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Neogene glacial record from the Sirius Group of the Shackleton Glacier region, central Transantarctic Mountains, Antarctica

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ABSTRACT

Neogene glacigenic strata, collectively referred to as the Sirius Group, are widely distributed throughout the Transantarctic Mountains. The group is particularly well exposed near the head of Shackleton Glacier (85°10′ to 85°40′S) on Roberts Massif and at Bennett Platform. These deposits are critical for examining the nature of former ice flow from the East Antarctic Ice Sheet into the Ross Embayment. The Sirius Group rests on a glacially grooved and striated pavement named herein the "Shackleton erosion surface." The sub–Sirius Group surface on Roberts Massif was of low relief, and glaciogenic sediment was deposited on it as a sheet of uniform thickness. At Bennett Platform, stratigraphic sections attain a thickness of 110 m thick and are subdivided into the Shackleton Glacier Formation (maximum thickness 98 m) and the overlying Bennett Platform Formation (44 m), separated by an unconformity. A third, older, lithified diamictite containing wood fragments occurs as clasts within these formations and as boulders in the modern lateral moraines of Shackleton Glacier. The dominant facies, massive diamict, is interpreted primarily as lodgement till. Other facies indicate glaciofluvial and glaciolacustrine deposition. Facies associations suggest deposition either by sliding temperate or by polythermal glaciers, under much warmer conditions than those of today. Widespread large- and small-scale faulting has affected the Sirius Group and underlying rocks to the extent that inland exposures are over 500 m higher than those to the north, over a distance of 30 km. Thus, at the time of deposition of the Sirius Group, the mountains were probably lower, and the ice sheet was much thinner.

Keywords: Neogene, glacial record, Sirius Group, Antarctica, Shackleton Glacier, Transantarctic Mountains.

INTRODUCTION

Neogene glaciogenic deposits that are scattered throughout the Transantarctic Mountains and collectively known as the Sirius Group have been the subject of intense debate in connection with efforts to resolve the history of the East Antarctic Ice Sheet. Two somewhat polarized schools of thought have emerged. On the one hand, the so-called ''Stabilist'' school has argued that the Sirius Group deposits in the Dry Valleys of Victoria Land are relatively old and that the landscape in this region has remained stable at least since 14 Ma, i.e., since middle Miocene time (e.g., Marchant et al., 1993, 1996; Sugden et al., 1993; Sugden, 1996; Stroeven et al., 1998; Stroeven and Kleman, 1999). On the other hand, the ''Dynamicists'' have argued on the basis of data from the Beardmore Glacier region, ~800 km to the south, that the ice sheet, although it formed at least 35 m.y. ago (e.g., Hambrey and Barrett, 1993), was subject to major fluctuations until as recently as the Pliocene Epoch, 2.5 m.y. ago. These fluctuations are thought to have taken place under more temperate climatic and glacial regimes than those of the present day (e.g., Webb et al., 1984; McKelvey et al., 1991; Webb and Harwood, 1991; Wilson, 1995; Harwood and Webb, 1998).

Independent evidence for major fluctuations of the East Antarctic Ice Sheet until Pliocene time has also been presented from another part of the ice sheet, the Lambert Glacier and Prydz Bay region (Hambrey and McKelvey, 2000a, 2000b; McKelvey et al., 2001), far removed from the tectonic complications that confuse the debate in the Transantarctic Mountains. Each viewpoint is based on internally consistent evidence, but, as yet, the conflict concerning the timing of the switch from a dynamic, temperate glacial regime to a cold stable one remains unresolved.

In spite of all this discussion concerning the history of the East Antarctic Ice Sheet, few detailed sedimentological studies have been undertaken on the Sirius Group, yet such work is needed in order to determine the paleoenvironmental, topographic, and tectonic context of glaciation in the Neogene Period. This paper, although not addressing the age question directly, is intended as a contribution to the debate, by providing a rigorous sedimentological underpinning for one area that is critical for establishing past ice-sheet dynamics.

A series of major glaciers dissect the 4000-m-high Transantarctic Mountains and drain a large part of the East Antarctic Ice Sheet (Figs. 1A, 1B). These glaciers, including the Reedy, Scott, Amundsen, Shackleton, and

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Beardmore in the central Transantarctic Mountains, occupy major troughs. The glaciers currently flow into the basins of the West Antarctic rift system in the Ross Embayment, where they float and coalesce to form the Ross Ice Shelf. These glaciers, therefore, have provided conduits for sediment to be transported from the interior of Antarctica and the Transantarctic Mountains to the rift basins (Webb, 1994), where several hundred meters of glaciogenic sediment have accumulated (e.g., Cooper et al., 1991; Hambrey and Barrett, 1993; Barrett, 1996). A key question that remains unresolved, however, is the relationship between glaciation style and tectonic uplift.

Numerous localities of Sirius Group strata have been identified throughout the Transantarctic Mountains (Fig. 1B) (Denton et al., 1991; Webb and Harwood, 1991; Stroeven, 1997), especially along the flanks of the major troughs. These strata are important because they provide evidence of the nature and stability or instability of the East Antarctic Ice Sheet at a time when it fluctuated strongly, prior to the establishment of the present cold ice sheet, which is much less dynamic. Although Sirius Group strata (consisting mainly of diamicts) are superficially similar throughout the region, dating is limited, and it is likely that they are of wide-ranging ages. For this reason, it is necessary to undertake detailed sedimentological and paleontological investigations, linked to an understanding of tectonic evolution of the Transantarctic Mountains, at key sites. A number of these sites are located in the upper reaches of Shackleton Glacier, where ice from the Polar Plateau enters a major trough (Fig. 1C). Here, a record of glacial erosional and depositional processes is preserved, close to one of the positions where ice from the East Antarctic Ice Sheet spills out from the interior and flows toward the Ross Embayment. Although preserved on the flanks of the present Shackleton trough, the glacial deposits are not lateral moraines, but represent remnants of more extensive sedimentary successions.

The purpose of this paper is to present the results of extensive sedimentological investigations, including section logging, facies analysis, clast-fabric measurements to establish paleo–ice-flow directions, clast-shape analysis to determine modes of glacial transport, and lithologic analysis to determine provenance of the sediment. These data are combined with studies of sub–Sirius Group geomorphology and studies of the tectonic changes that have taken place since deposition of the group.

PREVIOUS INVESTIGATIONS IN THE SHACKLETON GLACIER AND ADJACENT REGIONS

Deposits of the Sirius Group have been known from the Shackleton Glacier region for more than 30 yr, although our field work has shown that it is more widely distributed than previously described; it includes spatially extensive deposits over much of the northern ‘‘lowlands’’ of Roberts Massif and occurs in additional sections along the flanks of the glacier (Fig. 1C). Initial observations of ‘‘ancient’’ glacial deposits were made during the course of exploratory geologic (McGregor, 1965) and pedologic (Claridge and Campbell, 1968) investigations. The first substantive investigations on the Sirius Group were made on Bennett Platform and Roberts Massif in the early 1970s (Mayewski, 1975; and Mayewski and Goldthwait, 1985). These authors recorded a generalized section and discovered a sub-Sirius glaciated pavement at these two locations, respectively. Mahaney (1995) undertook scanning-electron-microscope studies on Sirius Group ‘‘tills’’ from Roberts Massif and identified crushed and weathered quartz grains indicative of intense weathering from an earlier (assumed pre–early Miocene) interglacial. In addition, he found that the quartz grains possessed deep corrosion features typical of thick continental ice, unlike quartz grains modified beneath mountain glaciers ($<$500 m ice thickness).

Passchier (2001) used a range of techniques to evaluate the provenance of Sirius Group deposits throughout the Transantarctic Mountains (including Shackleton Glacier). She concluded that deposition of the Sirius Group took place as a result of glacial denudation of the Transantarctic Mountains over a long period, rather than during a single short phase.

Age determinations remain to be undertaken on the Sirius Group strata at Shackleton Glacier directly. Mayewski and Goldthwait (1985) surmised that, by comparison with the Dry Valleys, the age of the group exceeded 4.2 Ma. However, such an inference has been shown to be untenable, on grounds of both distance and different tectonic and uplift histories (Stroeven, 1997; Van der Wateren et al., 1999). The nearest dated successions comparable to the Sirius Group in the Shackleton Glacier region are those of the Dominion Range of the upper Beardmore Glacier region. These deposits have yielded both Pliocene and Miocene ages, although the ages are controversial.

