanning electron microscope, transmission electron microscope, or histological preparations; or to make any other physical alteration of the specimens must be requested in writing before such specimen manipulations are allowed. All preparations made must be returned to NMNH when the loan is returned.
- The NMNH reserves the right to grant or deny any loan requests.

Past, present, and future

As research support needs have changed in recent years, the USAP program at the NMNH has evolved from a predominantly sorting and processing activity to a program charged with managing the massive collection of polar invertebrates and their associated data. The ultimate goal is to make the specimens and related data more accessible to polar scientists worldwide. In 1997, we expect to initiate an awards program that will help fund systematic research projects based on our polar collections.

The NMNH will continue to function as a national archiving and distribution center for polar natural history specimens and associated data. The NMNH looks forward to another 30 years of cooperative polar research with NSF.

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References

Anonymous. 1969. The Smithsonian Oceanographic Sorting Center. *The Science Teacher,* 36(3), 29–31.

Fehlmann, H.A. 1966. Recording of data for specimens collected under the U.S. Antarctic Research Program. *Antarctic Journal of the U.S.*, 1(5), 225.

Landrum, B.J. 1972. Antarctic information services at the Smithsonian Oceanographic Sorting Center. *Antarctic Journal of the U.S.*, 7(5), 212–213.

Landrum, B.J. 1975. Technical support for systematic biology. *Antarctic Journal of the U.S.*, 10(1), 313–315.

Landrum, B.J. 1980. Support of biological studies. *Antarctic Journal of the U.S.*, 15(5), 226.

Landrum, B.J. 1981. Antarctic biological collections. *Antarctic Journal of the U.S.*, 16(5), 231.

Landrum, B.J., and K.G. Sandved. 1969. An operational data processing system for natural history specimens. *Antarctic Journal of the U.S.*, 4(6), 278–284.

Simmons, K.L., and B.J. Landrum. 1973. Sea floor photographs. *Antarctic Journal of the U.S.*, 8(3), 128–133.

Wallen, I.E., H.A. Fehlmann, and C. Stoertz. 1968. The Smithsonian Oceanographic Sorting Center. *Journal of the Washington Academy of Sciences*, 58, 191–200.

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MARINE AND TERRESTRIAL GEOLOGY AND GEOPHYSICS

Initial results of geologic investigations in the Shackleton Range and southern Coats Land nunataks, Antarctica

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We present here initial results of geologic investigations conducted during the 1993–1994 field season in the Shackleton Range and the southern Coats Land nunataks (Dalziel et al. 1994) (figure 1). The major goal of this study is to test the "SWEAT" (Southwest U.S.–East Antarctica) hypothesis, which proposes that Laurentia and East Antarctica–Australia were juxtaposed in the Proterozoic and formed part of the supercontinent, Rodinia (Dalziel 1991; Moores 1991). The SWEAT hypothesis suggests that the approximately 1.0-billion-year-old rocks of the southern Coats Land nunataks are a continuation of the 1.0- to 1.3-billion-year-old Grenville Province of North America and that approximately 1.6- to 1.8-billion-year-old rocks of the Yavapi/Mazatzal Province in the southwestern U.S. are correlative with broadly similar-age rocks in the Shackleton Range. We are examining the hypothesis by

- comparing the igneous rocks of the southern Coats Land nunataks and basement rocks of the Shackleton Range with their proposed equivalents in the southwestern U.S.;
- attempting to correlate the late Neoproterozoic Watts Needle Formation, which is exposed in the southern Shackleton Range, with similar-age sequences in Australia and western North America;
- determining paleomagnetically the position of the east antarctic craton relative to Laurentia between approximately 1.0 and 0.7 billion years ago.

Southern Coats Land nunataks

The Bertrab, Littlewood, and Moltke nunataks are exposed along the southeastern Weddell Sea coast and are herein collectively referred to as the southern Coats Land nunataks (figure 2). We mapped and sampled the Bertrab and Littlewood nunataks but were unable to visit Moltke Nunatak, which is exposed in an ice-fall. Marsh and Thomson (1984) discuss the confusion over the exact location of the Bertrab Nunataks. Using air photographs and satellite data, these authors determined the position of the largest nunatak of the group as 77°53'S 34°38'W. We confirmed this position using a hand-held global positioning system device, which was also used to locate and map the other nunataks of the Bertrab and Littlewood Groups.

