Marine and terrestrial geology and geophysics

Antarctic seismology programs

JOHN S. DERR, *Albuquerque Seismological Laboratory, U.S. Geological Survey, Albuquerque, New Mexico 87115*

The new Global Seismograph Network, consisting of some 150 very-broadband, digital stations worldwide, presently includes five stations in Antarctica. Those at South Pole (SPA), Palmer (PMSA), and Casey (CASY) are sponsored by the Incorporated Research Institutions for Seismology (IRIS). Those at Vanda (VNDA) and Scott Base (SBA) are sponsored by the U.S. Air Force and include provision for real-time telemetry. Except for Casey, a cooperative project with the Australian Geological Survey, all are installed and maintained by the U.S. Geological Survey, Albuquerque Seismological Laboratory (USGS/ASL) through grants from the National Science Foundation (NSF). Instrumentation, data-acquisition systems, and data availability are described in Peterson and Hutt (1989). [The Federation of Digital Seismograph Networks (FDSN), consisting of some 250 stations worldwide, includes these five stations, plus five others in Antarctica: Dumont d'Urville, Mawson, Sanae, Syowa, and Terra Nova Bay.]

Some of these sites have been recording seismic data for over 30 years as a part of the Worldwide Standard Seismograph Network (WWSSN). This instrumentation, and its several upgrades, has now been replaced by modular, state-of-the-art sensors, digitizers, data processors, and recording systems. This new technology permits remote diagnostics (where phone lines or Internet connections are available), facilitates repairs by modular replacement, and permits evolutionary upgrades as new components become available. What has not changed is the severe antarctic environment, which continues to pose challenges to instrumentation and personnel support.

All data-processing and recording units are in heated facilities at manned bases. To minimize seismic noise, seismometers are generally placed in remote vaults requiring only minimal heat or in boreholes requiring no heat. Each year, new technicians are trained in system maintenance and seismogram interpretation and supported with extensive advice by electronic mail from Albuquerque. This arrangement minimizes special trips by experienced technicians.

The Dry Valleys Seismograph Project was established in cooperation with the New Zealand Antarctic Program to record broadband, high-dynamic-range digital seismic data at a remote site far removed from the environmental noise on Ross Island. The McMurdo Dry Valleys offer some of the few locations on the continent where bedrock can be accessed directly. The sensor systems in the Wright Valley consist of a triaxial broadband borehole seismometer located at a depth of 100 meters and a vertical short-period instrument located at a depth of 30 meters. The seismic data are digitized at this location and, along with environmental data, are telemetered via a radio-frequency link to a repeater at Mount Newall and on to the Hatherton Laboratory at Scott Base. The data processor at Scott Base processes and formats the data to be recorded on magnetic tape as well as transmitting the data to a McMurdo computer system to be put on the Internet. The data are then received from the Internet at ASL to be distributed to the seismological community. To preserve data flow from this area, we have installed a backup seismometer at Scott Base (in the old WWSSN vault), so that if the telemetry link between Scott Base and Vanda fails, the local seismometer can be substituted and can use the same data-processing system and link to Internet for near-real-time data access.

Activity this past year has been a maintenance effort on the system to improve the reliability of the thermoelectric power generators at the Mount Newall repeater site and the Wright Valley site. The maintenance effort on the existing system will continue until new power equipment and shelters are installed in the 1998–1999 austral summer season.

At South Pole, ASL now operates the University of California at Los Angeles gravimeter with a modern, 24-bit data system, collocated with the very broadband seismic sensors. These sensors have been moved from their old location in a building to their current location in a tunnel, in an attempt to avoid drift of the horizontal components from building pressures. The current location, at the edge of the tunnel, is not fully successful in avoiding the microtilt of the floor caused by the pressure of the walls, so a new site will be chosen where they can be in the center of the tunnel. Ultralong-period data from these instruments show the fundamental modes of the free oscillations of the Earth, at periods of up to 53 minutes. Everywhere else on Earth, these modes are split by the Earth's rotation into multiple peaks: only at South Pole is it theoretically possible to record unsplit modes and measure the precise center frequency.

Experience with the Global Seismograph Network is leading seismologists to place greater value on near-real-time data from selected stations around the world. One of the most useful advances in this area would be to have access to a full-time, high-data-rate channel from the South Pole. Such data could be instrumental in rapid determination of focal mechanisms for large Southern Hemisphere earthquakes, and could help in identifying suspicious events for the comprehensive test ban treaty.

The major thrust in coming field seasons will be to relocate the South Pole seismic station 5 to 10 kilometers from the present habitation. Tests have shown that the primary source of noise on the current seismometer is tractors, and that it would be attenuated into the background noise at a distance of about 8 kilometers and a depth of about 200 meters. Constructing the new South Pole Station will add significantly to this noise problem, so we are planning to relocate the seismometers to a borehole in a seismically quiet zone, for maximum noise reduction.

The lack of land and the remoteness of islands in the Southern Hemisphere have meant many fewer seismograph stations, resulting in poorer coverage of earthquakes and less knowledge of the seismicity of oceanic ridges. With the planned coverage of this hemisphere shown in the figure, IRIS hopes to improve this situation. Stations in Antarctica are especially important because they provide important azimuthal coverage for earthquakes below the equator, thus significantly improving the accuracy of epicentral locations. These data are essential to the scientific community for providing accurate locations and source parameters for Southern Hemisphere events, leading to improved understanding of the tectonics of the southern lithospheric plates and the Earth's interior.

The following people contributed significantly to supporting various aspects of these stations: Rhett Butler, IRIS; Don Albert, Cold Regions Research and Engineering Laboratory; and Bob Hutt, Bob Reynolds, Gary Holcomb, ASL. Significant financial support was received from the National Science Foundation (grant EAR 95-29992), IRIS, and the Air Force Technical Applications Center.

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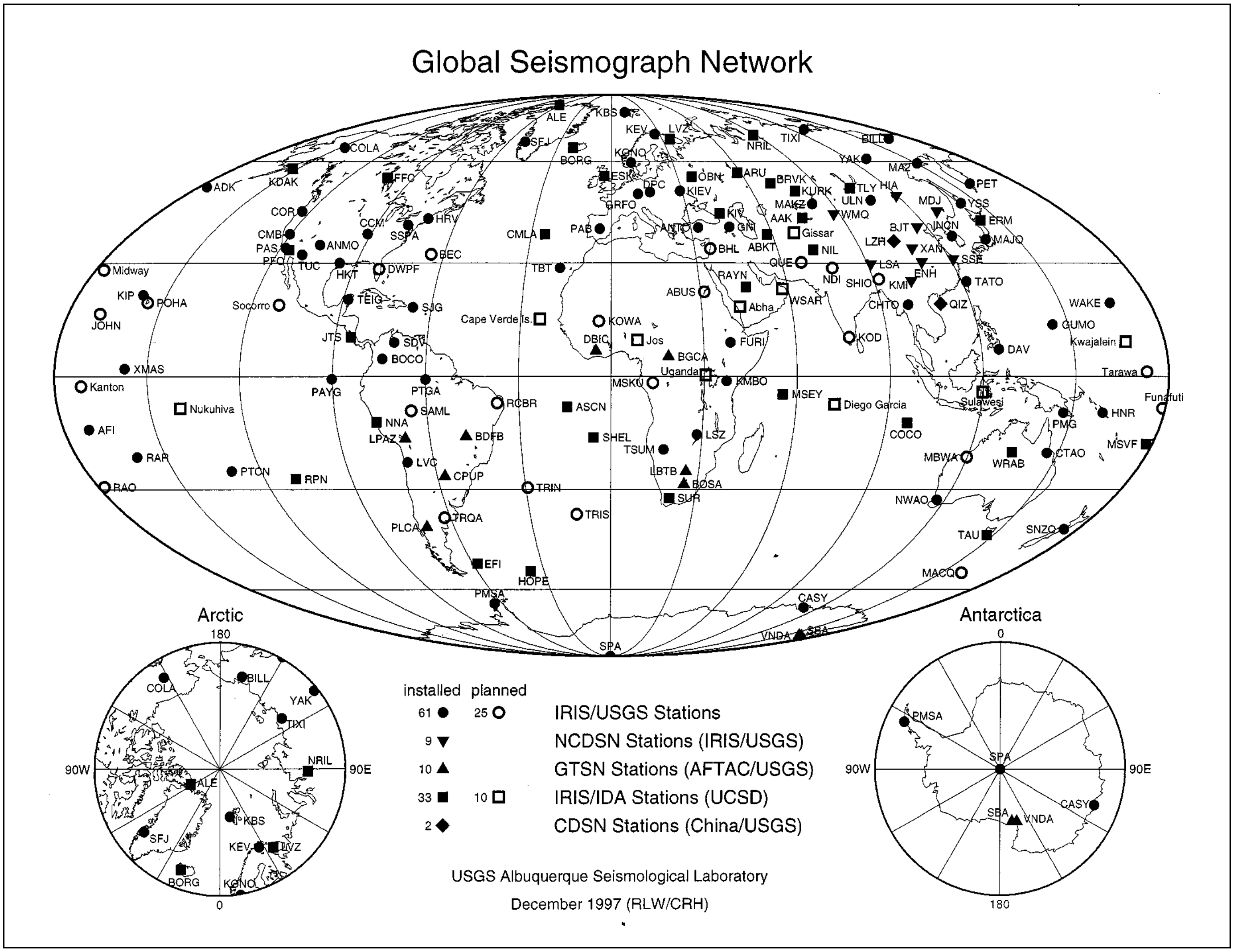

Global Seismograph Network

Cambrian magmatic rocks of the Ellsworth Mountains, West Antarctica

MARGARET N. REES, EUGENE I. SMITH, *and* DEBORAH L. KEENAN, *Department of Geoscience, University of Nevada, Las Vegas, Nevada 89154*
ERNEST M. DUEBENDORFER, *Department of Geology, Northern Arizona University, Flagstaff, Arizona 86011*

A critical element in reconstructing the paleo-Pacific margin of Gondwanaland is the Ellsworth-Whitmore mountains terrane that lies between the Transantarctic Mountains and Antarctic Peninsula (Storey et al. 1988). Paleomagnetic data suggest that during the Cambrian, the terrane lay near the juncture of Africa and Antarctica (Grunow 1995). Nevertheless, much of the tectonic history of this terrane is equivocal and numerous conflicting models have been proposed regarding its tectonic setting and timing of magmatism (Vennum et al. 1992; Grunow 1995; Curtis and Storey 1996; Dalziel 1997). Thus, one aspect of our larger Ellsworth Mountains project focused on the geochemistry and geochronology of magmatic rocks in the northern Heritage Range of the Ellsworth Mountains (figure 1). We conducted fieldwork during the 1996–1997 austral summer and subsequently completed laboratory analyses.

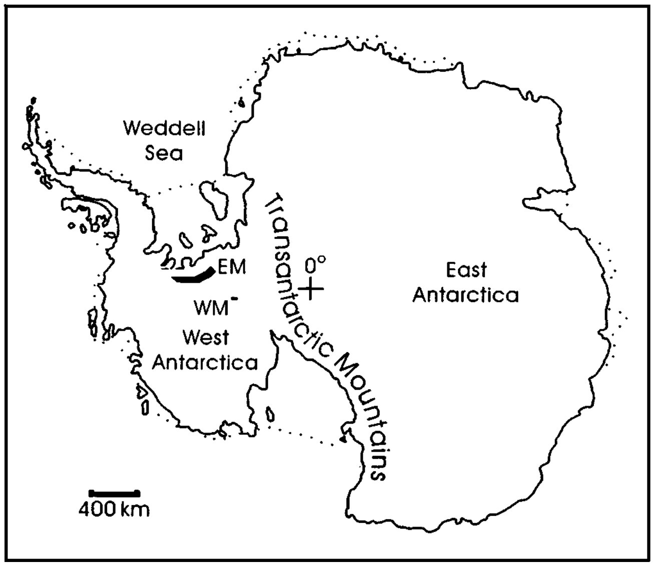

Figure 1. Index map of Antarctica with location of the Ellsworth Mountains (EM) and Whitmore Mountains (WM).