Initial field results from the current project in the Shackleton Glacier region concerning stratigraphy and structural relationships were reported by Webb et al. (1996a, 1996b, 1996c). This paper does not purport to offer new evidence for the age of the Sirius Group, but it does provide evidence for style of glaciation, multiplicity of events, and subsequent tectonic events that should be taken into account in future assessments of Cenozoic climatic change.

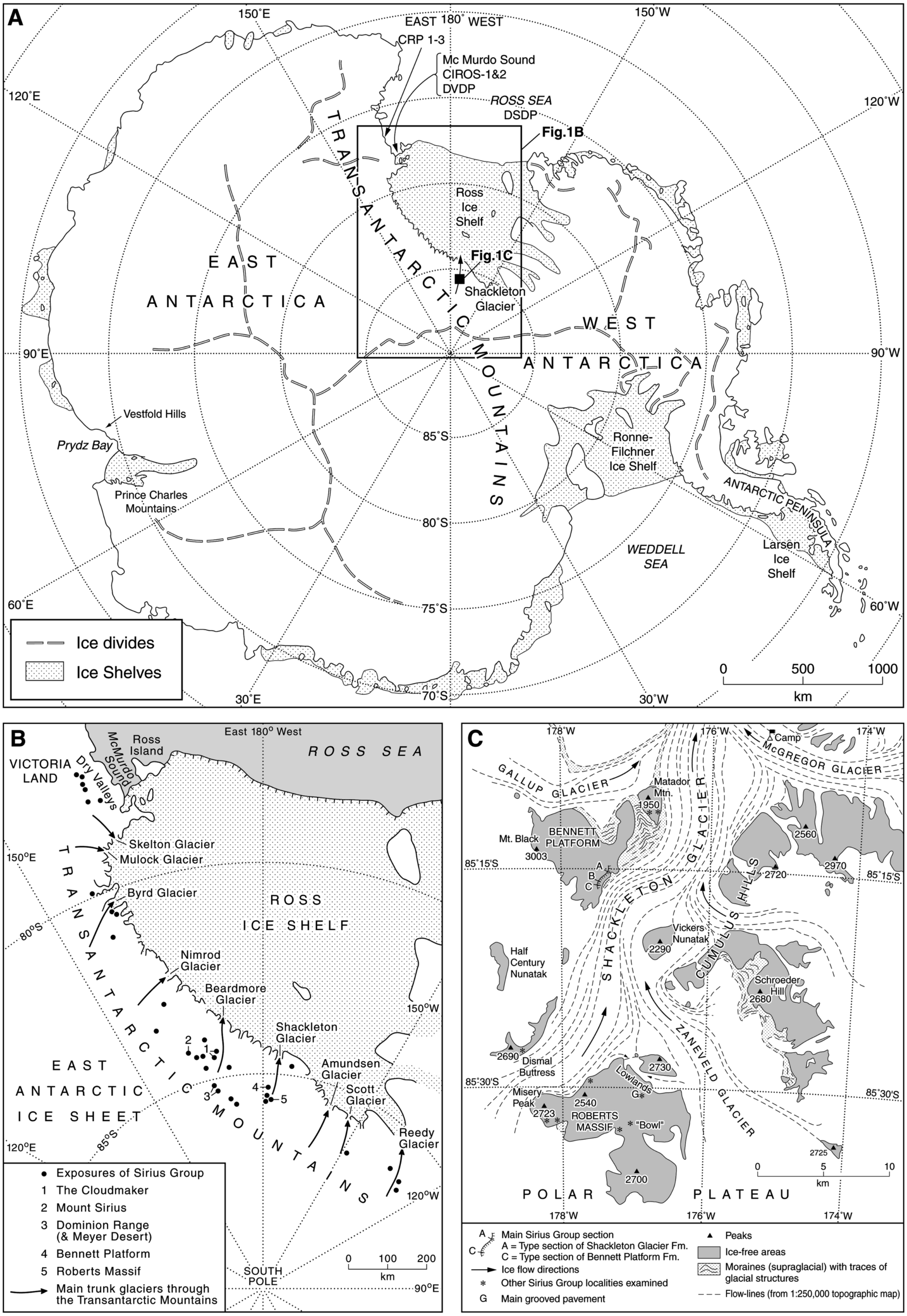
GEOGRAPHIC AND GEOLOGIC SETTING

The Transantarctic Mountains form the uplifted flank of the West Antarctic rift system, active throughout much of the Cenozoic Era (Fitzgerald et al., 1986; Behrendt and Cooper, 1991). The Transantarctic Mountains comprise a series of discrete structural blocks, bounded by faults, each with its own distinct Neogene history of glaciation and down-cutting (Van der Wateren et al., 1999). The Shackleton Glacier region lies within the Beardmore block which is thought to have remained at low elevation during the Miocene Epoch, whereas to the north, the Victoria Land block (including the well-studied Dry Valleys) was being uplifted. The uplift history of the Beardmore block is more recent and continued at least into late Neogene time (e.g., Mercer, 1972; Fitzgerald, 1994; Webb et al., 1996d).

Shackleton Glacier itself is a north-flowing trunk glacier, discharging ice from the East Antarctic Ice Sheet through the Transantarctic Mountains into the Ross Ice Shelf (Fig. 1B). It is ~130 km long and 7–11 km wide and descends from an elevation of ~2400 m to under 200 masl (meters above sea level). Field work was undertaken during the 1995–1996 season and focused on two relatively ice-free areas on either side of upper Shackleton Glacier—Roberts Massif and Bennett Platform (Fig. 1C).

Roberts Massif is a largely ice-free nunatak measuring ~10 by 10 km and characterized by considerable topographic relief ranging from 2723 masl at Misery Peak to ~2000 m. A relatively low area in the northern part of Roberts Massif is covered by several hundred square meters of diamict of the Sirius Group, which in places rests on a grooved, striated, and polished dolerite surface. Further exposures occur on the southern margin of the massif, just above the level of Polar Plateau ice and in a several-meter-thick section on the Shackleton Glacier flank of the massif. Each of these areas was investigated in some detail.

Bennett Platform lies on a similar-sized nunatak crowned by Mount Black (3003 masl), some 25 km downstream from the ice-


A
150°E
EAST 180° WEST
150°W
CRP 1-3
Mc Murdo Sound
CIROS-1&2
DVDP
ROSS SEA
DSDP
120°E
120°W
Fig.1B
TRANSANTARCTIC MOUNTAINS
Ross Ice Shelf
Fig.1C
Shackleton Glacier
EAST ANTARCTICA
WEST ANTARCTICA
90°E
90°W
85°S
Vestfold Hills
Prydz Bay
Ronne-Filchner Ice Shelf
Prince Charles Mountains
80°S
ANTARCTIC PENINSULA
WEDDELL SEA
Larsen Ice Shelf
60°E
75°S
60°W
Ice divides
Ice Shelves
0
500
1000
km
30°E
70°S
30°W
B
Ross Island
McMurdo Sound
East 180° West
ROSS SEA
VICTORIA LAND
Dry Valleys
Skelton Glacier
Mulock Glacier
150°E
TRANSANTARCTIC MOUNTAINS
Byrd Glacier
ROSS ICE SHELF
80°S
Nimrod Glacier
Beardmore Glacier
150°W
Shackleton Glacier
EAST ANTARCTIC ICE SHEET
Amundsen Glacier
Scott Glacier
Reedy Glacier
1
2
3
4
5
120°E
85°S
120°W
Exposures of Sirius Group
1 The Cloudmaker
2 Mount Sirius
3 Dominion Range (& Meyer Desert)
4 Bennett Platform
5 Roberts Massif
Main trunk glaciers through the Transantarctic Mountains
SOUTH POLE
0
100
200
km
90°E
C
178°W
176°W
174°W
Camp
McGREGOR GLACIER
GALLUP GLACIER
Matador Mtn.
1950
Mt. Black
3003
BENNETT PLATFORM
2560
85°15'S
A
B
C
2720
2970
85°15'S
SHACKLETON GLACIER
CUMULUS HILLS
Vickers Nunatak
2290
Half Century Nunatak
Schroeder Hill
2680
2690
Dismal Buttress
ZANEVELD GLACIER
2730
85°30'S
Lowlands
G
85°30'S
Misery Peak
2723
2540
ROBERTS MASSIF
"Bowl"
2700
2725
0
5
10
km
POLAR PLATEAU
178°W
176°W
174°W
Main Sirius Group section
A = Type section of Shackleton Glacier Fm.
C = Type section of Bennett Platform Fm.
Ice flow directions
Other Sirius Group localities examined
Main grooved pavement
Peaks
Ice-free areas
Moraines (supraglacial) with traces of glacial structures
Flow-lines (from 1:250,000 topographic map)

sheet edge, on the western flank of Shackleton Glacier. Bennett Platform is an extensive area of undulating upland, and its eastern flank, overlooking Shackleton Glacier, consists of a near-vertical cliff of diamict resting on the eroded top of a dolerite sill; the top of the cliff is ~150 m above the glacier surface, which here lies at 1820 masl. This cliff provides the reference section for Sirius Group stratigraphy in this region, and several measured vertical profiles of varying detail are presented from this locality.