The Bertrab Nunataks are composed of red-to-gray weathering, fine- to medium-grained, oligoclase-phyric, isotropic granophyre, which is cut by flow-banded rhyolite dikes and altered, mafic dikes (figure 2*C*) (Toubes Spinelli 1983; Marsh and Thomson 1984; Gose et al. 1997). The five small outcrops of the Littlewood Nunataks (figure 2*D*) are composed of red-weathering, densely silicified rhyolite (Aughenbaugh, Lounsbury, and Behrendt 1965). Storey, Pankhurst, and Johnson (1994) report a whole-rock rubidium-strontium (Rb-

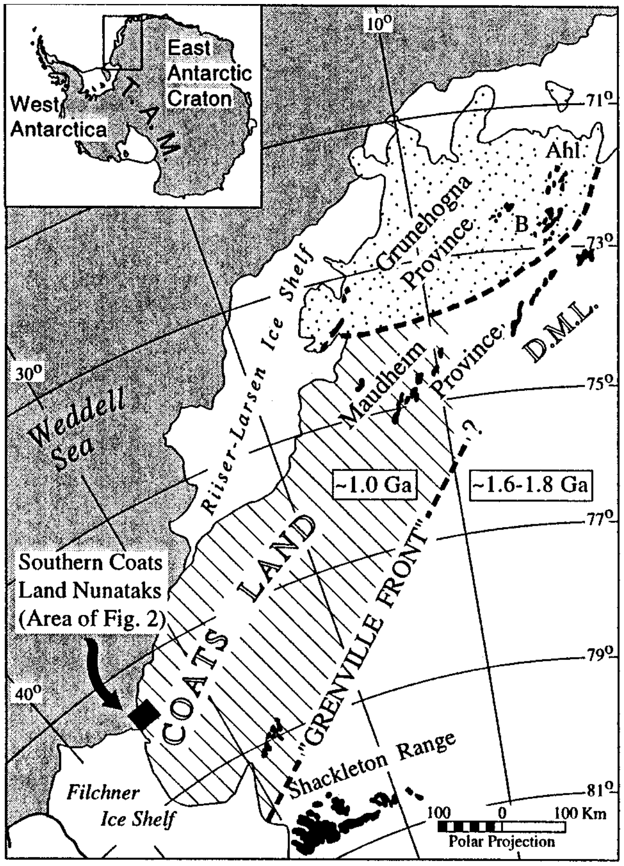

Figure 1. Map of the Weddell Sea margin of the east antarctic Precambrian craton (see inset), showing location of the "Grenville Front," as suggested by Dalziel (1992), the Maudheim and Grunehogna Provinces (from Moyes, Barton, and Groenewald 1993), the Shackleton Range, and the location of the southern Coats Land nunataks. Generalized areas of rock exposure are shown in black. Abbreviations: Ahl, Ahlmannryggen; B, Borgmassivet; D.M.L., Queen (Dronning) Maud Land; T.A.M., Transantarctic Mountains (after Gose et al. 1997). (Ga denotes billion years.)

Sr) age of 1,076±7 million years for the Bertrab granophyre and a recalculated whole-rock Rb-Sr age of 976±35 million years for a mixture of samples from Bertrab and Littlewood nunataks. Aughenbaugh et al. (1965) report a whole-rock potassium-argon (K-Ar) age of 840±30 million years for rhyolite at the largest outcrop of the Littlewood Nunataks.

Uranium-lead (U-Pb) isotopic analyses of two fractions of zircon from the Littlewood rhyolite and two fractions of titanite from the Bertrab granophyre yield concordant U-Pb ages of 1,112±4 million years and 1,106±3 million years, respectively (Gose et al. 1997). The ages represent a crystallization age for the rhyolite and a cooling age for the granophyre. These ages support earlier suggestions of a cogenetic origin for the granophyre and rhyolite and indicate cooling of the granophyre below the magnetite Curie Point (580°C) by approximately 1.1 billion years ago.