The Cambrian Heritage Group is composed of volcanic and sedimentary rocks (figure 2) (Webers et al. 1992) that are unconformably overlain by the Ordovician(?)–Devonian siliciclastic Crashsite Group (Duebendorfer and Rees in press). The dominant structures in the range, which are attributed to the Triassic Ellsworth/Gondwanide Orogeny, are north-northwest-trending folds and a series of east-vergent stacked thrust sheets that have disrupted the stratigraphic succession. In addition, the Heritage Group preserves evidence of an earlier pre-Crashsite Group deformation that is attributed to deformation within the Ross orogen (Duebendorfer and Rees in press).

Volcanic rocks within the dominantly sedimentary succession of the Heritage Group are present in the Union Glacier and Springer Peak formations (figure 2) (Webers et al. 1992). In the Union Glacier Formation, basalt to andesite hyaloclastite deposits, and flows and interbedded sedimentary rocks locally are cut by dikes of basalt. The hyaloclastite deposits have yielded uranium/lead (U/Pb) zircon ages of 512±14 million years (Van Schmus personal communication). This date, together with other stratigraphic data (Duebendorfer and Rees in press) and the timescale of Shergold (1995), suggests deposition during the late Early Cambrian or early Middle Cambrian.

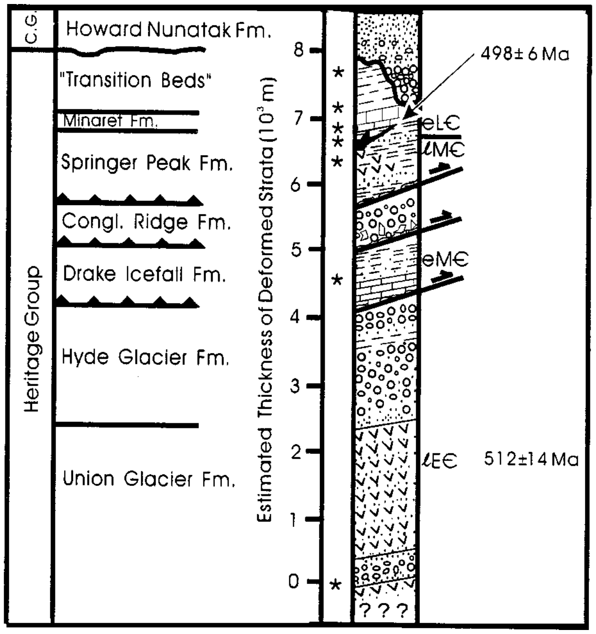

Figure 2. Tectono-stratigraphic column of the Heritage and Crashsite (CG) groups in the northern Heritage Range of the Ellsworth Mountains. Symbols within column are standard lithological notation. * represents level of faunal collections. Faulted contacts indicated by bold lines with arrows. Abbreviations along right side indicate in ascending order: late Early Cambrian, early Middle Cambrian, late Middle Cambrian, early Late Cambrian. Ages are U/Pb zircon dates from volcanic rocks in the Union Glacier Formation and a sills and dikes intruding the Springer Peak Formation. (Ma denotes million years.)

The Union Glacier volcanic rocks are subalkaline, tholeitic basalt and picritic basalt with 50 to 62 weight percent silica (SiO_2). Alumina (Al_2O_3), titania (TiO_2), ferric iron (FeO), lime (CaO), magnesia (MgO), and soda (Na_2O) decrease with increasing SiO_2. Their magnesium number (Mg#; magnesium divided by the sum of magnesium plus iron) varies from 42 to 65. These rocks are enriched in light rare earth elements (LREE) when compared to chondritic abundances (60–200×) and display negative niobium (Nb), tantalum (Ta), and titanium (Ti) anomalies. Epsilon neodymium (Nd) varies from +2 to –1, and initial strontium-87/strontium-86 ($^{87}Sr/^{86}Sr$) between 0.7043 and 0.7095. Their geochemistry is very similar to that of mid-oceanic ridge basalt from the Gulf of California (Saunders et al. 1982), and they have trace element abundances reflecting asthenospheric and lithospheric mantle and crustal components. Nd model ages of 0.9 to 1.0 billion years from the Union Glacier volcanic rocks (Walker personal communication) may suggest the age of the underlying lithosphere of the newly formed narrow ocean basin (figure 3A).

Pillow basalt and flows cut by diabase and gabbro dikes and sills are present in the Springer Peak Formation (figure 2). Locally, isolated basalt flow lobes are interbedded with latest Middle Cambrian fossiliferous shale and limestone that indicate mafic magmatism continued in the region until approximately 500 million years ago, using the timescale of Shergold (1995).

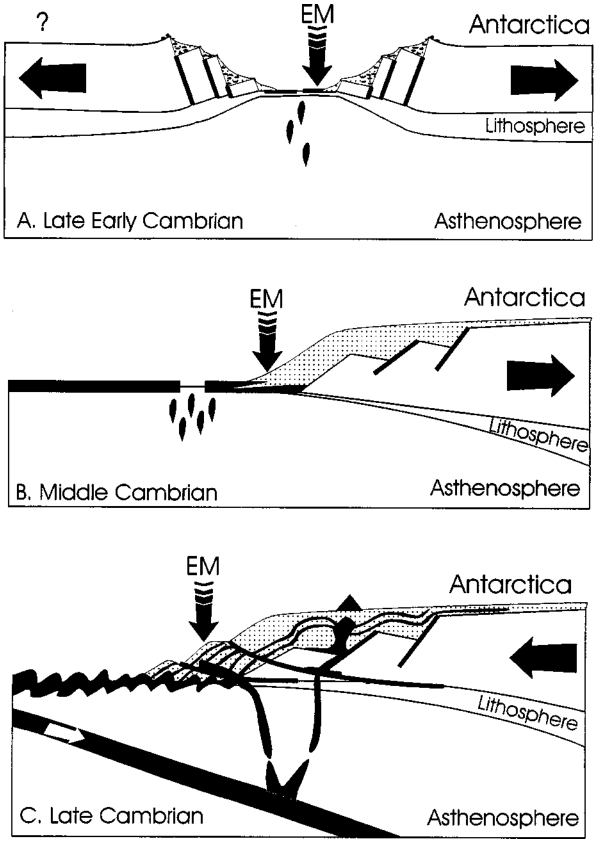

Figure 3. Cartoon, which is not to scale, represents three proposed phases of tectonic and magmatic events recorded in the Cambrian Heritage Group. EM represents the approximate relative location of the Ellsworth Mountains. *A*. Rifting initiating formation of a narrow ocean basin. *B*. Continued spread of narrow ocean basin and lithosphere delamination. *C*. Initiation of narrow ocean basin closure with associated subduction related magmatism and deformation.

Springer Peak Formation volcanic rocks are subalkaline, calc-alkalic basalt, andesite, and trachyandesite with 37 to 50 percent SiO_2. Al_2O_3, TiO_2, and CaO decrease with increasing SiO_2. Their Mg# varies from 42 to 65. These rocks have low rubidium (Rb), potassium (K), and Sr due to alteration and lack high field strength element (Nb, Ta) anomalies when normalized to primitive mantle. They are moderately enriched in LREE (40–80× chondrite), have an epsilon Nd of +5, and initial $^{87}Sr/^{86}Sr$ of 0.705. The basalt is similar to enriched mid-oceanic ridge basalt (MORB) although their higher barium (Ba) and Sr may suggest either source heterogeneity, alteration, or minor sediment input. We suggest that they erupted in an ocean basin wider than that represented by Union Glacier volcanics and in which the lithospheric mantle had been delaminated (figure 3*B*).

Dacite and rhyolite sills and dikes were observed in the Springer Peak Formation on Yochelson Ridge in the Heritage Range. These rocks, however, have yielded zircon U/Pb dates of 498±6 million years (Van Schmus personal communication). Again using the timescale of Shergold (1995), these rocks could represent a Late Cambrian magmatic episode that postdated the Springer Peak Formation and predated deposition of the Crashsite Group.

These intrusions are calc-alkaline dacite and rhyolite with SiO_2 content between 75 to 87 percent SiO_2, and Mg# between 22 and 40. They are enriched in large-ion lithophile elements (LIL) and LREE (500× chondrite) but depleted in Ba and Sr. They have negative anomalies at Nb and zirconium (Zr), a very strong negative anomaly at Ti when compared to primitive mantle, and distinct negative europium (Eu) anomaly compared to chondrite. Epsilon Nd is +0.5 and intitial $^{87}Sr/^{86}Sr$ is 0.713. Tectonic discrimination diagrams suggest that the dacite and rhyolite intrusives formed in a continental arc setting. Furthermore, the geochemical and isotopic differences preclude these more felsic rocks of Yochelson Ridge from being produced by fractional crystallization of magmas that produced the mafic succession in the Springer Peak. Thus, the later felsic rocks represent closing of the narrow ocean basin and onset of subduction related magmatism (figure 3*C*).

Our geochemical and geochronological study of the Union Glacier and Springer Peak formations of the Heritage Group in the Ellsworth Mountains indicates opening of a narrow ocean basin during late Early through Middle Cambrian time. The subsequent Late Cambrian arc magmatism together with deformation and low-grade metamorphism of the Heritage Group and the angular unconformity at the base of the overlying Crashsite Group are compelling evidence that the Ellsworth–Whitmore mountains terrane lay within the Cambrian mobile belts of the paleo-Pacific-facing margin of Gondwanaland.

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A Jurassic prehnite vein intruding the Permian–Triassic boundary at Graphite Peak, Antarctica

GREGORY J. RETALLACK, *Department of Geological Sciences, University of Oregon, Eugene, Oregon 97403*

The Permian-Triassic boundary was the greatest of all mass extinctions both on land and in the sea (Retallack 1995). In the central Transantarctic Mountains, this boundary has been placed at the conformable contact between the Buckley and overlying Fremouw Formation (Barrett, Elliot, and Lindsay 1986). This placement, based on paleontological and lithological criteria, has been recently confirmed by carbon isotopic analysis of kerogen across this boundary (Krull et al. 1996). This interval was cleared of scree on Graphite Peak (figures 1 and 2*A*) in search of event deposits that might reveal what happened at this greatest of all life crises. At one location (85°3.0'S 172°21.7'E), the basal Fremouw Formation was a distinctive claystone breccia with shocked quartz grains, which provide evidence of large asteroid or comet impact (Retallack, Seyedolali, et al. 1996). At another locality 200 meters (m) along strike (85°2.9'S 172°21.1'E) in the basal Fremouw Formation, is a distinctive rock that is the subject of this report (figures 1 and 2).

This intriguing rock is friable and sooty with dark green spherulites up to 2 millimeters in diameter of prehnite. In thin section, these spherulites dominate the texture of the rock (figure 2*B*). Mineral identification was confirmed by x-ray diffraction and by Cameca electron microprobe analyses (table). A count of 500 points indicated that this rock (R2087) had 68.6 volume percent prehnite, with common opaque grains and matrix (15.8 percent), and small amounts of quartz (8 percent), calcite (4.2 percent), clay (2.0 percent), andradite garnet (0.8 percent), and feldspar (0.6 percent).