Two additional small exposures were examined briefly: Dismal Buttress opposite Roberts Massif and Matador Mountain, just north of Bennett Platform. Although small patches of Sirius Group were observed at Half Century Nunatak, Schroeder Hill, and Landry Bluff (Cumulus Hills) (Fig. 1C), no additional sections were observed, despite an aerial survey covering ~1750 km^2, and extending as far east as Amundsen Glacier (Fig. 1B) (Webb et al., 1996a).

The stratigraphic succession underlying the Sirius Group in the upper Shackleton Glacier region is represented by sills of Jurassic Ferrar Dolerite intruded into Triassic sandstones of the Beacon Supergroup. The strata are approximately flat-lying but are heavily faulted; fault blocks stand up as mesas or form dry depressions and small rift basins. Some faults also dislocate the Sirius Group.

The greater part of the Sirius Group was probably stripped off by major late Pliocene–Quaternary ice expansions and redeposited in the Ross Embayment. The evidence for this expansion is indicated (1) on Roberts Massif by glacially abraded upper surfaces on the Sirius Group (including diamict scarred by chattermarks), and (2) by the truncation of the sections flanking Shackleton Glacier.

The Quaternary record is limited to a suite of closely spaced moraines, no more than a few meters high, best developed on Roberts Massif. The angular and coarse nature of this debris, which was probably deposited by cold ice, contrasts markedly with Sirius Group lithofacies. The contemporary weathering style of the Sirius Group in the Shackleton Glacier area is different from that in the Dry Valleys. Meltwater from snow banks causes sapping of the diamict matrix at the base of cliffs, resulting in undermining and minor collapses of the cliffs. Meltwater also produces rills a few centimeters in width on steep slopes of Sirius Group outcrops and resedimentation of the matrix in lobes a few meters wide. Sirius Group diamict exposed to wind action shows a characteristic weathering style: pedestals of diamict with perched boulders.

METHODS

The methods utilized in this investigation included measurement of stratigraphic sections, documentation and interpretation of lithofacies, inspection of sub–Sirius Group erosion surfaces and recording features associated with faulting.

Stratigraphy

Stratigraphic sections were measured on a meter scale through the Sirius Group at several locations by using a tape, their positions being fixed with a Garmin GPS instrument. Sections were followed upward or downward in stepwise fashion at the foot of cliffs, rather than taking a vertical line through the cliffs. However, at one locality at Bennett Platform (southern end of cliffs), access to the section was only possible by roped descent down a gully that split the cliff face. A number of intervals, where vertical facies changes are rapid, were measured at the centimeter scale.

Facies Analysis

Lithologic logging was accompanied by detailed facies analysis, coupled with assessment of lateral changes where possible, clast-fabric determinations, clast-shape analysis, examination of surface features on clasts, and identification of clast lithology. All of these studies are needed to determine the mode of sedimentation and gain some idea of the thermal regime of the associated ice masses.

Clast shapes were determined with the Powers roundness method (Powers, 1953) for numerous sets of 50 clasts, representing most facies containing gravel, but these data are only summarized here. Shape analyses are grouped according to facies. Two-dimensional horizontal clast-fabric measurements were made (1) in the vertical measured sections and (2) in many areas where Sirius Group sediment was exposed on flat or gently inclined surfaces; the results were plotted on rose diagrams. Fifty clasts with axial ratios in excess of 1.5:1 were selected randomly at each site. In order to assess whether apparent preferred orientations were statistically significant, the χ^2 test was applied (cf. Hambrey, 1989). These data were used to determine the ice-flow directional signature, as well as gain some insight into the depositional process. These data have been reinforced by measurements of three-dimensional fabrics of the long axes of 50 elongate clasts at several sites, mainly in the vertical sections at Bennett Platform. These data were plotted on lower-hemisphere Schmidt equal-area stereographic projections, and their eigenvalues were calculated, allowing better discrimination of the mode of deposition of the sediment through comparison with results from known environments. Fabric data alone cannot be regarded as a reliable indicator of depositional process in glacial environments (Bennett et al., 1999a). However, they can help reinforce interpretations and, in appropriate lithofacies, provide a good indication of ice-flow direction.

Documentation of Sub–Sirius Group Surfaces

Sub-diamict surfaces, especially those of Ferrar Group dolerite, were examined, both on the ground and in aerial photographs, for signs of glacial grooving and striations, pre-Sirius Group weathering, and post-Sirius faulting. Clast-fabric analysis was undertaken in diamict directly above the erosion surfaces in order to determine whether deposition immediately postdated erosion.

Evaluation of Faulting

Normal faulting of the Sirius Group and underlying bedrock was widely recognized during the field program and was seen on aerial photographs available subsequently. Displacements of a few meters to several tens of meters were readily identified. The style of faulting and associated modification of the Sirius Group was documented, especially the relationship between ice-flow directional indicators and fault blocks. However, in the absence of detailed and accurate topographic maps, precise spatial relationships of faults could not be determined.

Figure 1. Location maps of (A) Shackleton Glacier in relation to the East and West Antarctic Ice Sheets; (B) the Transantarctic Mountains, showing Sirius Group outcrops (after Denton et al., 1991); (C) upper Shackleton Glacier area, showing location of sections A–C measured and other sites (asterisks) investigated. Ice-flow directions are indicated.

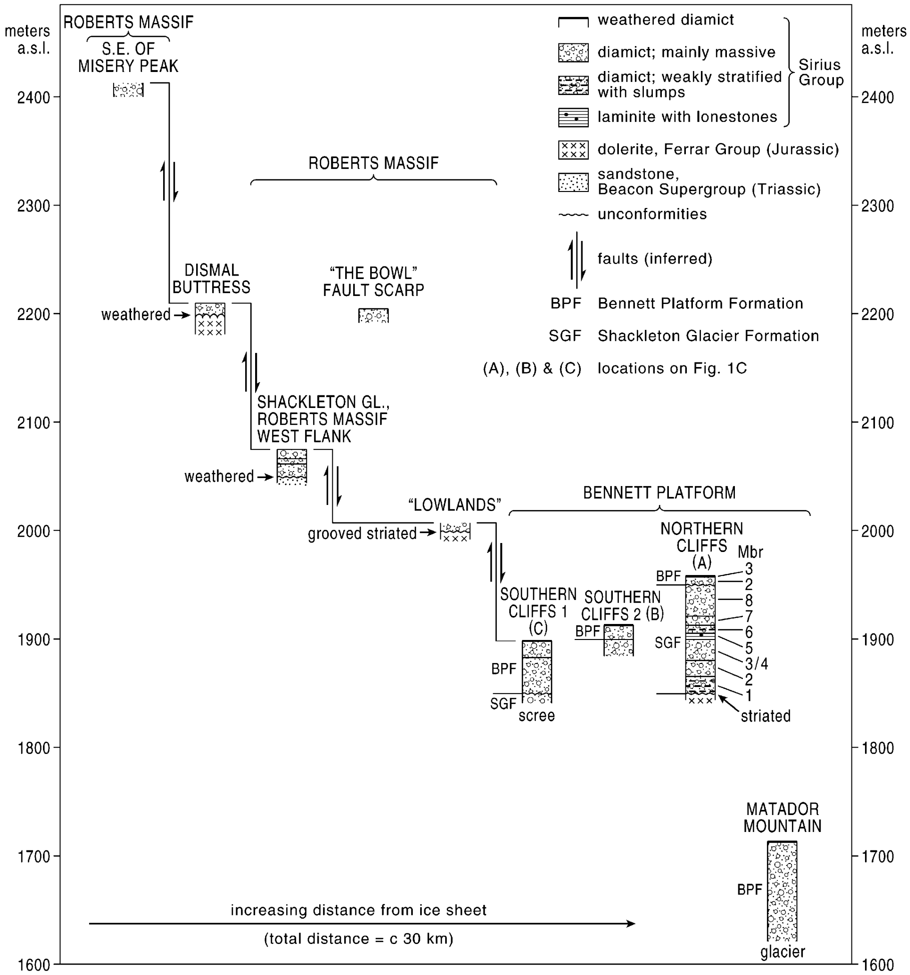


Figure 2. Generalized relationships between stratigraphic sections investigated in the Shackleton Glacier area and height above sea level. See Figure 1C for location of sections. Normal faults are inferred from field observations of topography and aerial photography.