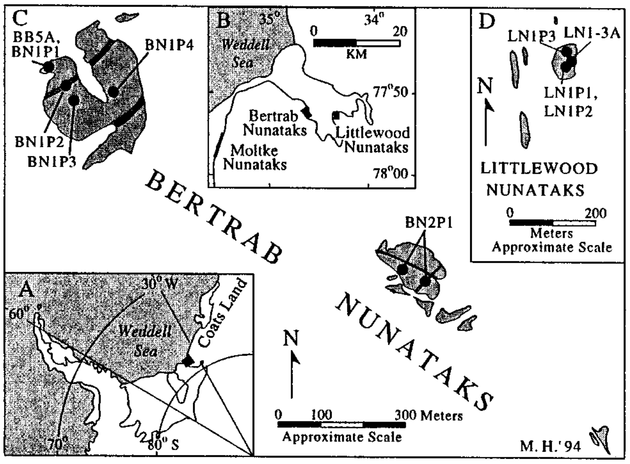

Figure 2. Maps of the Bertrab and Littlewood nunataks showing the location, geology, and sampling sites. The location of inset *B* is shown by the black box in inset *A*. Inset *B* shows the location of the Bertrab and Littlewood Nunataks. Medium shading in main figure (*C*) and inset *D* denotes granophyre at the Bertrab Nunataks and rhyolite at the Littlewood Nunataks. Within the Bertrab Nunataks, solid, black lines are mafic dikes and northeast-trending, shaded dikes are rhyolite (after Gose et al. 1997).

Eighty-four oriented samples were collected from six sites (four in the granophyre and two in rhyolite dikes) at the Bertrab Nunataks and three sites in the rhyolite at the Littlewood Nunataks (figures 2*C* and *D*). Rock magnetic and petrologic studies indicate that magnetite is the dominant carrier of magnetic remanence in the Bertrab granophyre and hematite is the carrier for the Littlewood rhyolite. Site means of the Bertrab and Littlewood samples are indistinguishable and yield a mean pole position of 23.9°S 258.5°E with an error of a_{95}=4.00 (Gose et al. 1997). The remanent magnetization is interpreted as a primary thermal remanent magnetization. This interpretation is supported by a lack of evidence for later thermal resetting (Aughenbaugh et al. 1965; Marsh and Thomson 1984; Gose et al. 1997), as well as a broad similarity of the Coats Land pole position with paleopoles obtained from approximately 1.0-billion-year-old rocks in Queen Maud Land (Hodgkinson 1989; Peters 1989) (figure 3) and dissimilarity to poles obtained from younger rocks in Antarctica (cf. DiVenere, Kent, and Dalziel 1995; Grunow 1995).

After rotation of the east antarctic craton about an Euler pole consistent with the SWEAT reconstruction, our new Coats Land pole falls directly on the Laurentian apparent polar wander path (APWP), lending support to the Rodinian reconstruction of Dalziel (1991) (figure 3). Our approximately 1,100-million-year-old Coats Land pole, however, overlaps poles that define the 1,000-million-year-old segment of the Laurentian APWP. Uncertainties in the age of magnetization acquisition for both the poles of the Laurentian APWP and the Coats Land pole may account for this discrepancy.

Shackleton Range

The Shackleton Range is composed of Paleo- to Mesoproterozoic basement gneisses and granitoids overlain by upper Neoproterozoic and lower Paleozoic supracrustal rocks (Marsh 1983; Pankhurst, Marsh, and Clarkson 1983). Concurrent studies of the basement and supracrustal rocks are underway with the aim of comparing the tectonic history of the range with equivalent age rocks in the southwestern United States. Our initial efforts have focused on isotopic and structural studies of basement rocks and a paleomagnetic study of the overlying Neoproterozoic clastic and carbonate rocks of the Watts Needle Formation of the Read Mountains in the southern Shackleton Range (figure 1).