The prehnite-rich layer is 13 centimeters (cm) thick, shows crude lineation comparable to bedding, and coarsens in grainsize upward. The uppermost 3 cm is indurated with prehnite, whereas the lower 10 cm is friable with soot. This layer is not quite parallel to bedding (figure 2*A*). Above it, is the basal sandstone of the Fremouw Formation with a distinctive Dolores paleosol comparable to one found at the base of the Fremouw Formation in the main section 200 m to the east (Retallack, Krull, and Robinson 1996). The light gray sandstone and olive cherty underclay below the prehnite layer also can be correlated with beds below the uppermost coal of the Buckley Formation 200 m to the east.

Prehnite veins, cement, and nodules are commonly associated with the Jurassic (165–180-million-year-old) Ferrar Dolerite in the central Transantarctic Mountains and probably formed at temperatures of at least 300°C (Barrett et al. 1986). Although this example from Graphite Peak has some features similar to a sedimentary deposit, its mineral composition indicates formation as a thin strata-concordant vein. Its black color and friable sooty nature may have resulted from alteration of the uppermost coal seam of the Buckley Formation. This seam may have provided a plane of weakness for this

Electron microprobe analysis of minerals in a vein near the Buckley–Fremouw Formation contact, Graphite Peak, Antarctica

Mineral	Silica (SiO_2)	Titania (TiO_2)	Alumina (Al_2O_3)	Ferrous oxide (FeO)	Manganese oxide (MnO)	Magnesia (MgO)	Lime (CaO)	Soda (Na_2O)	Potash (K_2O)	Total
Prehnite	43.91	0.06	24.01	0.52	0.16	0.06	26.60	0.01	0.01	95.34
	44.11	0.03	24.03	0.51	0.05	0.01	26.77	0.03	0	95.54
	44.20	0.01	23.86	0.43	0.05	0.03	26.99	0.08	0	95.64
	43.65	0.08	24.21	0.41	0.06	0	26.98	0	0.02	95.40
Andradite	37.78	0.05	21.59	29.04	0.76	6.56	3.74	0.21	0.01	99.54
	38.49	0.15	21.46	26.85	0.66	6.23	6.91	0.02	0	100.77

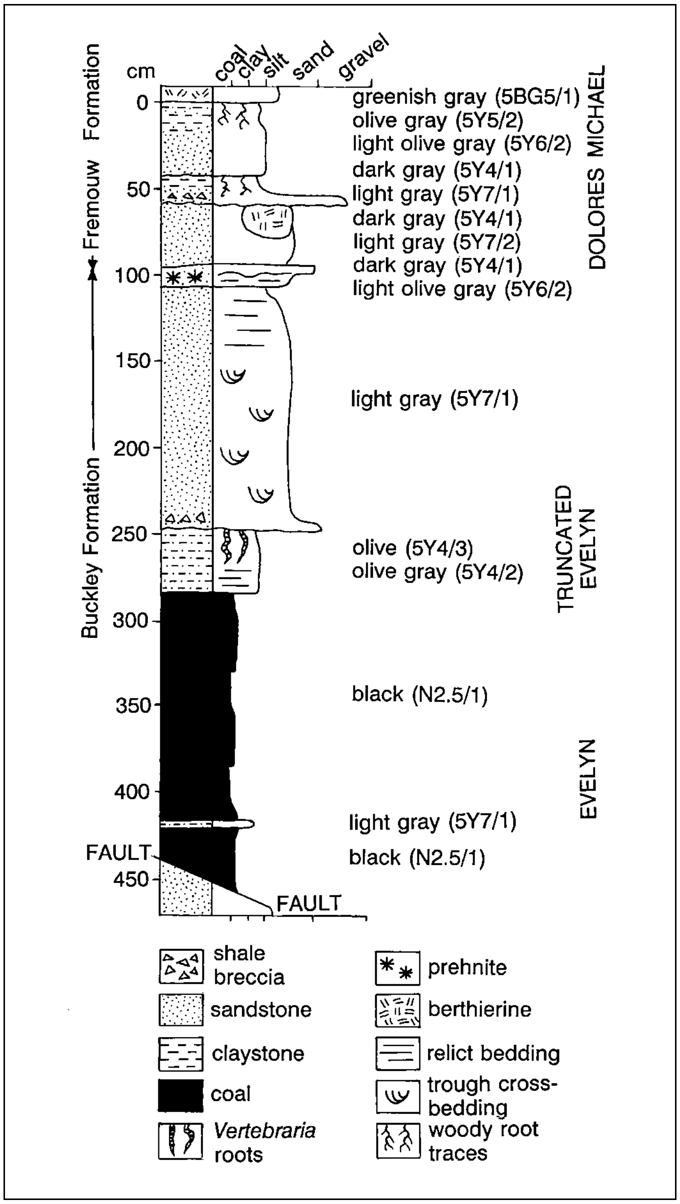

Figure 1. Measured section of the Buckley–Fremouw Formation contact on Graphite Peak, showing an unusual prehnite vein concordant with the boundary. Paleosol names follow terminology of Retallack, Krull, and Robinson (1996).

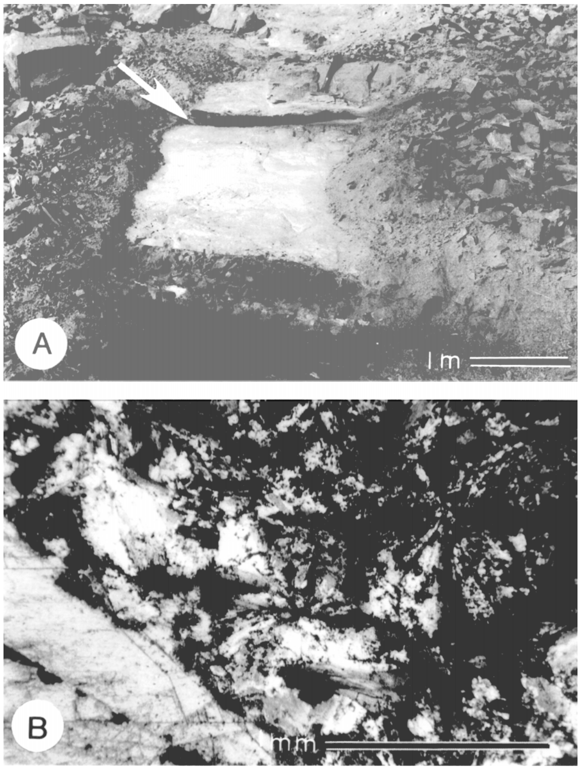

Figure 2. Field photo (*A*) and photomicrograph under crossed nicols (*B*) of prehnite-vein near the boundary of the Buckley and Fremouw Formations at Graphite Peak, Antarctica. The subhorizontal prehnite vein is at the white arrow (*A*) in a vertical section that has been cleared of scree and swept clean with a broom. Bar scales are 1 m (for *A*) and 1 mm (for *B*).

hydrothermal vein from a nearby sill and small-scale (10-m throw) normal fault visible on the western flank of the ridge here. The Permian–Triassic sequence in this ridge below Graphite Peak dips at 18°S and is both floored and capped by large sills of Ferrar Dolerite.

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Permian coprolites from Graphite Peak, Antarctica

GREGORY J. RETALLACK *and* EVELYN S. KRULL, *Department of Geological Sciences, University of Oregon, Eugene, Oregon 97403*

We report here the first known evidence for Permian vertebrates in Antarctica in the form of coprolites. Numerous coprolites were collected (Condon Collection, University of Oregon specimens F35111–35123) from a sandstone of the lower Buckley Formation [270 meters (m) below contact with Fremouw Formation in measured section of Barrett, Elliot, and Lindsay (1986)] of mid-Permian age (Farabee, Taylor, and Taylor 1991) in the slopes just above the moraine wall of the Falkenhof Glacier below Graphite Peak, central Transantarctic Mountains (85°2.9'S 172°21.3'E, elevation 2,600 m; figure 1). The sandstone matrix has large trough crossbeds similar to those found in paleochannels. It also contains large blocks of paleosol claystone and numerous permineralized logs in its basal 3 m. The coprolites are most common within a 2-m interval, 6 m above the base of the paleochannel. Our measurements of the long axis of 56 specimens showed a surprising uniformity of orientation (figure 2), aligned with paleocurrents for the Buckley Formation at Graphite Peak (Isbell 1991).

The coprolites are helical, pupiform, and discoidal in shape (figure 3). The helical coprolites have internal seams of carbonaceous sandstone marking the internally juxtaposed coils (figure 3*D*). They lack internal lumen or mucosal folds. They also are variable in degree of unravelling and in size, so were probably not fossilized intestinal contents [enterospirae or cololites of McAllister (1985)]. Pupiform coprolites show a terminal segment helically wrapped and probably were also pinched off from a helically valvate anus before full extrusion.

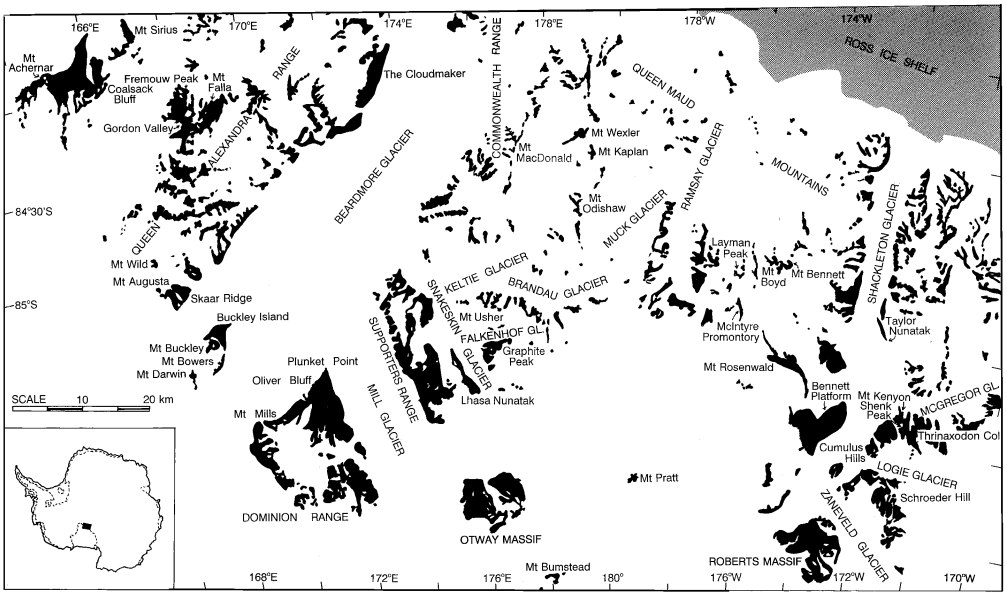

Figure 1. Location of Graphite Peak in the central Transantarctic Mountains.

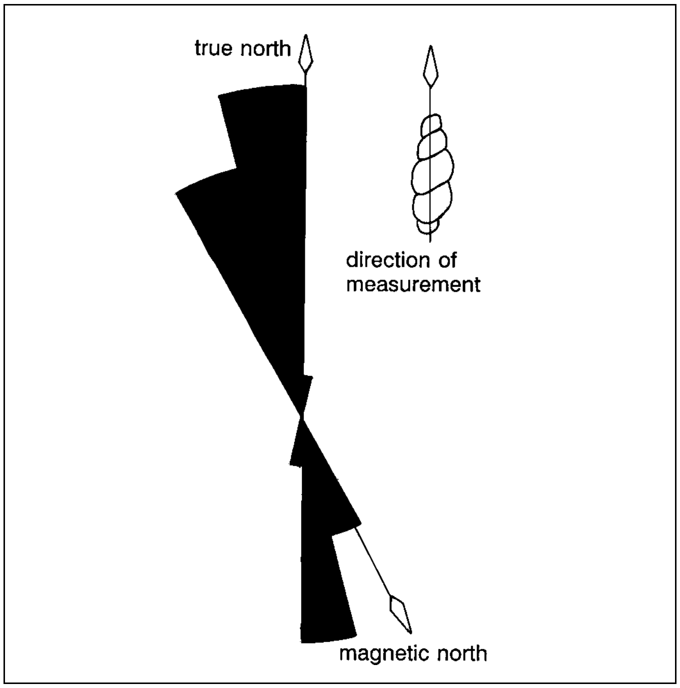

Figure 2. Orientation of 56 coprolites from the Permian Buckley Formation at Graphite Peak, Transantarctic Mountains, with sketch showing the direction measured.