STRATIGRAPHY OF SIRIUS GROUP

The stratigraphy of the Sirius Group in the upper Shackleton Glacier region and the group's relationship with elevation and the underlying Ferrar Group dolerite and Beacon Supergroup is summarized in Figure 2. The formal definition of the stratigraphy is based on logged sections at Bennett Platform. Two formations are defined: the lowermost one is named the ''Shackleton Glacier Formation'' after the adjacent glacier (Fig. 3A), and the uppermost one is named the ''Bennett Platform Formation'' after the bench that forms its upper surface (Fig. 3B). Both formations are dominated by diamicts that are typically highly indurated (but not lithified), poorly sorted sediment. Therefore, they are transitional between rocks (diamictite) and soft sediment (diamicton), and so the all-embracing term ''diamict'' (Harland et al., 1966) is used in this paper. An older lithified outcrop of diamictite evidently exists up-glacier, either below the ice sheet or beneath the surface of upper Shackleton Glacier. This unit is represented both in subglacially derived boulders along the east and west flanks of the glacier and in clasts *within* Bennett Platform and Shackleton Glacier Formations.

Erosion Surfaces

Where exposed, the base of the Sirius Group rests mainly on Ferrar Group dolerite sills that are typically 50–200 m thick. This relationship is probably a function of not only the dominance of dolerite in the area, but also the much greater resistance it offers to glacial erosion in comparison with the sandstone of the Beacon Supergroup into which it is intruded. In terms of weathering, two main types of dolerite exist: a resistant, fine-grained, reddish-brown variety and a grayish-green coarse-grained variety that is deeply weathered and friable.

Glacially abraded surfaces are associated with the fine-grained dolerite and are especially well developed in the northern lowlands of Roberts Massif (Fig. 4) (Webb et al., 1996b). Here, an area of some 25 km^2 of pavement has been partially exhumed, providing one of the most extensive glacially eroded paleosurfaces yet found in Antarctica (Fig. 4A). We refer to this as the ''Shackleton erosion surface.'' Although extensively weathered along irregular sets of vertical joints, the surface preserves a uniform pattern of grooves with amplitudes of 2–3 m and wavelengths of 5–10 m (Fig. 4B). Freshly exposed surfaces are preserved adjacent to and beneath remnant patches of Sirius Group sediment. These bear fine-scale features of glacial abrasion, such as polish and striae (Fig. 4C), and of rock fracture including crescentic gouges and rare friction cracks. Both the grooves and dominant striae indicate northward flow, matching approximately the preferred orientation of clast fabric in the overlying diamicts. However, there are also finer striae trending westward, although these are probably associated with local Quaternary ice, as they can also be linked to chattermarks imprinted *on top* of indurated diamict matrix of the Sirius Group in the vicinity. The Shackleton erosion surface is disrupted by faults (Fig. 4A), as are Sirius Group strata. Displacements across the faults range from 2 to >100 m.

Fresh-looking striations on flat to gently inclined fine-grained dolerite surfaces are also present at the Bennett Platform, where small areas are exposed below the diamict successions of both formations. It is thus likely that the Shackleton erosion surface in some places is the product of a number of glacial erosional events. These striations also suggest a paleo–ice-flow direction that varies from north to northeast, whereas the modern Shackleton Glacier at this point has an east-northeast flow direction. There is no clear relationship with clast fabric in the basal diamicts at Bennett Platform, although stratigraphically higher diamicts do show a matching trend.

Where Sirius Group diamicts rest on the coarse-grained variety of dolerite, as in parts of the northern lowlands of Roberts Massif (near the ''Bowl''; Fig. 1C) and at Dismal Buttress, the rock is deeply weathered, and no abrasion features are observable. Indeed, at Dismal Buttress, relatively sound rock, weathered along vertical joints, passes upward into fractured and weathered bedrock, in part disaggregated into its constituent grains to give an incipient mineral soil. Finally, the weathered bedrock passes up transitionally into diamict.

Locally, Beacon Supergroup surfaces are capped by Sirius Group diamicts, but the actual contact was observed only on the Shackleton Glacier flank of Roberts Massif. Here, the rock is deeply weathered and fragmented, and no abrasion surfaces are evident. In the northern lowlands, weathered joints in sandstone bedrock contain clastic dikes of diamict that were injected from above during deposition of the Sirius Group. These dikes remained in the sandstone even after removal of the Sirius Group during the Pleistocene Epoch.

Shackleton Glacier Formation (96–100 m; 85.258°S, 177.401°W)

The Shackleton Glacier Formation is best exposed in unstable cliffs of diamict resting on dolerite that mark the southeastern edge of Bennett Platform. The stratigraphy is disrupted in several places by blocks that have undergone rotational failure and collapse. The formation is defined at the northern limit of the cliffs (section A in Fig. 1C). The formation is divided into eight informal members (Fig. 5). It is dominated by diamict, but there are also thin gravel horizons, breccia beds, and, in the middle of the section, a laminite-dominated member with dispersed clasts. Member 1, at the base, is not well exposed near the main section, but can be seen in a near-complete slumped block directly below the main section, a short distance above glacier level. Here, as elsewhere, member 1 rests directly on fine-grained striated dolerite of several meters relief. Member 8 at the top is either only patchily exposed or too difficult of access, although its composition can clearly be seen in the upper cliffs. The diamict and minor laminite in the glacier-flank section at Roberts Massif bear the strongest similarity to the Shackleton Glacier Formation, suggesting that they may correlate across the glacier.

Nature of Boundary Between Formations

The boundary between the Shackleton Glacier Formation and Bennett Platform Formation at Bennett Platform is an unconformity of several tens of meters relief. Although at the scale of individual exposures, diamicts above and below make differentiation difficult, the differences become apparent when viewed from a distance. The unconformity lies within a few meters of the top of the cliffs at their northern end (Fig. 5), whereas in the lower southern cliffs, it truncates several members