In the central Read Mountains, the basement comprises middle amphibolite to granulite-grade gneisses, amphibolites, and migmatites intruded by variably foliated to unfoliated granitoids (Read Group; Olesch et al. in press). Foliated but nonmylonitic migmatites and relict granulites occur north of an east-west striking, south-dipping zone of intense mylonitization, the Read Mountain Mylonite Zone (RMMZ) (Helper, Grimes, and Dalziel 1995), that transects the central part of the range. Grain size reduction textures in quartz and feldspar within mylonites of a variety of lithologies are consistent with shearing at amphibolite facies conditions. Subparallel zones of phyllonite and lower temperature mylonite within the southern portion of the RMMZ indicate renewed or continued motion at greenschist facies conditions. Both fabrics are cut by subhorizontal to moderately north-dipping, brittle shears and faults. Maximum ages of mylonitization and dynamic metamorphism are constrained by new U-Pb zircon ages of approximately 1,790 million years and approximately 1,785 million years (Helper unpublished data) for a slightly discordant, dioritic layer of mylonitic orthogneiss and a concordant deformed tonalite dike, respectively. These ages are interpreted as crystallization ages of the igneous precursors. The tonalite dike is subparallel to the mylonitic foliation and is boudinaged but not internally foliated, possibly indicating late-kinematic emplacement. Further U-Pb dating of cross-cutting dikes and granitoids, as well as high-grade orthogneisses, is presently underway to constrain the minimum age of ductile deformation and to directly date the metamorphism.

The Watts Needle Formation is composed of a lower clastic and upper carbonate unit that rests nonconformably on