Some of the discoidal masses with radiating cracks and ridges are preserved in the same manner as the associated helical and pupiform coprolites, and appear to be unravelled helices (figure 3*E* and *F*).

The coprolites consist of sandstone. Their matrix is 22.8 volume percent calcite and 9.0 percent clay by point counting 500 points in petrographic thin section. Most of the grains are sand-size and consist of quartz (23 percent), feldspar (12.4 percent), and metamorphic rock fragments (22.4 percent), with traces of hornblende (3.0 percent), mica (2.4 percent), coal fragments (0.2 percent), and other dark brown grains (3.8 percent). Many of the dark brown grains had an internal structure like that of ganoin (figure 3*G*) and are probably scales of paleoniscid fish. The scales are 0.5–1 millimeters (mm) long and 0.2–0.4 mm thick. From observations of complete Permian paleoniscid fish fossils from Germany and Texas, these scales would have come from animals 10–30 centimeters (cm) long. The elongate helical coprolites average 173 mm long ($n=10$, $\sigma_n=41$ mm, $r=99–240$ mm), 75 mm wide ($n=10$, $\sigma_n=14$ mm, $r=50–100$) but only 44 mm thick ($n=10$, $\sigma_n=8$ mm, $r=34–64$) due to postdepositional compaction. They are comparable in size and shape to a specimen of Triassic age from Graphite Peak (misidentified as a large snail by Barrett et al. 1986). They are much larger than Jurassic helical coprolites previously

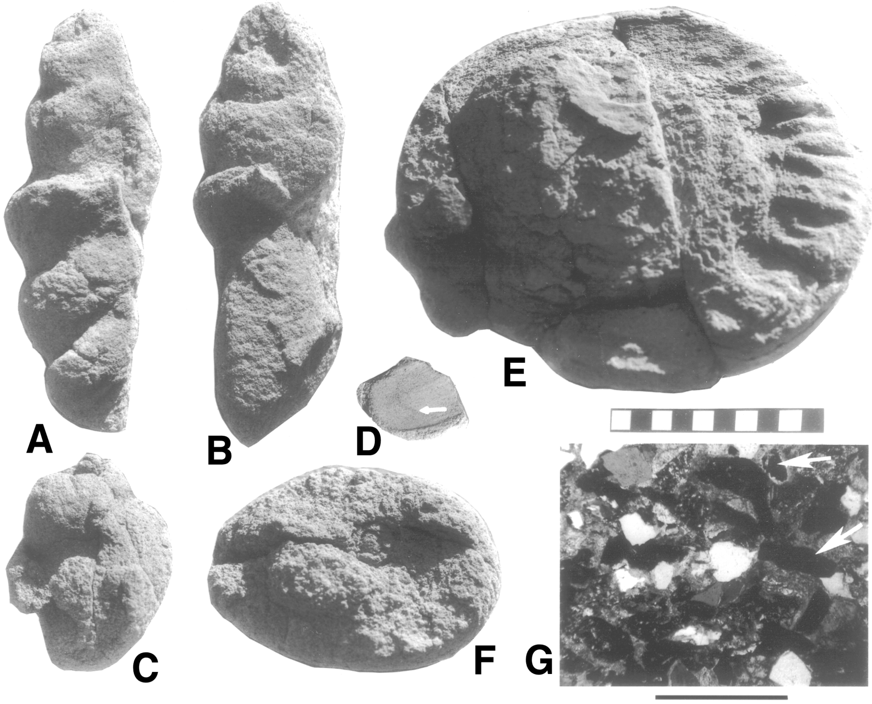

Figure 3. Permian coprolites from the Buckley Formation at Graphite Peak (*A*–*F*), with a sawn cross section (*D*) and photomicrograph under crossed nicols (*G*), from the Buckley Formation at Graphite Peak, central Transantarctic Mountains. White arrow in *D* indicates internal carbonaceous seam of helix. White arrows upper right in *G* show tabular near-opaque grains interpreted as paleoniscid fish scales. Scale bar for fossils: 10 cm graduated in cm and for photomicrograph 1 mm. Condon Collection, University of Oregon specimen numbers are F35111A (*A*), F35111B (*B*), F35112D (*C*), F35118C (*D*), F35119 (*E*), F35122 (*F*), and F35118C (*G*).

recorded from Antarctica (Tasch 1976; Doyle and Witham 1991).

Helical coprolites are formed by the helical intestine of many kinds of fish, including cyclostomes, placoderms, acanthodians, bowfin (*Amia*), garpike (*Lepisosteus*), chimaeras, sharks, and lungfish (Jain 1983; Coy 1995). Freshwater sharks and lungfish have a fossil record in the Middle Devonian of Antarctica and Australia (Long 1991; Young 1993) and sharks in the Permian of Australia (Long 1991). A loose helix and unravelling after sitting on the bottom for a few hours are characteristics of lungfish feces (Jain 1983), which are very similar to the fossils. A dipnoan bottom-feeding behavior would also be compatible with the sediment-rich nature of the coprolites, as argued for comparable scroll coprolites (Gilmore 1992). Coprolites of this size would be produced by living lungfish (*Neoceratodus forsteri*) some 2–6 m long (Jain 1983).

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Neogene paleosols of the Sirius Group, Dominion Range, Antarctica

GREGORY J. RETALLACK *and* EVELYN S. KRULL, *Department of Geological Sciences, University of Oregon, Eugene, Oregon 97403*

The age and paleoclimate of fossils in the Sirius Group of the central Transantarctic Mountains have been controversial. Some see its fossil plants and diatoms as evidence of a major warming (5–10°C) and recession of the east antarctic ice some 3 million years ago (Webb and Harwood 1993). Others find more compelling evidence elsewhere for stability of east antarctic ice and warming of no more than 3°C and so regard the diatoms as surface contaminants (Burckle and Potter 1996) or the Sirius Group as geologically older than 3 million years (Kennett and Hodell 1996). Here we bring a new line of evidence to the dispute, that of fossil soils.

Our observations were confined to the Sirius Group exposed from Meyer Desert down to Oliver Bluff, where we recognize three distinctly different pedotypes (figures 1 and 2). The Siesta pedotype was named for its sunny aspect during our midnight rendezvous on a spur at the northeast edge of Oliver Bluff in the sequence of the lower Oliver Platform (85°6.8'S 166°43.2'E). This paleosol is the one noted 52 meters (m) above the base of unit 4 in section 5 of Webb et al. (1987). It overlies horizons yielding plant fossils from their unit 1/2 boundary to 4.5 m up into unit 4. The Siesta paleosol has a subsurface cemented zone (petrogypsic or By horizon) of fine-grained gypsum (figure 2*C*). The most weathered part of the profile (horizon Bw) is a little more clayey and ferruginized brownish red than the rest of the profile. The upper part of the profile has sparse drab-haloed root traces and irregular dikes of gray sand.

Peligro paleosols are named for exposures in the steep scarp in the central part of the Meyer Desert (85°11.4'S 166°47.1'W) and particularly the profile 16 m below the crest of the ridge (figures 1 and 2). The sequence on the upper Oliver Platform overlies a basement paleovalley at a high elevation (2,200 m) and, following the logic of a flight of postincisive terraces, is geologically older than the sequence (at 1,700 m) with the Siesta paleosol at Oliver Bluff (McKelvey et al. 1991). Peligro paleosols are similar to Siesta profiles but lack the gypsic horizon. Both Siesta and Peligro paleosols include dikes of gray sand in the reddish brown conglomerate of their Bw horizons. Viento paleosols are yellowish brown and thin. They are best represented by a profile 8 m below the crest of the ridge (figure 1).

Observations in petrographic thin sections confirm field impressions that these profiles are little weathered. Hypersthene grains persist unaltered in the paleosols from the parent Ferrar Dolerite. The profiles are unreactive to a dilute (10 percent) hydrochloric acid solution, but limestone clasts persist through the profile. Clay minerals determined by x-ray diffraction include mostly illite and chlorite, with only traces of smectite. Chemical analysis of the Siesta pedotype by AA

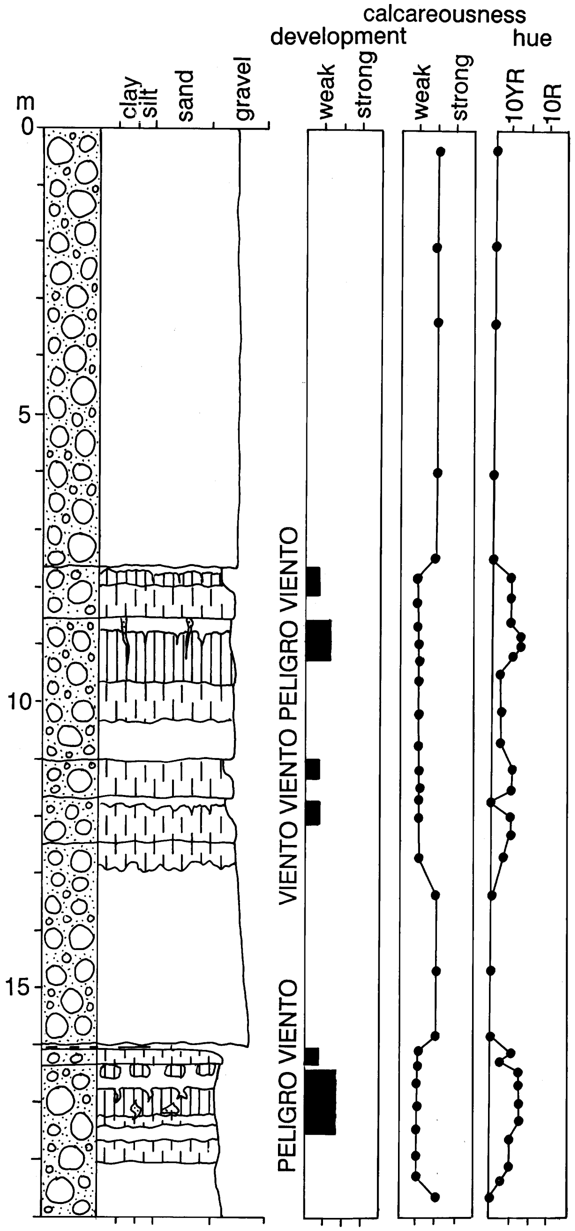

Figure 1. A measured section of paleosols down from the crest of the prominent scarp in central Meyer Desert, Dominion Range, Antarctica. Names are pedotypes, or field names, for recognizably different kinds of paleosols. Black boxes represent position of paleosols, their width corresponding to development. Scales of calcareousness are from relative reaction with dilute hydrochloric acid and hue is from a Munsell color chart. For key to lithological symbols, see figure 2.