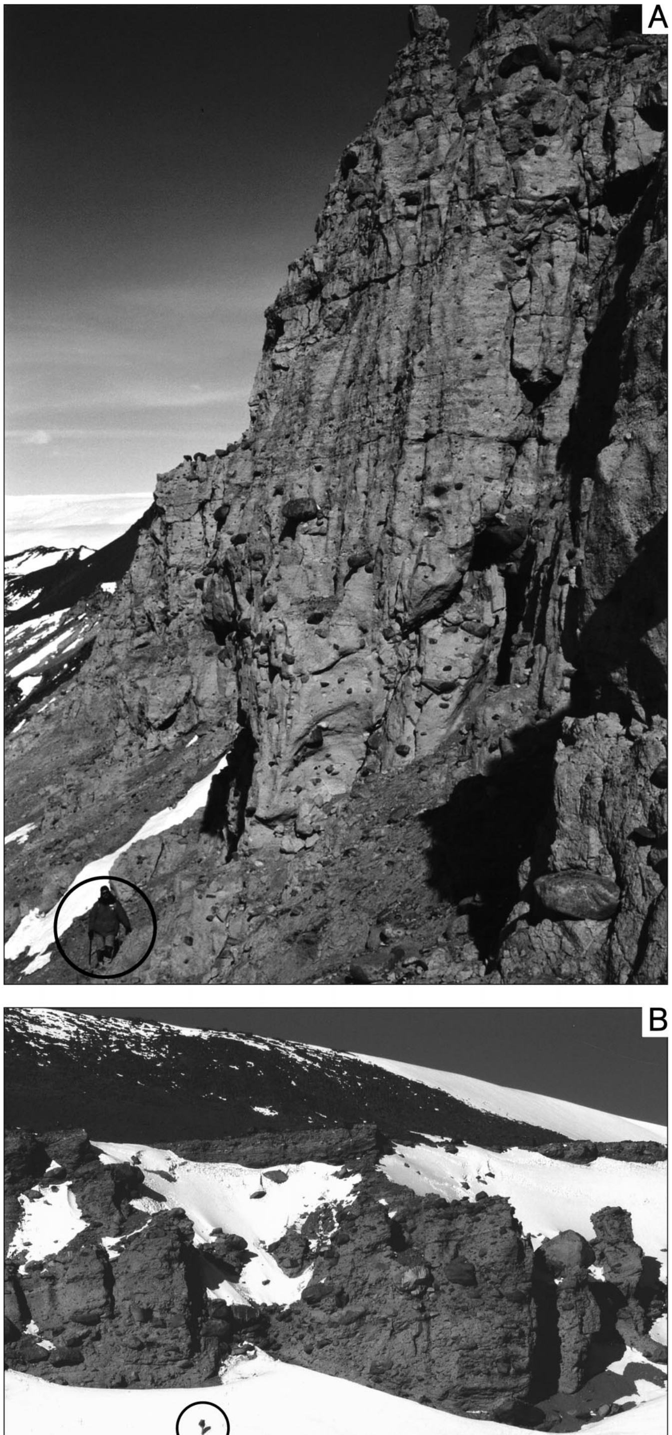


Figure 3. Key stratigraphic sections at Bennett Platform. (A) The middle and upper parts of the Shackleton Glacier Formation, comprising massive and weakly stratified diamicts. (B) Bennett Platform Formation, comprising massive diamict with exceptionally large boulders. Note the person for scale (ringed) in both cases.

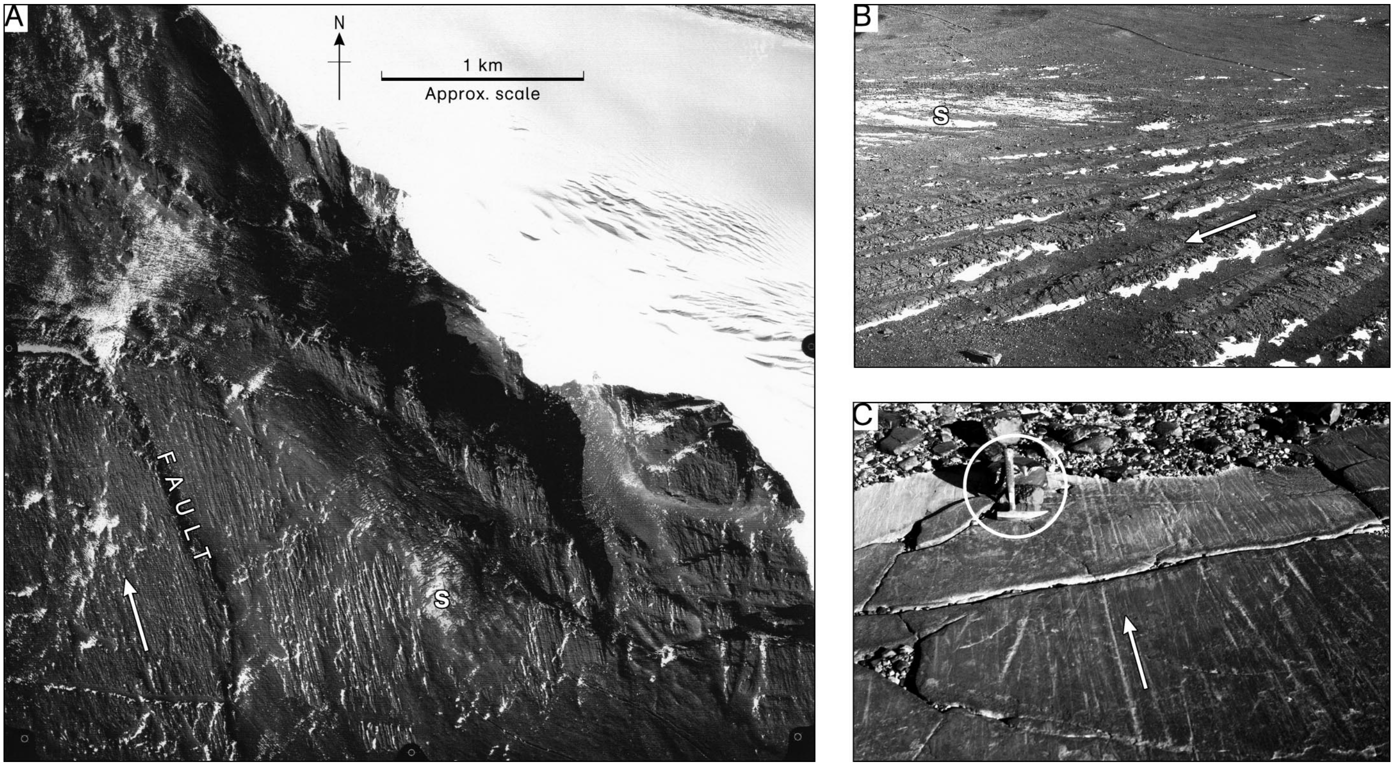


Figure 4. Sub–Sirius Group erosion surface at Roberts Massif adjacent to the unnamed branch of Zaneveld Glacier. (A) Vertical aerial view illustrating prominent south to north grooving, intersected by faults. The light patch marked "S" is Sirius Group diamict resting directly on the erosion surface. Darker diffuse areas are of Quaternary drift. Photograph by U.S. Geological Survey. (B) Oblique aerial view of grooves in jointed dolerite (amplitude of grooves is a few meters) and the overlying Sirius Group marked "S." Ice-flow direction indicated by arrow. (C) Polished and striated dolerite surface associated with grooving; wind-deflated Sirius Group is at top of picture. Ice-flow direction indicated by arrow; hammer (ringed) for scale.

of the Shackleton Glacier Formation to below the level of the cliffs and down to the level of the dolerite. In the adjacent nunatak to the north, Matador Mountain, the unconformity below Bennett Platform Formation is largely obscured by loose debris from above.

Bennett Platform Formation (44 m; 85.279°S, 177.502°W)

Named after the elevated platform bordering the Sirius Group cliffs on the west side of Shackleton Glacier, Bennett Platform Formation is best exposed in the lower, strongly gullied cliffs to the south of the main cliffs (section C in Fig. 1C). The type section (Fig. 6) designated is the thickest part of the succession visible in these lower cliffs and was measured along the northern flanks of a narrow ice-filled gully. Here, the formation is 44 m thick and rests unconformably on member 6 of the Shackleton Glacier Formation (Fig. 6), identified by tracing it through the cliff from the measured section just described. Bennett Platform Formation is also dominated by diamict, but is distinguishable in having much larger boulders of dolerite (several meters across) and a unique style of weathering, which produces pedestal-like forms with boulders perched precariously on thin columns of diamict. Three members are distinguished: member 1, at the base, consists of a few thick beds of diamict with erosional contacts between them; member 2 is a much more variable unit, with coarse, angular boulder beds alternating with diamict; and member 3 represents a lag deposit from wind deflation of member 2. Member 1 and the lower part of member 2 pinch out northward, leaving only 6 m of interbedded gravels, sand, and diamict just below the lag deposit at the top of the main cliffs. Elsewhere, similar facies are present at Matador Mountain and Dismal Buttress (Fig. 7), and correlation between Bennett Platform Formation and these other sites is suggested.

Upper Surface of the Sirius Group

One or more later glacial events have stripped away most of the Sirius Group, leaving truncated remnants only in topographic hollows and on the flanks of Shackleton Glacier. There is little indication of the age of the subaerially exposed surface of the Sirius Group, but it has been modified by three important processes: (1) the development of polar soils (Campbell and Claridge, 1987) with concentrations of salts and accompanied by salt weathering of clasts; (2) deflation by wind, leaving concentrations of boulders characterized by deeply pitted and polished surfaces; and (3) minor reworking of the surface and deposition of angular blocks by cold-based ice, in places forming distinctive moraine ridges up to a few meters in height.