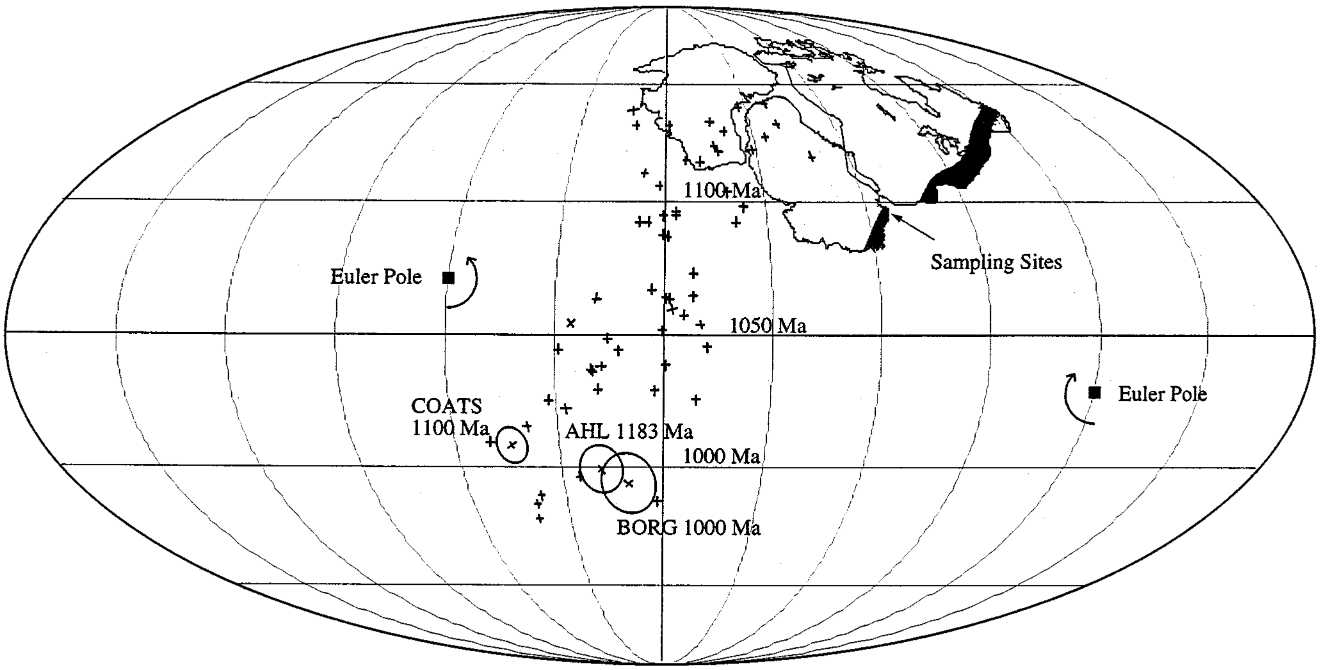

Figure 3. Precambrian virtual geomagnetic pole positions (VGPs) from Antarctica with their 95 percent circles of confidence and ages shown after rotation of the antarctic poles around an Euler pole consistent with the SWEAT reconstruction. Abbreviations: COATS, southern Coats Land (Gose et al. 1997); BORG, Borgmassivet (Hodgkinson 1989); AHL, Ahlmannryggen (Peters 1989). Crosses indicate North American paleopoles which define the Laurentian APWP with generalized ages shown for the path. North America is shown in present-day coordinates with Antarctica and Australia restored to the SWEAT reconstruction at approximately 750 million years. The Grenville Province and its proposed continuation into Antarctica is indicated by dark shading (after Gose et al. 1997). (Ma denotes million years.)

Mesoproterozoic granitoids (Marsh 1983). A Vendian age has been assigned on the basis of acritarchs, stromatolites, and a whole-rock Rb-Sr model age of 720 million years (Golovanov et al. 1979; Pankhurst et al. 1983; Weber 1991). A detailed study of this unit may enable us to correlate it with other well-studied Vendian units worldwide (cf. Kirschvink et al. 1991).

We collected oriented samples from both the granitic basement (31 samples) and overlying Watts Needle Formation (157 samples) at Mount Wegener and Nicol Crags. Samples were drilled at approximately 1.0-meter intervals and 10 or more cores were collected at selected stratigraphic horizons.

Paleomagnetic results from basal red siltstones and sandstones of the Watts Needle Formation at Mount Wegener yield a preliminary mean pole position at 18.5°S 44.3°E with an $a_{95}=7.50$ (Hutson, Gose, and Dalziel 1995). A quartz arenite layer that underlies the upper carbonate section at Mount Wegener yields a preliminary mean pole position at 4.3°S 56.4°E with an $a_{95}=11.10$ (Hutson et al. 1995). A well-defined component of primary remanent magnetization for these units was not reset during later tectonic events (e.g., Ross Orogeny). Evidence for this interpretation includes the following:

- both normal and reversed polarities in samples from the quartz arenite unit and
- our pole positions, which are clearly different from published Early Paleozoic pole positions for the antarctic craton (cf. Grunow 1995).

Paleopoles from the Watts Needle Formation fall close to North American paleopoles of similar age after rotation of East Antarctica into a position adjacent to western North America, as suggested by the SWEAT hypothesis. The paleomagnetic data from the Watts Needle Formation support the juxtaposition of the Laurentian and east antarctic cratons at approximately 750 million years ago.

Paleomagnetic studies of basement rocks of the Read Mountains and the lower Paleozoic Blaiklock Glacier Group are underway. Initial results from a conglomerate test in the Blaiklock Glacier Group suggest that a primary magnetization component may be recovered from these clastic rocks.

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References

Aughenbaugh, N.B., R.W. Lounsbury, and J.C. Behrendt. 1965. The Littlewood Nunataks, Antarctica. *Journal of Geology*, 73(6), 889–894.

Dalziel, I.W.D. 1991. Pacific margins of Laurentia and East Antarctica/Australia as a conjugate rift pair: Evidence and implications for an Eocambrian supercontinent. *Geology*, 19(6), 598–601.

Dalziel, I.W.D. 1992. Antarctica: A tale of two supercontinents? *Annual Review of Earth and Planetary Sciences*, 20, 501–526.

Dalziel, I.W.D., M.A. Helper, F.E. Hutson, and S.W. Grimes. 1994. Geologic investigations in the Shackleton Range and Coats Land nunataks, Antarctica. *Antarctic Journal of the U.S.*, 29(5), 4–6.

DiVenere, V., D.V. Kent, and I.W.D. Dalziel. 1995. Early Cretaceous paleomagnetic results from Marie Byrd Land, West Antarctica: Implications for the Weddellia collage of crustal blocks. *Journal of Geophysical Research*, 100(B5), 8133–8151.