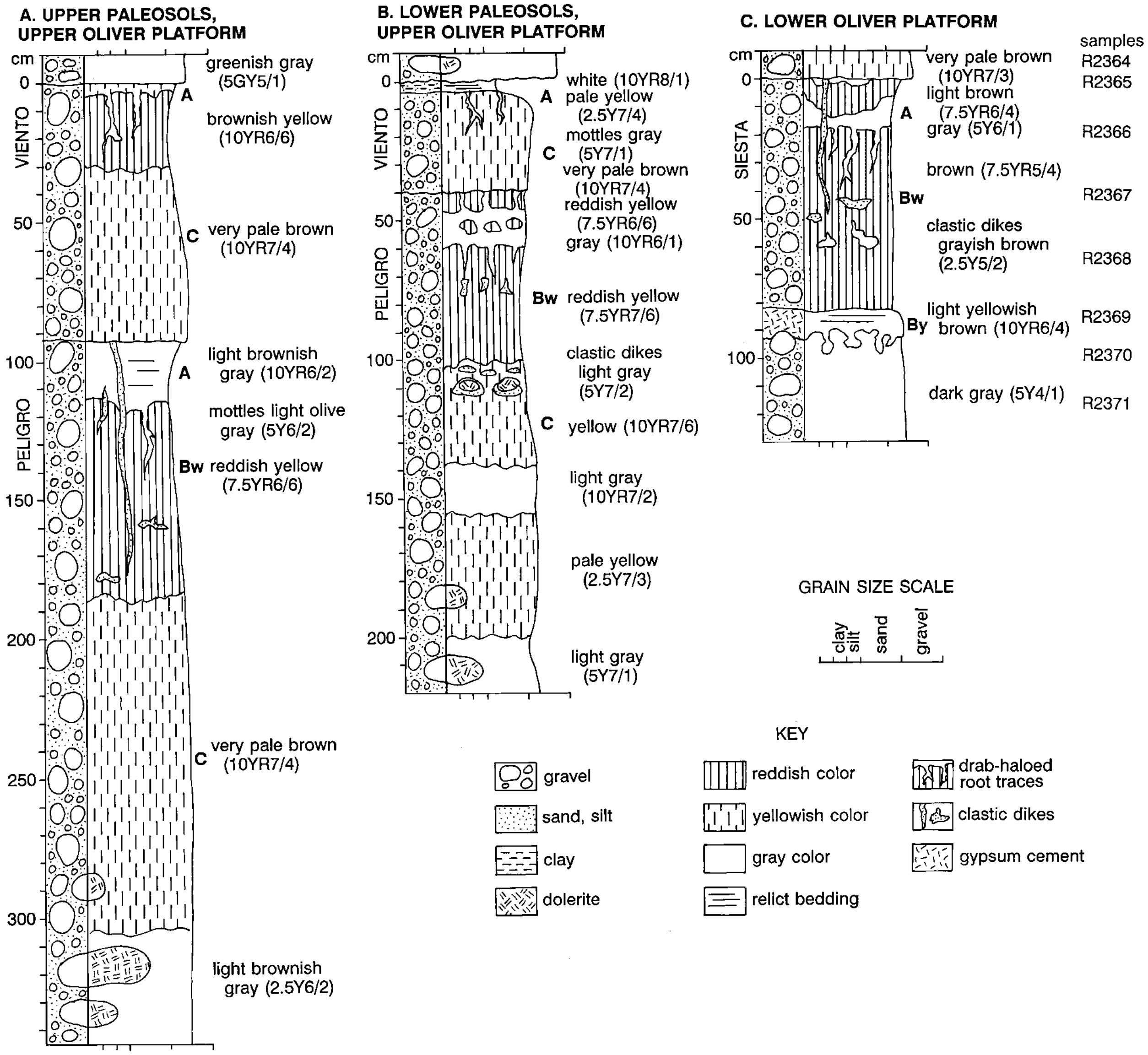

Figure 2. Detailed sections of recognized pedotypes in the Sirius Formation of the Dominion Range: (*A*, left) upper Viento and Peligro pedotypes from central ridge in Meyer Desert; (*B*, center) lower Viento and Peligro paleosols from central ridge in Meyer Desert; and (*C*, right), Siesta pedotype on spur east of Oliver Bluff.

shows evidence of only modest weathering (table 1). Indeed the degree of reddening, clay formation, and salt leaching is only about twice that in soils of the Dominion Range (Bockheim, Wilson, and Leide 1986). Viento, Peligro, and Siesta paleosols are comparable to xerous antarctic soils of progressively greater surface age (Campbell and Claridge 1987).

Comparison of the paleosols with modern soils (table 2) confirms their similarity with soils of the transition zone between polar desert and tundra (Bockheim and Ugolini 1990), as indicated by McKelvey et al. (1991). Comparable soils to Viento and Peligro paleosols support cushion plant-lichen communities including the woody plant *Salix arctica* on beach ridges of Truelove Lowland, Devon Island, Canadian Arctic, where mean annual temperature (MAT) is –16°C, mean annual precipitation (MAP) is 130 millimeters (mm), and a growing season of 69–99 days has temperatures of 1.3–13.6°C (Walker and Peters 1977). Such an assessment is compatible with recent interpretation of fossil *Nothofagus* from the Meyer Desert Formation as prostrate, dry tundra shrubs (figure 3; Francis and Hill 1996). Also comparable to the paleosols in depth and degree of weathering are soils of Enderby Land, Antarctica (MAT –11°C, MAP 600 mm; Bockheim and Ugolini

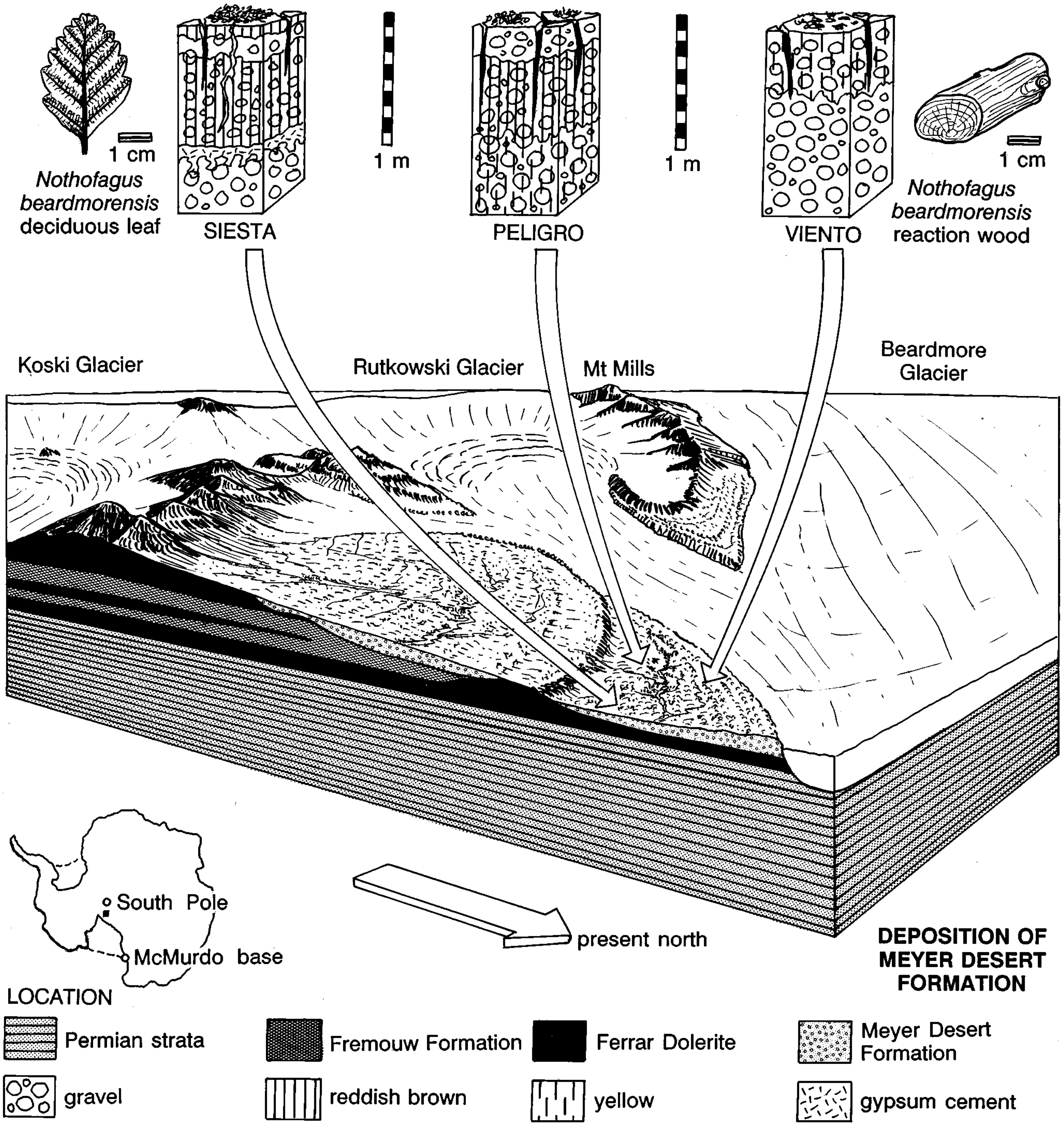

Figure 3. A reconstruction of soils and vegetation in Meyer Desert during deposition of the Sirius Group. Peligro and Viento pedotypes are presumed precursors in development toward the Siesta pedotype, but the type Peligro and Viento pedotypes are in the upper Oliver Platform. The South Pole is 500 kilometers south in the direction of the Beardmore Glacier.

Table 1. Major element (weight percent) and selected trace-element (barium, strontium, and zirconium in parts per million) composition and bulk density (in grams per cubic meter) of Siesta pedotype paleosol at Oliver Bluff, Dominion Range, Antarctica

Sample	Silica (SiO_2)	Titania (TiO_2)	Alumina (Al_2O_3)	Ferric oxide (Fe_2O_3)	Ferrous oxide (FeO)	Manganese oxide (MnO)	Magnesia (MgO)	Lime (CaO)	Soda (Na_2O)	Potash (K_2O)	Phosphorus oxide (P_2O_3)	Loss on ignition	Total	Barium	Strontium	Zirconium	Density
2364	59.58	0.48	11.53	3.55	1.35	0.09	2.80	6.24	2.06	1.98	0.07	7.97	97.87	448	172	143	2.24
2365	57.94	0.52	12.83	3.86	1.93	0.11	3.13	6.96	2.18	1.73	0.08	5.96	97.43	476	222	137	2.24
2366	59.96	0.48	11.59	3.30	1.48	0.09	2.72	6.36	2.08	1.75	0.10	7.41	97.50	465	203	141	2.12
2367	62.96	0.48	11.53	1.99	2.44	0.09	2.49	5.47	2.16	2.02	0.04	5.21	97.15	471	176	147	2.52
2368	63.45	0.47	11.40	1.74	2.61	0.08	2.23	5.24	2.18	1.83	0.05	5.51	97.09	479	173	153	2.50
2369	68.18	0.42	11.22	1.41	2.19	0.07	1.79	3.07	2.27	2.04	0.10	4.17	97.18	482	161	142	2.27
2370	61.45	0.56	13.46	2.09	3.60	0.11	3.56	5.10	2.12	1.53	0.09	4.33	98.40	456	44	10	2.44
2371	62.60	0.55	12.65	3.14	1.93	0.10	2.80	3.97	2.12	1.86	0.11	5.82	97.87	505	204	177	2.47

Table 2. Identification of paleosols of the Meyer Desert Formation in classification of modern soils

Pedotype	Campbell and Claridge (1987) stage	Bockheim and Ugolini (1990) soil	FAO (1974) World Map of Soils	U.S. taxonomy (Soil Survey Staff 1997; Bockheim 1997)
Viento	2 (20,000–100,000 years)	Red ahumisol	Gelic regosol	Cryorthent
Peligro	3 (390,000–340,000 years)	Subantarctic brown	Cambic arenosol	Cryochrept
Siesta	4 (800,000–920,000 years)	Subantarctic brown	Cambic arenosol	Gypsicryid

1990). The paleosols show much less podzolization, lessivage, or peat accumulation than found under conditions of subantarctic tundra or southern Chilean moorland or woodland, that have been suggested as paleoclimatic analogs for conditions during deposition of the Sirius Group (Mercer 1986). Paleosols of the Sirius Group in the Dominion Range are neither evidence for extreme warming and deglaciation nor for glaciers the same size as now but for an intermediate position of modestly, but significantly, warmer and wetter climates than present (figure 3). From this perspective, a Pliocene (3-million-year-old) age for *Nothofagus* leaves in the Sirius Formation is not especially anomalous.