Erratics from Older Glaciogenic Strata

In lateral moraines along the flanks of Shackleton Glacier and the unnamed branch of Zaneveld Glacier are boulders of diamictite, sandstone, and conglomerate that are truly lithified, unlike the two formations just described. Because these boulders comprise facies that reveal evidence of glaciation, such as striated clasts, they are assigned provisionally to the Sirius Group, although the precise

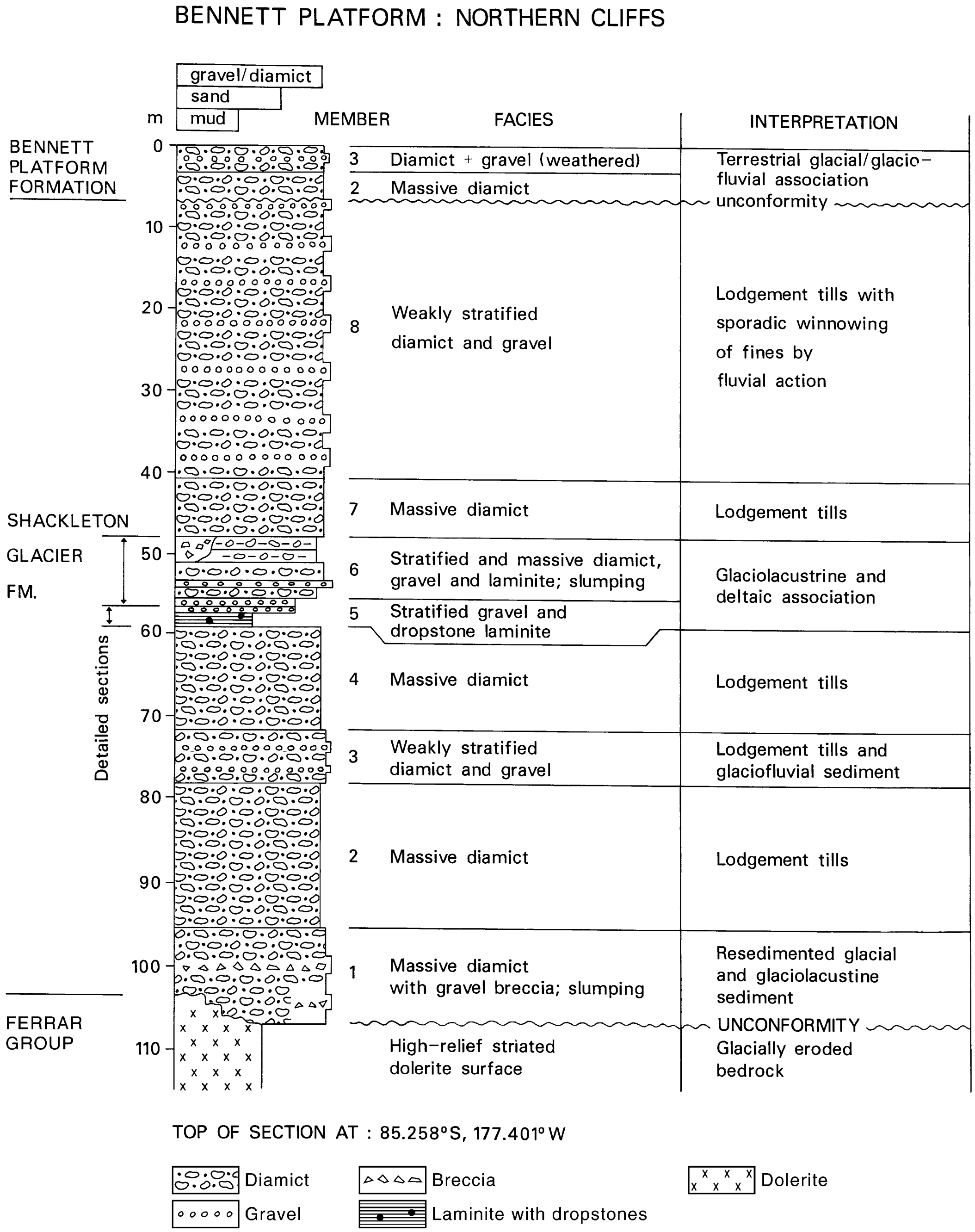


Figure 5. Measured section showing stratigraphy, facies, and interpretation of the Shackleton Glacier Formation at its type section, which lies at the northernmost end of Bennett Platform cliffs (location A in Fig. 1C). Note that member 1 of the overlying Bennett Platform Formation is missing at this locality.

stratigraphic context is unknown. Partially silicified wood fragments were observed in one diamictite boulder. A boulder containing well-sorted conglomerate consists predominately of Ferrar dolerite clasts, indicating a post-Jurassic age, and subordinate Beacon Supergroup clasts. There is no sign of high-grade metamorphic basement clasts, except possibly splintered quartz grains (B.C. McKelvey, 2000, personal commun.). The high degree of lithification of the boulders suggests that they are considerably older than the exposed sections of Sirius Group described herein and were probably derived from below glacier level. Similar lithified clasts of diamictite have been noted by two of the authors (Webb and Harwood) in the Dominion Range (upper Beardmore Glacier), in moraine of Mill Glacier near Plunket Point, and in the Meyer Desert. Because 150 km or more separates these occurrences, it is evident that the source of these diamictite clasts may be widespread on the inland flanks of the Transantarctic Mountains.

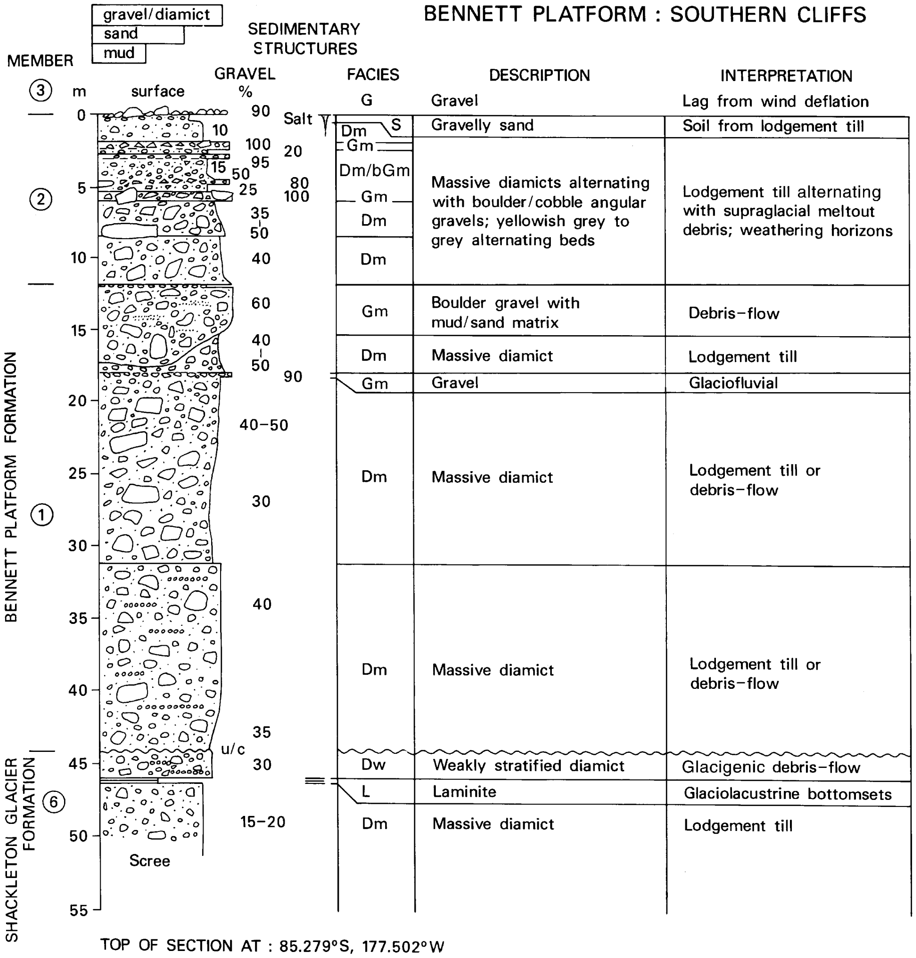


Figure 6. Measured section showing stratigraphy, facies, and interpretation of Bennett Platform Formation at type section (see location C in Fig. 1C for location and Table 1 for facies abbreviations; u/c—unconformity).

FACIES ANALYSIS

Description of Lithofacies

Eleven lithofacies have been identified (some of which are divided into several subfacies) from four measured sections with a cumulative thickness of 250 m (Table 1). The principal characteristics of these 11 facies, with their subfacies, together with their interpretations, are given both in Table 2 and in three lithologic logs (Figs. 5, 6, 7). Clast-fabric data are presented in two forms: as two-dimensional rose diagrams (Fig. 8) and as three-dimensional lower-hemisphere Schmidt equal-area projections (Fig. 9).