Golovanov, N.P., V.E. Mil'shteyn, V.M. Mikhaylov, and O.G. Shulyatin. 1979. Stromatoliths and microphytoliths of the Shackleton Range (western Antarctica). *Doklady Akademii Nauk*, SSSR. 249(4), 977–979. [In Russian]

Gose, W.A., I.W.D. Dalziel, M.A. Helper, F.E. Hutson, and J.N. Connelly. 1997. Paleomagnetic data and U-Pb isotopic ages from Coats Land, Antarctica: A test of the Laurentian-East Antarctic ("SWEAT") connection. *Journal of Geophysical Research*, 102(B4), 7887–7902.

Grunow, A.M. 1995. Implications for Gondwana of new Ordovician paleomagnetic data from igneous rocks in southern Victoria Land, East Antarctica. *Journal of Geophysical Research*, 100(B7), 12589–12603.

Helper, M.A., S.W. Grimes, and I.W.D. Dalziel. 1995. Basement-cover relations and fabrics of the central Read Mountains, Shackleton Range, Antarctica. Seventh International Symposium on Antarctic Earth Sciences, Siena, Italy. [Abstract]

Hodgkinson, G.R. 1989. Palaeomagnetic studies in western Dronning Maud Land, Antarctica. (Unpublished Masters of Science thesis, Department of Geophysics, University of Witwatersrand, Republic of South Africa.)

Hutson, F.E., W.A. Gose, and I.W.D. Dalziel. 1995. Paleomagnetic results from the Neoproterozoic Watts Needle Formation, Shackleton Range, Antarctica. Seventh International Symposium on Antarctic Earth Sciences, Siena, Italy. [Abstract]

Kirschvink, J.L., M. Magaritz, R.L. Ripperdan, A.Yu. Zhuravlev, and A.Yu. Rozanov. 1991. The Precambrian/Cambrian boundary: Magnetostratigraphy and carbon isotopes resolve correlation problems between Siberia, Morocco, and South China. *GSA Today*, 1(4), 69–71, 87, 91.

Marsh, P.D. 1983. The Late Precambrian and Early Paleozoic history of the Shackleton Range, Coats Land. In R.L. Oliver, P.R. James, and J.B. Jago (Eds.), *Antarctic earth science*. Canberra: Australian Academy of Science.

Marsh, P.D., and J.W. Thomson. 1984. Location and geology of nunataks in north-western Coats Land. *British Antarctic Survey Bulletin*, 65, 33–39.

Moores, E.M. 1991. The Southwest U.S.–East Antarctica (SWEAT) connection: A hypothesis. *Geology*, 19(5), 425–428.

Moyes, A.B., J.M. Barton, Jr., and P.B. Groenewald. 1993. Late Proterozoic to Early Paleozoic tectonism in Dronning Maud Land, Antarctica: Supercontinental fragmentation and amalgamation. *Journal of the Geological Society London*, 150, 833–842.

Olesch, M., H.M. Braun, E.N. Kamenev, G.I. Kamenev, and W. Schubert. In press. Read Group. In J.W. Thomson (Ed.), *British Antarctic Survey Geomap 4*.

Pankhurst, R.J., P.D. Marsh, and P.D. Clarkson. 1983. A geochronological investigation of the Shackleton Range. In R.L. Oliver, P.R. James, and J.B. Jago (Eds.), *Antarctic earth science*. Canberra: Australian Academy of Science.

Peters, M. 1989. Igneous rocks in western and central Neuschwabenland, Vestfjella and Ahlmannryggen, Antarctica: Petrography, geochemistry, geochronology, paleomagnetism, geotectonic implications. *Berichte zur Polarforschung* (Vol. 61). Bremerhaven, Germany: Alfred-Wegener-Institute for Polar and Marine Research.

Storey, B.C., R.J. Pankhurst, and A.C. Johnson. 1994. The Grenville Province within Antarctica: A test of the SWEAT hypothesis. *Journal of the Geological Society London*, 151, 1–4.

Toubes Spinelli, R.O. 1983. Geology of the Bertrab Nunatak, Argentinian sector of Antarctica. *Contribucion Instituto Antarctico Argentino*, 296, 1–9. [In Spanish]

Weber, K. 1991. Microfossils in Proterozoic sediments from the Southern Shackleton Range, Antarctica: A preliminary report. *Zeitschrift für Geologie Wissenschaft*, 19(2), 185–197.