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Geologic studies in the Prince Albert Mountains

DAVID H. ELLIOT, THOMAS H. FLEMING, CHRISTOPHER CONAWAY, *and* PETER BRADDOCK,
Byrd Polar Research Center and *Department of Geological Sciences, Ohio State University, Columbus, Ohio 43210*

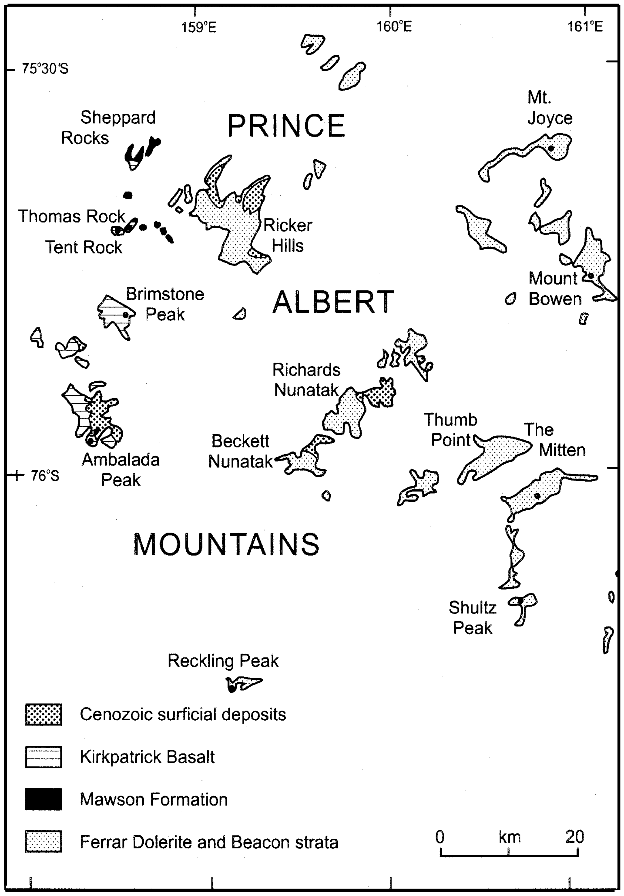
As part of a continuing program of investigations into the Jurassic magmatic rocks associated with Gondwanaland breakup, the Mawson Formation, Kirkpatrick Basalt, and Ferrar Dolerite were examined in the Prince Albert Mountains (figure) between 13 January and 4 February 1997. Put-in and pick-up were by LC-130, and the field investigations were aided by 2 days of helicopter support. This region was initially investigated by Skinner and Ricker (1968) and later more detailed observations and sample collections were made by Kyle (1979) and Wörner (1992).

The pyroclastic rocks of the Mawson Formation were examined at Ambalada Peak, at Thomas Rock and outcrops to its east and north, and at Sheppard Rocks. Although referred to as the "Exposure Hill Formation" by Wörner (1992), Kyle (1979) first noted the occurrence of these rocks and referred them to the "Mawson Formation"; his terminology is followed here. The pyroclastic rocks include breccias, lapilli tuffs, and tuffs. Armored lapilli, cored bombs, and fluidal basalt fragments are sparsely distributed in the breccias; outsize clasts are locally common, and in some outcrops, sedimentary rock fragments are an important component of the breccias. These and other features are indicative of hydrovolcanic processes having a role in the formation of these breccias, as has been documented for the correlative rocks in the central Transantarctic Mountains (Hanson and Elliot 1996). Thin sequences of lapilli tuff and tuff also occur and appear to include both airfall and base surge deposits. Two short sections consist of volcaniclastic strata with interbedded accretionary lapilli tuff: these rocks have similarities to the Carapace Sandstone (Ballance and Watters 1971). The upper and lower contacts of the formation are exposed at Thomas Rock, but the geologic relations are unclear because of apparent tilting of the Mawson Formation strata. Rocks similar to the lapilli tuffs and tuffs of the Mawson Formation are interbedded in the lower part of the basalt sequence at Thomas Rock. A short visit to Reckling Peak revealed the presence of Triassic strata cut by dolerite intrusions and intrusion breccias. The possible ignimbrite mentioned by Wörner (1992) was not located, and pumice fragments were not observed at Thomas Rock. The exposed and measured section at Ambalada Peak was only 70 meters thick, compared with the 200 meters reported by Kyle (1979); it is possible that additional unexamined or unexposed strata make up the difference.

The Kirkpatrick Basalt at Brimstone Peak was examined and collected in detail for geochemistry and radiometric age dating. Collections of secondary minerals were made at Brimstone Peak and Tent Rock to study the postmagmatic hydrothermal circulation systems. Sills at Thumb Point, The Mitten, Richards Nunatak, Beckett Nunatak, and Shultz Peak were also examined, and detailed collections were made for geochemical and isotopic study.

Inclement conditions curtailed the last week of fieldwork and prevented some objectives in the Ambalada Peak–Griffin Nunatak region from being met.

Thanks are given for the logistic support provided by U.S. Navy VXE-6 Squadron and Petroleum Helicopters, Inc. This field research was supported by National Science Foundation grant OPP 94-20498 to the Ohio State University.



Location and simplified geologic map of the Prince Albert Mountains region, southern Victoria Land. Ferrar Dolerite sills are co-extensive with the Beacon Supergroup strata; however, the Beacon rocks are much subordinate to the sills and form only thin sequences between the sills or occur as rafts within the sills.

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Stratigraphy and depositional environments of Permian postglacial rocks exposed between the Byrd and Nimrod Glaciers

GINA SEEGERS SZABLEWSKI, *ERM-North Central, Inc., Milwaukee, Wisconsin 53202*
JOHN L. ISBELL, *Department of Geosciences, University of Wisconsin–Milwaukee, Milwaukee, Wisconsin 53201*

Permian postglacial rocks exposed in the area between the Nimrod and Byrd Glaciers (figure 1) were studied during the 1993–1994 austral summer. Prior to this field season, upper Paleozoic rocks in the central Transantarctic Mountains were known to occur only in the area from just north of the Nimrod Glacier to the Ohio Range (Laird, Mansergh, and Chappell 1971; Elliot 1975; Barrett 1991; Collinson et al. 1994; figure 1). Upper Paleozoic rocks, including the postglacial shales and sandstones, are now known to extend to at least the Byrd Glacier (Isbell et al. 1994). The purpose of this article is to provide a brief description of the postglacial rocks in this area and to interpret their environment of deposition. Laird et al. (1971) first correlated postglacial rocks just north of the Nimrod Glacier with rocks of the Mackellar Formation in the Beardmore Glacier region. Because these rocks can be traced as far as the Wallabies Nunataks (figure 1), we apply the name "the Mackellar Formation" to all postglacial shale and sandstone successions between the Nimrod and Byrd Glaciers. In this area, rocks of the Mackellar Formation include all shale and thin fine- to medium-grained sandstone beds that occur above a sharp contact with diamictites of the underlying Pagoda Formation and below the gradational contact with thick medium-grained sandstones of the overlying Fairchild Formation (Isbell et al. 1994). Rocks of the Mackellar Formation range from 16 to 52 meters (m) thick, and the thickest rocks occur in the central portion of the study area near Chappell Nunataks (figure 1). The postglacial rocks thin toward the Byrd Glacier as well as toward the Ross Ice Shelf and the polar plateau.

In the study area, rocks of the Mackellar Formation occur in multiple coarsening-upward successions (CUSs). A complete CUS contains, in ascending order, the following lithofacies:

- shale,
- shale and interbedded fine- to medium-grained sandstone, and
- medium-grained sandstone containing foreset beds (figure 2).

These lithofacies form one to three 16- to 30-m-thick CUSs.

The shale lithofacies at the base of the CUS is in sharp contact with either diamictite at the top of the Pagoda Formation or with medium-grained sandstone at the top of an underlying CUS (figure 2). These black to gray shales are 1 to 5 m thick and are laterally continuous across outcrop faces. Claystone occurs at the base of this lithofacies and grades progressively upward into alternating laminae of mudstone and siltstone and ultimately into alternating laminae of mudstone and very fine-grained sandstone.

The shale lithofacies grades upward into the 7.5- to 30-m-thick shale and interbedded very fine- to medium-grained sandstone lithofacies (figure 2). Sandstone layers in this lithofacies

- are 0.002 to 2 m thick;
- rest on sharp to erosional bases;
- display graded bedding; and
- are dominated by horizontal laminations with primary current lineations, trough cross-laminae, and climbing ripple laminations.

Small load structures and small-scale overturned and folded laminae are also common. Individual beds, which thin and fine laterally, display a slight downward dip in a direction parallel to paleocurrent orientations. These beds grade laterally into finer grained deposits. Rare symmetrical ripples occur on the updip portions of the dipping sandstone beds. A low-diversity ichnofacies containing *Isopodichnus* occurs on shale and sandstone bedding planes.

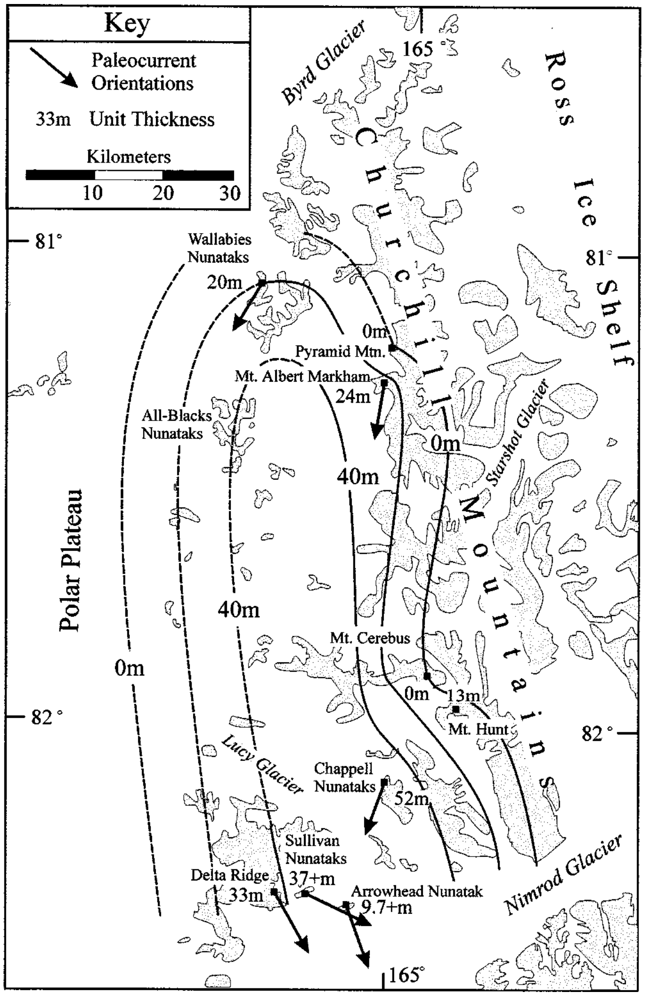

Figure 1. Location map of the area between the Byrd and the Nimrod Glaciers showing paleocurrent orientations and isopachs of the Mackellar Formation.