Massive diamict (abbreviated lithofacies Dm in Tables 1 and 2 and Figs. 6 and 7) is the dominant lithofacies, representing 57% of the total logged section in the Shackleton Glacier Formation and 75% in Bennett Platform Formation. Massive diamict also represents, in terms of area, the most extensive lithofacies on Roberts Massif (Fig. 10A). Here, the diamict fractures along subhorizontal surfaces that commonly bear slickensides, oriented approximately parallel to the clasts. Typically, massive diamict has a pale gray muddy sand matrix and boulders commonly up to 1 m in diameter in the Shackleton Glacier Formation and up to 5 m in Bennett Platform Formation. Texturally, most diamicts are the clast-rich sandy variety according to the classification of Moncrieff (1989; modified by Hambrey, 1994).

Weakly stratified diamict (lithofacies Dw), with bedding on the meter-plus scale, defined by thin concentrations of gravel or a few siltstone laminae, makes up over 25% of the Shackleton Glacier Formation and is gradational with massive diamict (Fig. 10B). Also gradational with massive diamict are muddy *cobble* and *boulder gravels* in Bennett Platform Formation, forming 19% of the measured strata (Fig. 10C). The matrix appears similar; only the proportion of gravel clasts varies.

Both types of diamict and the massive boulder gravel contain clasts, which range in shape from very angular to rounded, with subangular and subrounded varieties predominating. Clasts are mainly of dolerite; many are polished and have striations and faceted surfaces. Some boulders, exposed on relatively flat surfaces, show streamlined characteristics, such as bullet-nosed shapes (Fig. 10D), with striations bending around the boulder in the direction of flow (as determined from fabrics and the underlying grooved bedrock). Nearly all of these diamicts possess a strong preferred orientation fabric, observable even to the naked eye. χ^2 values are exceptionally high—many exceed 15, which is the value above which preferred orientations are significant at the 0.01 level (Fig. 8). Similarly, for three-dimensional fabrics, eigenvalues are also high and plot clearly within the lodgement till field of Dowdeswell et al. (1985) (Figs. 9, 10A). There is a high level of consistency in the preferred orientations, despite the complex topography on which the Sirius Group now lies. Fabric data over Roberts Massif show a swinging ice-flow trend ranging from southwest to northeast in the south, adjacent to the ice sheet, to one of south-north orientation over the northern lowlands. At Bennett Platform, orientations are invariably south to north and southwest to northeast. A few beds in the Shackleton Glacier Formation (massive diamict type 2) and Bennett Platform Formation (massive muddy gravel type 1) show more diffuse fabrics and contain intraclasts of laminite.

The remaining lithofacies are better sorted. There is a variety of *massive gravel* (lithofacies Gm) with a sandy rather than a muddy matrix in the sections at Bennett Platform, although these amount only to a few percent of the total strata. In member 2 of Bennett Platform Formation, massive gravel includes beds of unweathered, very angular, angular, and subangular boulders, cobbles, and pebbles (Fig. 10E); highly weathered, angular boulders; sandy pebble/cobble beds with mainly subrounded clasts; and in member 3, on the present-day land surface, concentrations of heavily pitted, polished, and disintegrated gravel of all sizes with interspersed sand (lithofacies bGm, Gm; massive gravel types 2–7, Table 2). At Dismal Buttress, Bennett Platform Formation contains massive pods and horizons of massive angular gravel within a reddish iron-stained matrix (Fig. 7).

Weakly stratified pebble/cobble gravels (lithofacies Gw) are found primarily in the Shackleton Glacier Formation (8% of measured section), with less than 1% in Bennett Platform Formation. Both pebble and cobble gravels are present that tend to form interbeds tens of centimeters thick in massive or weakly stratified diamict units, and their clasts are mainly subrounded and subangular. In Bennett Platform Formation (members 2 and 3), reddish iron staining and thin iron-pan horizons are associated with the gravels (Fig. 11).

Well-stratified to poorly stratified gravel (lithofacies Gs, Gw) forms one major and a number of thin beds in members 3, 5, and 8) of the Shackleton Glacier Formation (1% of section) (Fig. 10F). The thicker bed (member 5b, Fig. 12) comprises pebble/cobble gravel with sandy matrix and subrounded and subangular clasts: internally, the bedding dips as much as 5° relative to adjacent beds, which are horizontal.

A number of *breccia* (lithofacies B) beds occur near the base of the Shackleton Glacier Formation and represent 5% of the measured sections. The clasts are mainly angular and include both bedrock (dolerite) and intraformational (laminite) clasts; the matrix is diamict-like, and the lithofacies is transitional with diamict (Dm) type 2 lithofacies.

Minor amounts of *sand* and *sandstone* (lithofacies S) are present in thin nonstratified beds, lenses, or wedge-like features. Small pebbles may be present, and yellow staining is evident in some beds.

Fine-grained lithofacies occur only in the middle of the Shackleton Glacier Formation (member 5a, Fig. 13). Of these, *laminite* (lithofacies L) is most abundant (nearly 2% of section) and consists of millimeter- or submillimeter-scale couplets of sand and silt or of sand and mud. The laminite contains outsized clasts up to boulder-size that deform the laminae (Fig. 10G). In places, pebble-sized clasts of diamict are abundant (Fig. 10H). The laminite is interbedded with centimeter-scale, internally structureless diamict and gravel beds. A variety of soft-sediment deformation structures are also present, including convolute lamination, slump folds, and microfaults (Fig. 10I). Another fine-grained lithofacies is dark gray *mud* (in contrast to the light gray color, which is characteristic of all other lithofacies), but is only a few centimeters thick.

At the top of the Sirius Group, especially at Bennett Platform, the surface layers, comprising mixed gravel and diamict, contain undifferentiated salt. The salt ranges from small flecks to sandy silt-wedge–like forms and layers, a few tens of centimeters below the surface.

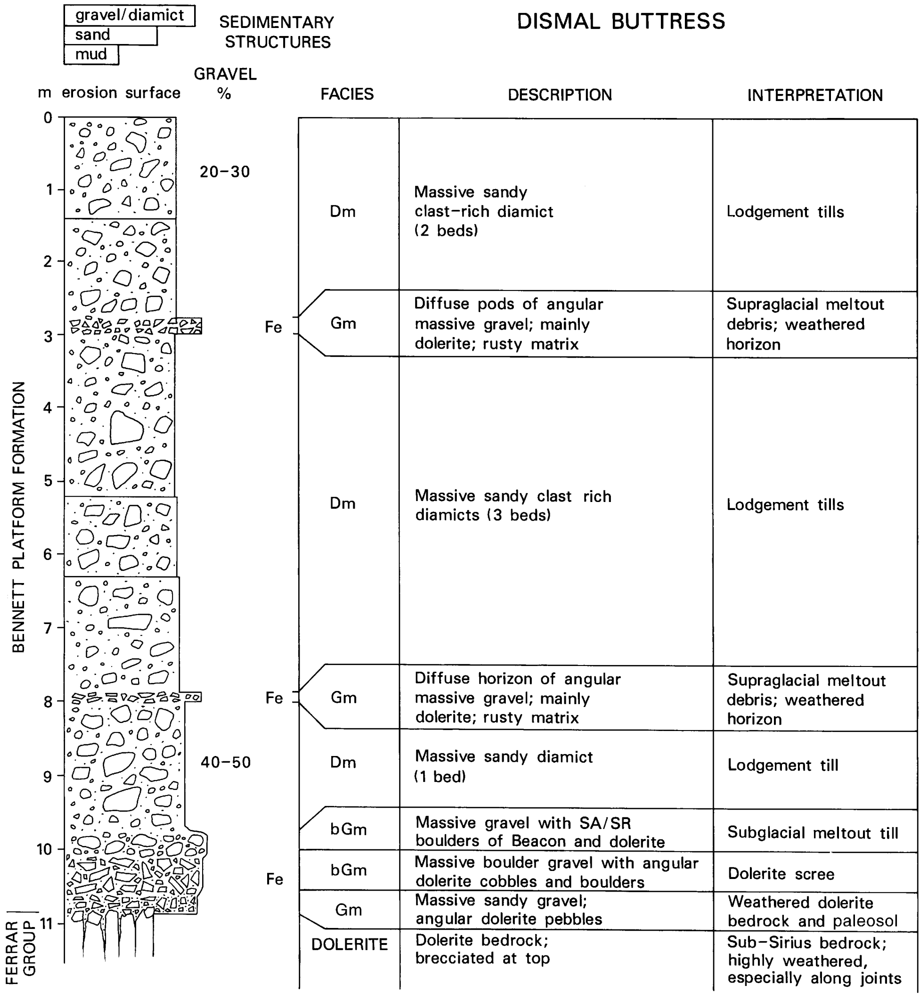


Figure 7. Measured section showing stratigraphy, facies, and interpretation of part of the Sirius Group at Dismal Buttress (see Fig. 1C for location and Table 1 for facies abbreviations; SA/SR—subangular/subrounded).