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OCEAN STUDIES

Laboratory observations of ice-floe processes made during long-term drift and collision experiments

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This article describes visual observations made during long-term multifloe drift experiments which were carried out in the refrigerated wave tank at the U.S. Army Cold Regions Research and Engineering Laboratory. The tank's length, width, and height are 36.58 meters (m), 1.22 m, and 0.61 m, respectively. A paddle spanning the width of the tank was at the far upstream end, and a gravel beach with a 1:10 slope was at the downstream end. The purpose of these tests was to determine the drift velocity and collision frequency of individual ice floes and how these factors influenced the formation of a solid ice cover. Three different wave conditions were tested, each chosen to minimize the wave reflection from the beach. The resulting wave periods ranged from 1.71 to 2.73 seconds. The air temperature during these tests was –12°C to –5°C.

The ice floes used for these experiments were cut from a seeded ice sheet, grown under still-water conditions. The ice sheet was composed of randomly oriented, nearly spherical crystals whose average diameter was 1.1 millimeter (mm). The average thickness of the ice sheet was 1.26 centimeters (cm). These parameters were chosen to mimic newly formed pancake ice floes. Once the ice sheet was stiff enough to handle,

Test conditions

Test number	Wave period (seconds)	Water depth (m)	Number of floes	Front condition	Back condition	Average ice thickness (cm)
1	2.73	0.460	23	Open water	Open water	1.10
2	2.73	0.445	30	Open water	Open water	1.18
3	2.73	0.440	39	Random floes	Random floes	1.41
4	1.71	0.430	33	Random floes	Open water	1.17
5	1.71	0.437	47	Random floes	Open water	1.14
6	1.71	0.450	42	Random floes	Open water	1.68
7	2.16	0.435	50	Random floes	Open water	1.15

individual floes with a width of 20 cm and a length spanning the width of the tank were cut. Seven long-term drift experiments were performed. The motion of the floes was recorded using two time-lapse videocameras. The tests lasted 10–12 hours. The number of floes cut for each test varied from 23 to 50. The average number of floes per wavelength ranged from 16 to 28. The water surface conditions in front of and behind the floes were also varied. For the first two tests, there was open water in front of and behind the cut floes. For the next test, there were random floes in front of and behind the cut floes. For the final four tests, there were random floes in front of and open water behind the cut floes. The test conditions are summarized in the table.

To begin each test, the wave paddle was started, and the wave field was allowed to set-up. The floes were then held parallel to the wave front and as steady as possible to achieve an initial velocity of 0. After being released, the floes tended to twist slightly so that they were at an angle to the wave. The floes were not all oriented the same though. A floe's position relative to the wave was influenced by its neighbors unless there was open water between them. Thus, floe orientation tended to occur in groups. Occasionally, some floes were observed to rotate 90°. These floes did not follow the wave surface because they were too rigid to bend. Some floes pivoted about their centers. Most, though, began to oscillate back and forth. Thus, neighboring floes would come together and move apart. This caused water to be pumped onto the floes' surfaces resulting in the ice's surface becoming softer. This phenomenon was also observed in the field by Henderson (1962). If these floes were left undisturbed, this softer surface refroze, causing the floes to thicken.

Upon release, the floes were seen to drift downstream, toward the beach. At the same time, frazil formed in the open-water areas. Because some reflection occurred, there was always an open-water area at the beach where new frazil formed before being pushed upstream. Thus, the frazil was thinnest at the beach and thickest next to the floes. The force on the floes caused by this frazil growth was stronger than the wave drift force. This resulted in the floes being slowly pushed backward toward the paddle. This backward drift was not constant. Periods of no drift were interspersed with periods of drift as high as 0.00175 meters per second. The average drift velocity was $1\text{–}2\times10^{-4}$ meters per second. The magnitude of the drift and the pattern of drift vs. no drift was not related to the initial test conditions.