The sandstone foreset lithofacies occurs at the top of the uppermost CUS (figure 2) and consists of 5- to 10-m-thick beds of medium-grained sandstone, which dip at 1° to 29° in a direction parallel to paleocurrent orientations. These beds grade downdip into fine- to very-fine-grained sandstones of the underlying shale and sandstone lithofacies. Sandstone foreset beds are overlain by medium-grained sandstones of the Fairchild Formation throughout the Nimrod-Byrd area.

Paleocurrent orientations and sandstone-shale ratios vary across the study area. Paleocurrent orientations directed obliquely toward the Ross Ice Shelf occur in rocks exposed in the Geologist Range, whereas in the Churchill Mountains and nearby Nunataks, directions oriented obliquely toward the polar plateau were recorded (figure 1). Regional paleocurrent orientations are toward the location of the present Weddell Sea. The highest sandstone-shale ratios occur near the Byrd Glacier and decrease toward the Nimrod Glacier.

In the Nimrod-Byrd area, rocks of the Mackellar Formation record flooding of the depositional basin following the demise of the upper Paleozoic ice sheet in Antarctica. The contact between the glacial rocks and the postglacial shales is a flooding surface that marks the change from glacial terrestrial to postglacial basinal conditions in central Transantarctic Mountains. The shale lithofacies represent distal fine-grained sedimentation far from the paleoshoreline. The overlying CUSs then record multiple progradational events as deltas introduced coarser clastics into the basin. Sandstone laminae and beds within the CUS were deposited by underflow currents with finer grained, thinner units representing distal delta front sedimentation. Sandstone foreset beds represent the delta mouth bars of prograding Gilbert-type deltas. The abundance of underflow deposits, Gilbert deltas, and the presence of the trace fossil *Isopodichnus* suggest that the Mackellar basin was characterized by freshwater conditions in this area. Sandstones of the overlying Fairchild Formation record a change from deltaic to fluvial conditions within central Transantarctic Mountains.

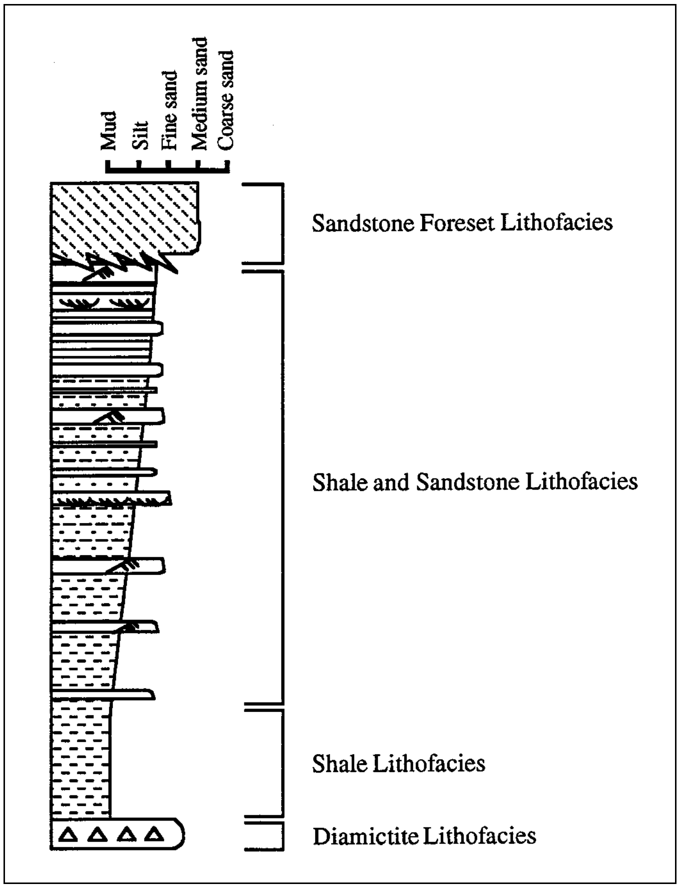

Figure 2. General coarsening-upward succession from the Mackellar Formation in the Nimrod-Byrd Glaciers area.

Deposition of the Mackellar Rocks in the study area occurred within a basin that narrowed and shoaled toward the Byrd Glacier. Paleocurrent orientations and isopachs suggest basin margins located along the present polar plateau and along the Ross Sea side of the Churchill Mountains (figure 1). We thank Shawn Norman for his assistance in the field. Antarctic Support Associates, the U.S. Navy Squadron VXE-6, and the National Science Foundation provided logistic support in

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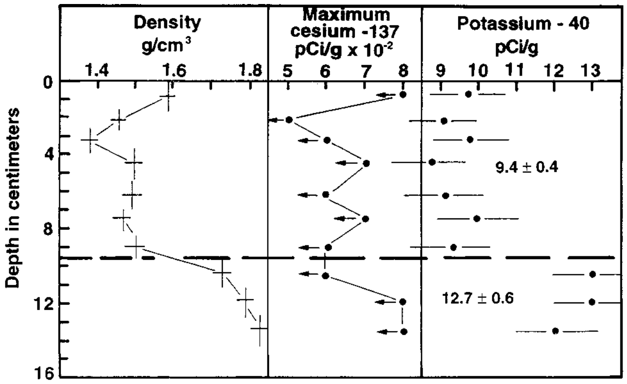
Search for anthropogenic cesium-137 in a soil profile in Beacon Valley, southern Victoria Land

G. Faure, J.A. Sipp, *and* G. Lee, *Department of Geological Sciences, Ohio State University, Columbus, Ohio 43210*

Cesium-137 is a product of nuclear fission of uranium-235. It has a half-life of 30.1 years, which means that more than 150 years must elapse before the decay rate of this radionuclide decreases to about 3 percent of its initial value. Cesium-137 has been widely dispersed in the Northern Hemisphere as a result of testing of nuclear weapons and processing of spent nuclear fuel used in uranium-fission reactors and because of the accidental explosion of a reactor in Chernobyl, Ukraine, on 26 April 1986 (Bunzl et al. 1995; He, Walling, and Owens 1996; Faure in press).

The cesium-137 that was released into the atmosphere by the reactor accident in Chernobyl has contaminated the Northern Hemisphere of the Earth including the United States and Canada, which received amounts of this nuclide equivalent to decay rates of 2.8×10^{15} Becquerels (Bq) and 2.5×10^{15} Bq, respectively (Anspaugh, Catlin, and Goldman 1988). One Bq is the amount of a radionuclide having a decay rate of 1 disintegration per second.

This study was undertaken to determine whether cesium-137 is detectable in soil of the ice-free valleys of southern Victoria Land. For this purpose, soil samples were collected in December 1994 at one location each in the Beacon Valley, in Wright Valley, and in Taylor Valley. At these locations, incremental layers of soil were removed from about 1,500 square centimeters of surface area and the depth intervals were later determined in the laboratory from the weights and measured densities of the samples shown in the figure.



Depth profiles of the density and the decay rates of cesium-137 and potassium-40 in a soil in Beacon Valley, southern Victoria Land.

Portions of the soil samples were analyzed by Teledyne Brown Engineering Environmental Services using gamma-ray spectrometry based on 12-hour counts of 10-gram samples. The results pertain not only to cesium-137, but also record the presence of certain radioactive atoms of actinium, thallium, bismuth, and lead that form naturally as decay products of uranium and thorium in the rocks of southern Victoria Land and elsewhere. In addition, potassium-40 (a long-lived, naturally occurring radioactive isotope of potassium) was detected in all soil samples recovered from the three sites. All of the observed counting rates were corrected for the efficiency of the detector and are expressed in units of picocuries per gram of sample, where 1 picocurie equals 0.037 Bq.

We present here only the results for the soil profile in Beacon Valley taken on the valley floor at about 77°52'S and 160°30'E at an elevation of 1,440 meters above sea level. The profile consists of 10 samples extending from the surface to a depth of 14.4 centimeters (about 5.7 inches). The pebble-sized rock clasts of the lag-gravel present at this site were removed before soil samples were taken.

The results in the figure indicate that the density of the soil increases at a depth of 9.64 centimeters from 1.49±0.07 to 1.78±0.05 grams per cubic centimeter. The decay rates of cesium-137, however, in the soil samples from Beacon Valley and from the other sites in southern Victoria Land are all *less* than the limit of detection of this nuclide, which varies from less than 0.05 to less than 0.08 picocuries per gram. Therefore, cesium-137 was *not* detected at any of the three locations in the ice-free valleys.

A decay rate of less than 0.08 picocuries of cesium-137 means that 1 gram of soil contains fewer than 4 million atoms of this radionuclide and that none may be present. In marked contrast, a soil sample from a prairie on the Marion campus of Ohio State University was found to contain 22±8 picocuries of cesium-137 per gram or almost 300 times more than the highest possible concentration recorded in the Beacon Valley samples.

The figure also demonstrates that the decay rate of potassium-40 in the layer of dense soil below a depth of 9.64 centimeters is 35 percent higher than that of the overlying soil. The increase in the potassium concentration of the soil at this site in Beacon Valley reveals the presence of stratification even though the grain-size distribution indicates that the entire soil is of glacial origin.

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The Dais layered intrusion: A new discovery in the Basement Sill of the McMurdo Dry Valleys

BRUCE D. MARSH *and* MICHAEL J. ZIEG, *M.K. Blaustein Department of Earth and Planetary Sciences, Johns Hopkins University, Baltimore, Maryland 12218*

Layered intrusions are of nearly mystical proportions in igneous petrology. Although they are sometimes unusually large, reaching approximately 500,000 cubic kilometers (km^3) for the Bushveld of South Africa, they are especially noted for their beautiful layers of minerals (Parsons 1987; Cawthorn 1996). The minerals normally found in common basaltic rocks have been somehow sorted to produce a high degree of order. What exact physical or chemical processes lead to this layering has long been debated. Do these layers simply reflect "snow fall" events where the crystallizing magma suddenly churned and sent down a shower of crystals? Could these layers reflect a chemical condition in the magma leading to locally preferred nucleation and growth of a certain mineral? Or could it be a combination of several chemical and physical processes? Regardless of the actual processes involved, however, layering surely records the temporal evolution of the magma much as tree rings do for trees. The main difficulty in reading layering is that the final rock texture, which is so critical to interpretation, generally results from a long and slow process of cooling that may erase, through annealing, sensitive indicators of the conditions of initial formation of the layer. And because cooling time increases with the square of body size, large layered intrusions have cooled so slowly that it is often difficult to recognize the original textures. Small magmatic bodies [i.e., those less than about 500 meters (m) thick] have short cooling times, but they generally show little or poorly developed layering. Thus, our understanding of how layering originates and evolves in magmatic systems contains a gap.

This gap may be closed by our recent discovery of a small layered intrusion associated with the Basement Sill in the McMurdo Dry Valleys. The Basement Sill has long been known to contain a tongue of large orthopyroxene crystals (i.e., phenocrysts) (Gunn 1966), but its tremendous aerial extent and locally massive character have only become appreciated over the past few years (Marsh 1996; Marsh and Philipp 1996).

The Basement Sill is a sheet of basaltic rock suddenly injected during the breakup of Antarctica and Africa about 180 million years ago. The sill crops out over an area of about 5,000 km^3 from Cathedral Rocks in the south to the Debenham Glacier area in the north and also perhaps well beyond this region. Northeast of Lake Vida, the Basement Sill reaches a thickness of about 700 m. We have traced the tongue of phenocrysts throughout the dry valleys.

A distinctive feature of the phenocryst tongue is the presence of slight but pervasive layering. The layers, often more aptly described as stringers, are exclusively due to natural sorting of the two principal constituent minerals; orthopyroxene (brown-green) and plagioclase feldspar (white). The layers or stringers are found only in the tongue, usually reach thicknesses of only a few centimeters, and are laterally continuous up to about 10 m.