Besides drifting, the floes were also seen to collide. If the floes had rough edges, the floes would stick together instead of bouncing apart after contacting one another. The measured restitution coefficient averaged 0.14 for the clean collisions. The collisions appeared to coincide with the peak of the wave. Thus, collisions would be seen progressing downstream from floe to floe much like the metal balls in a Newton's cradle. The frequency of collisions was approximately the wave frequency. Often, a floe was seen to collide with one neighbor several times then collide with its other neighbor before returning to the first neighbor.

Floes were also seen to raft onto one another. This was caused by the floe field's need to relieve the pressure build up that resulted from the wave drift force being opposed by the expanding frazil. As stated earlier, many of the floes' surfaces were softened due to water being pumped onto them. When two floes began to raft, the bottom of the upper floe would push its way onto the lower floe. This motion was oscillatory. Thus, the surface of the lower floe would be scraped off ahead of the upper floe. This would cause the lower floe to become further submerged, softening it further. This process continued until the upper floe had totally rafted over the lower floe. Multiple rafting involving three or four floes was often seen. Occasionally, the rafting process would result in one of the floes breaking. The crack occurred perpendicular to the point of contact and seemed to be a fatigue problem.

It was also seen initially that some floes were not colliding and had open water surrounding them. In these cases, the frazil that formed in the open water adhered to the floe. Over time, this new growth hardened and thickened. Frazil that formed in the open-water area between the floes and the beach was seen to be pushed under the floes, adhering to the floes' bottoms. Along the width of a floe, this adhesion of frazil crystals was thinnest at the edges and thickest in the middle, creating a parabolic shape. Up to 6 cm of edge and bottom growth as a result of frazil adhesion was observed in a period of 2–3 hours. These same phenomena were observed in the Weddell Sea (Wadhams, Lange, and Ackley 1987; Wadhams and Holt 1991).

As has been mentioned previously, frazil formed in the open-water area between the beach and the floes. The floes essentially formed a solid barrier. Frazil could move beyond this only if it got swept underneath the floes, as was discussed in the previous paragraph. Otherwise, the frazil collected against the flow farthest downstream. As new frazil was being added at the beach, the older frazil abutting the floes became denser. The progressive wave action caused the frazil slurry to coalesce into small clumps or pancakes. These pancakes gradually grew in size and became stiffer. At this point, collisions between neighboring pancakes resulted in the formation of raised edges around the perimeter of the pancake due to the pumping of frazil crystals and water onto its surface. These raised edges formed only if there was some stiffness to the floe. Stiffer floes were observed to have higher edges. These pancakes were observed to freeze together and to raft, creating a thicker, larger, more solid ice cover. This ice cover was thinnest and softest at the beach where the wave action was greatest. These results suggest that the fact that the floes created a boundary beyond which the frazil could not move was important to the formation of the pancakes. They also suggest that wave action was important to this process.

The formation of pancakes from frazil and the eventual development of an ice cover from the pancakes have been observed to be the main ice-cover formation process in the southern oceans (Wadhams et al. 1987; Lange et al. 1989; Wadhams and Holt 1991). Other phenomena seen in the field, such as the pumping of water onto a floe's surface, were also successfully reproduced in the laboratory. New insight concerning the rafting and collision processes between neighboring floes was gained through these tests. Thus, it is seen that simple laboratory experiments are important tools in increasing our understanding of the freezing of the southern oceans and floe dynamics at the ice edge.

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References

Henderson, J.A. 1962. *Study of natural forces acting on floating ice fields* (U.S. Naval Civil Engineering Laboratory Contract Report NBy-32215). U.S. Naval Civil Engineering Laboratory: Port Hueneme, California.

Lange, M.A., S.F. Ackley, G.S. Diekmann, H. Eikenn, and P. Wadhams. 1989. Development of sea ice in the Weddell Sea, Antarctica. *Annals of Glaciology*, 12, 92–96.

Wadhams, P., and B. Holt. 1991. Waves in frazil and pancake ice and their detection in Seasat synthetic aperture radar imagery. *Journal of Geophysical Research*, 96(C5), 8835–8852.

Wadhams, P., M.A. Lange, and S.F. Ackley. 1987. The ice thickness distribution across the Atlantic sector of the antarctic ocean in midwinter. *Journal of Geophysical Research*, 92(C13), 14535–14552.

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