At the east end of the Dais in western Wright Valley is a well-developed layered intrusion about 200 m thick; the lower half is covered (*see* figure 1). The layering is evident on scales from centimeters to tens of meters. From as far away as 15 km down Wright Valley, the coarsest layering is evident as alternating light and dark bands. And close up, these coarse (10–30 m) bands consist of many smaller sublayers of from 1 centimeter (cm) to 3–4 m in thickness. On the outcrops, the coarse layering is unrecognizable unless its presence is already known. The alternating light and dark colors of these coarse layers suggest a slight, but distinctive, alternating dominance of orthopyroxene and plagioclase. Individual distinct layers generally do not exceed 20–30 cm in thickness and are often laterally continuous for only a few meters. But even where the rock appears unlayered, there is everywhere, however slight, modal banding. Plagioclase-rich layers are particularly distinct and two near the base of the exposed section (northeast Dais) are essentially anorthosites (15 and 35 cm thick, *see* figure 2). These layers are laterally continuous for about 50–70 m; they then fade and reappear laterally along strike at several more locations. The style of layering is generally maintained at each horizon even though specific layers may be discontinuous.

The loss of lateral continuity of these layers in several places may be related to depositional scouring as is often seen in particle debris flows or slurry flows. Some 20 m upward in this section is a large trough feature; it is perhaps 50 m wide and 3–5 m deep and consists of a well-sorted assemblage of small [1–3-millimeter (mm)] grains of orthopyroxene and plagioclase. The overall appearance is similar to a large block of sandstone. The trough appears to have been filled by settling of a vast assemblage of fine-grained minerals under quiet magmatic conditions.

Individual layers, regardless of size, show gradational bottoms and sharp tops; often there are local concentrations of long (3–4-cm) rodlike orthopyroxenes lying flat in the horizon of the layer itself. Grain size generally fines upward. Of the many types of layers, thin (approximately 10-cm) layers of massive orthopyroxene and plagioclase are distinctive. In hand sample, the plagioclase is not fine grained, as is generally seen, but is massive with interspersed massive clots of orthopyroxene. Local vertical pods of coarse, dark orthopyroxene are also evident, and they show an apparent cross-cutting relationship to the horizontal layers. Irregular in form, these pods are 2–3 m tall and up to 0.5 m wide.

The overall appearance of this layered sequence clearly represents a depositional sequence (as opposed to *in situ* crystallization) in a dynamic environment. The crystals involved in sorting, pyroxene and plagioclase, were carried by the invading magma. They did not grow after emplacement. That this layered body is near the inferred filling point of the Basement Sill itself (*see* Marsh and Philipp 1996), coupled with the juxtaposition of delicately sorted layers and scour and fill troughs, suggests local ponding of the infilling sill magma perhaps near the outer reaches of a periodically avalanching thick pile of crystals.

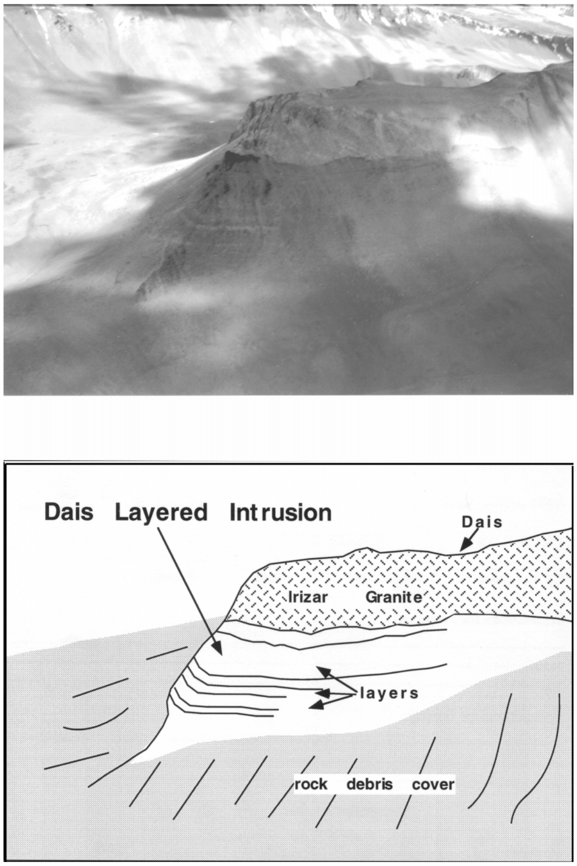

Figure 1. A photograph (*upper*) and a sketch copy (*lower*) of the Dais layered intrusion exposed in the cliffs of the east nose of the Dais of upper Wright Valley. The vertical thickness of the largest portion of the intrusion is about 200 m; a similar thickness is hidden by the debris cover. The intrusion is capped by the Irzar Granite, which is about 450 million years old.

The mechanism and efficiency of crystal sorting are clearly due to the great difference in size between the pyroxene (3–30-mm) and plagioclase (0.1–3-mm) crystals. Any slight concentration of pyroxene crystals functions as a sieve to the plagioclase crystals, allowing them to settle freely through the pyroxenes to form a layer of plagioclase. And pyroxene crystals isolated within a concentration of plagioclase settle due to their weight and size until encountering more pyroxenes. The natural tendency is to form layers of each mineral with the overall form of the layer reflecting its mode of deposition. The textures so formed are remarkably similar to those of the orthopyroxene/plagioclase rocks of the huge Stillwater layered intrusion of Montana. The principal differences

Figure 2. Anorthosite layers near the base of the exposed section of the Dais intrusion. The upper layer is about 35 cm thick and the lower one about 15 cm thick. John Philipp (left) and David Noe are resting on the upper layer.

are in the slightly larger size of the Stillwater plagioclase and the overall annealed form of the Stillwater textures. Both of these features are clearly due to the enormously longer cooling time (hundreds of thousands of years) of Stillwater, which allows for significant postdepositional recrystallization.

In summary, the presence of large concentrations of two minerals of disparate size and density in the Dais magma has unavoidably led to layering. The relatively short cooling time (approximately 1,000 years) of the Dais intrusion has preserved the original textures unusually well, making this body of perhaps singular importance to the study of layered intrusions.

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Global climate change and the paleoecology of echinoderm populations at Seymour Island, Antarctica

RICHARD B. ARONSON, *Dauphin Island Sea Lab, Dauphin Island, Alabama 36528*
DANIEL B. BLAKE, *Department of Geology, University of Illinois, Urbana, Illinois 61801*

The Phanerozoic history of marine benthic communities displays a strong environmental bias. New community types generally appeared in coastal environments and then spread to offshore habitats, replacing earlier community types along an onshore-offshore gradient (Bottjer and Jablonski 1988). During the Mesozoic, rapidly diversifying teleostean fishes and decapod crustaceans fundamentally changed community structure in shallow-water, soft-substratum habitats. The fossil record indicates that predators severely restricted or completely eliminated populations of epifaunal suspension-feeders living in those habitats (Vermeij 1987). Dense populations of ophiuroids and stalked crinoids had virtually disappeared from shallow water by the middle Cretaceous (Meyer and Macurda 1977; Oji 1985; Aronson 1992). Today, dense populations appear primarily (ophiuroids) or exclusively (stalked crinoids) in the deep sea, where predation pressure is lower than in most shallow-water environments (Gage and Tyler 1991). The predation-mediated restriction of epifaunal suspension-feeders was accompanied by a shift to infaunal, mollusk-dominated communities, which are characteristic of shallow-water, soft-substratum habitats in the Cenozoic (Sepkoski 1991).

In contrast to this general macroevolutionary trend, we discovered dense fossil populations of both ophiuroids and stalked crinoids in an upper Eocene, shallow-marine deposit at Seymour Island, 100 kilometers southeast of the tip of the Antarctic Peninsula (64°15'S 56°45'W). The La Meseta Formation on Seymour Island is a clastic deposit that probably represents a shallow submarine channel. Like most Cenozoic marine deposits that are fossiliferous, the La Meseta is rich in gastropod and bivalve shells (Stilwell and Zinsmeister 1992). Teleosts and decapods occur throughout the formation, and many of the mollusks bear antipredatory structural reinforcements suggesting intense predation pressure.

In December 1994, we located five dense assemblages of hundreds to thousands of ophiuroids (*Ophiura* n. sp.) and four assemblages of tens to hundreds of isocrinid (stalked) crinoids (*Metacrinus fossilis)* on Seymour Island. [Meyer and Oji (1993) and Blake and Aronson (in press–a and –b) describe the echinoderm fauna of the La Meseta Formation.] The dense ophiuroid assemblages covered a maximum area of 40 square meters and were no more than 10 centimeters thick. The crinoid assemblages were no thicker than a single layer of individuals. They were scattered over areas as large as 150 square meters, with dense concentrations covering 10–20 square meters. These autochthonous ophiuroid and crinoid assemblages appear to represent localized, short-lived populations. They were restricted to the uppermost of seven units of the La Meseta, and they were interbedded with the mollusk-rich horizons that dominate the formation.

The incidence of sublethal arm injuries can be used as a measure of predation pressure in ophiuroid and crinoid populations. For ophiuroids, sublethal damage is measured as the proportion of individuals regenerating one or more arms (Aronson 1991), and for crinoids it is measured as the proportion of regenerating brachitaxes (arm-branching series; Meyer and Oji 1993). Low incidences of sublethal damage to the ophiuroids and crinoids indicated that predation pressure was low in the Seymour Island populations (table).

The occurrence of dense ophiuroid and stalked crinoid populations in a late Eocene, shallow-water setting is anomalous. The stalked crinoids are particularly surprising, because they were supposedly driven out of shallow-water environments in the Mesozoic, tens of millions of years before La Meseta time. There was no obvious lithological or sedimentological reason for the abrupt occurrence of these ophiuroid- and crinoid-dominated horizons in the upper portion of the La Meseta Formation. Rather, it appears that changes in the physical environment in Antarctica created the ecological conditions that allowed the echinoderm populations to arise sporadically.

Summary of injury data on fossil populations of* Ophiura *n. sp. and* Metacrinus fossilis *from Seymour Island.

NOTE: The ophiuroid injuries are expressed as the percentage of individuals regenerating, and the crinoid injuries are expressed as the percentage of regenerating brachitaxes. Data are from Aronson, Blake, and Oji (1997).

Taxon	Number regenerating	Sample size	Percentage regenerating
Ophiura	3	243	1.23
Metacrinus	7	1,147	0.61

Global cooling accelerated in the late Eocene, particularly toward the end of La Meseta time (Mackensen and Ehrmann 1992). This long-term thermal trend was accompanied by increased upwelling in the southern oceans, including around the Antarctic Peninsula (Kennett and Warnke 1992; Diester-Haass and Zahn 1996). Upwelling would have increased nutrient availability, leading to increased productivity. Increased productivity would in turn have led to increased concentrations of particulate organic material, which would have provided a food source for the dense populations of suspension-feeding echinoderms. At the same time, declining temperatures probably disrupted predator-prey relationships between the echinoderms and the fish and crustaceans that ate them. The result was localized switching from a typically Cenozoic, high-predation, mollusk-dominated ecology to a more Paleozoic-type, low-predation, echinoderm-dominated community state.

Some components of the benthic fauna of Antarctica are taxonomically, functionally, and/or ecologically archaic (e.g., Dell 1972). The retrograde character of antarctic benthic communities may well have had its origin in the disruption of predator-prey interactions at the end of the Eocene. If this hypothesis is correct, then global climate change exerted the ultimate controlling influence on the distribution of species and the nature of trophic connections in Antarctica.

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