TABLE 1. SUMMARY OF LITHOFACIES DOCUMENTED IN FOUR MEASURED SECTIONS

Lithofacies	Shackleton Glacier Formation		Bennett Platform Formation	
	Thickness (m)	Thickness (%)	Thickness (m)	Thickness (%)
Massive diamict (Dm)	99.3	57.3	62.9	74.6
Weakly stratified diamict (Dw)	44.3	25.6	0.3	0.4
Massive muddy gravel (boulder-rich) (bGm)			16.1	19.1
Massive gravel (Gm)	0.4	0.2	3.4	4.0
Weakly stratified gravel (Gw)	14.3	8.3	0.7	0.8
Well-stratified gravel (Gs)	2.0	1.2		
Breccia (B)	9.1	5.3		
Sandstone/sand (S)	0.5	0.3	0.6	0.7
Laminite (L)	3.1	1.8		
Mud (M)	trace			
Salt			0.3	0.4
Totals	173.0	100	84.3	100

Note: (not all shown in figures): type section through Shackleton Glacier Formation and overlying Bennett Platform Formation, fault-block section through lower Shackleton Glacier Formation, and two sections through Bennett Platform Formation (including type section). Other sections are not included as correlation is not certain.

Lateral Continuity of Facies

In the main section at Bennett Platform, the members of each formation are laterally continuous for several hundred meters. Within each member, individual lithofacies exhibit variability. Diamict beds may be traced for several hundred meters, as may cross-stratified associations of gravel, sand, and laminite. Most lithofacies contacts are sharp, although truncation of beds is uncommon. Exceptions occur within members 5 and 6 of the Shackleton Glacier Formation, in which thin diamict beds truncate underlying laminite. At the formational level, Bennett Platform Formation cuts out members 6–8 of the Shackleton Glacier Formation along a major erosional unconformity.

Elsewhere, exposures are scattered and lack laterally continuous sections. However, on lower Roberts Massif, massive diamicts crop out in extensive flat and undulating surfaces. Here, the diamicts are uniform in texture and show a high consistency of clast orientation.

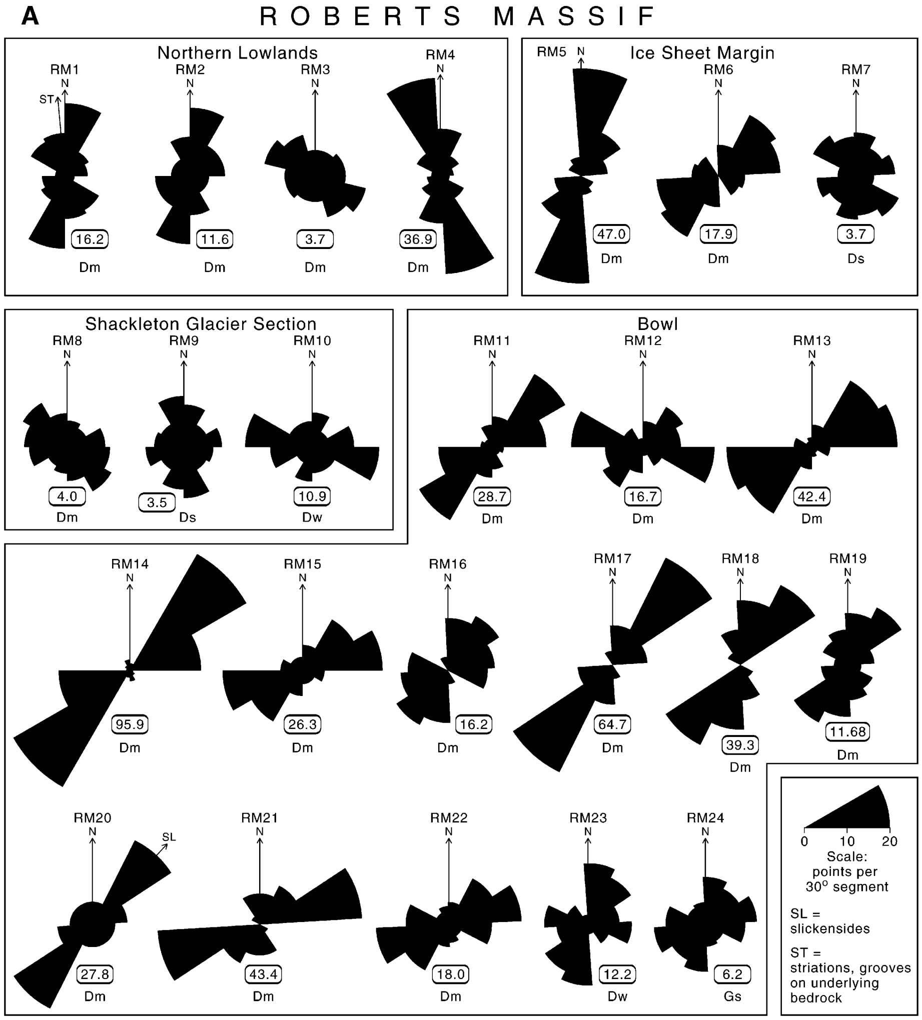


Figure 8. Two-dimensional clast-orientation fabrics from massive (Dm), weakly stratified (Dw), and well-stratified (Ds) diamicts and from massive (Gm) and stratified (Gs) gravels. Data are from the sections through the Shackleton Glacier and Bennett Platform Formations at Bennett Platform, documented according to member; and from spatially selected points in the Shackleton Glacier Formation at Roberts Massif (see Fig. 2 for relative elevations). Site numbers RM1–RM24 are from Roberts Massif, and BP1–BP23 are from Bennett Platform. Boxed numbers are χ^2 values. ST—striation orientation on underlying dolerite; SL—slickensides within diamicts; Mbr—member.

Interpretation of Lithofacies

Each lithofacies is interpreted, where appropriate, on the basis of its textural, clast-fabric, and clast-shape characteristics, as well as the context in which it occurs (Table 2). Massive and weakly stratified diamicts and boulder-rich massive gravels with mud-sand matrix are interpreted as lodgement till. Their preferred clast orientations are a good indication of ice-flow direction as well as mode of deposition (Dowdeswell et al., 1985; Dowdeswell and Sharp, 1986). The predominance of subangular and subrounded clasts, including striated, faceted, and bullet-shaped examples, are indicative of sediment that has been transported by wet-based glaciers in the zone of traction (cf. Boulton, 1978). Slickensides within the diamict at Roberts Massif are associated with internal shear structures, characteristic of some lodgement tills. The uniformity of diamict in the Shackleton Glacier Formation suggests that topography had little influence on deposition. No supraglacial debris is evident, and low-relief terrain is suspected. The larger boulders evident in Bennett Platform Formation suggest more actively eroding ice and close proximity of valley walls. A few massive diamict beds in the Shackleton Glacier Formation (type 2) and massive gravel in Bennett Platform Formation (type 1) show more diffuse fabrics and contain intraclasts of laminate; these diamicts are probably debris flows. Those in the Shackleton Glacier Formation were probably deposited in a subaquatic setting associated with an extensive lake.

The better-sorted gravel lithofacies have a variety of origins. Beds of fresh, angular, and very angular boulders, cobbles, and pebbles are, by comparison with modern glacial environments (Bennett et al., 1997), supraglacial facies, derived as a result of rockfalls from nearby valley sides; this interpretation applies particularly to Bennett Platform Formation. The occurrences of highly weathered angular boulders, near the contact with the underlying dolerite and sandstone, e.g., at Dismal Buttress and the Shackleton Glacier flank of Bennett Platform, are the product of deep weathering and partial incorporation into the basal Sirius Group beds as the ice flowed across these sites. Other weathering phenomena are indicated by the concentrations of heavily pitted gravel of all sizes with interspersed sand on the present-day land surface. These represent lag deposits that result from wind deflation. Tafoni (pitted) surfaces are common on dolerite boulders exposed to the prevailing down-glacier wind. Sandy pebble/cobble beds (both massive and stratified) with mainly subrounded and subangular clasts, associated with diamicts, are inferred to be the result of glaciofluvial activity, the fines having been washed away, leaving lags of coarse material.

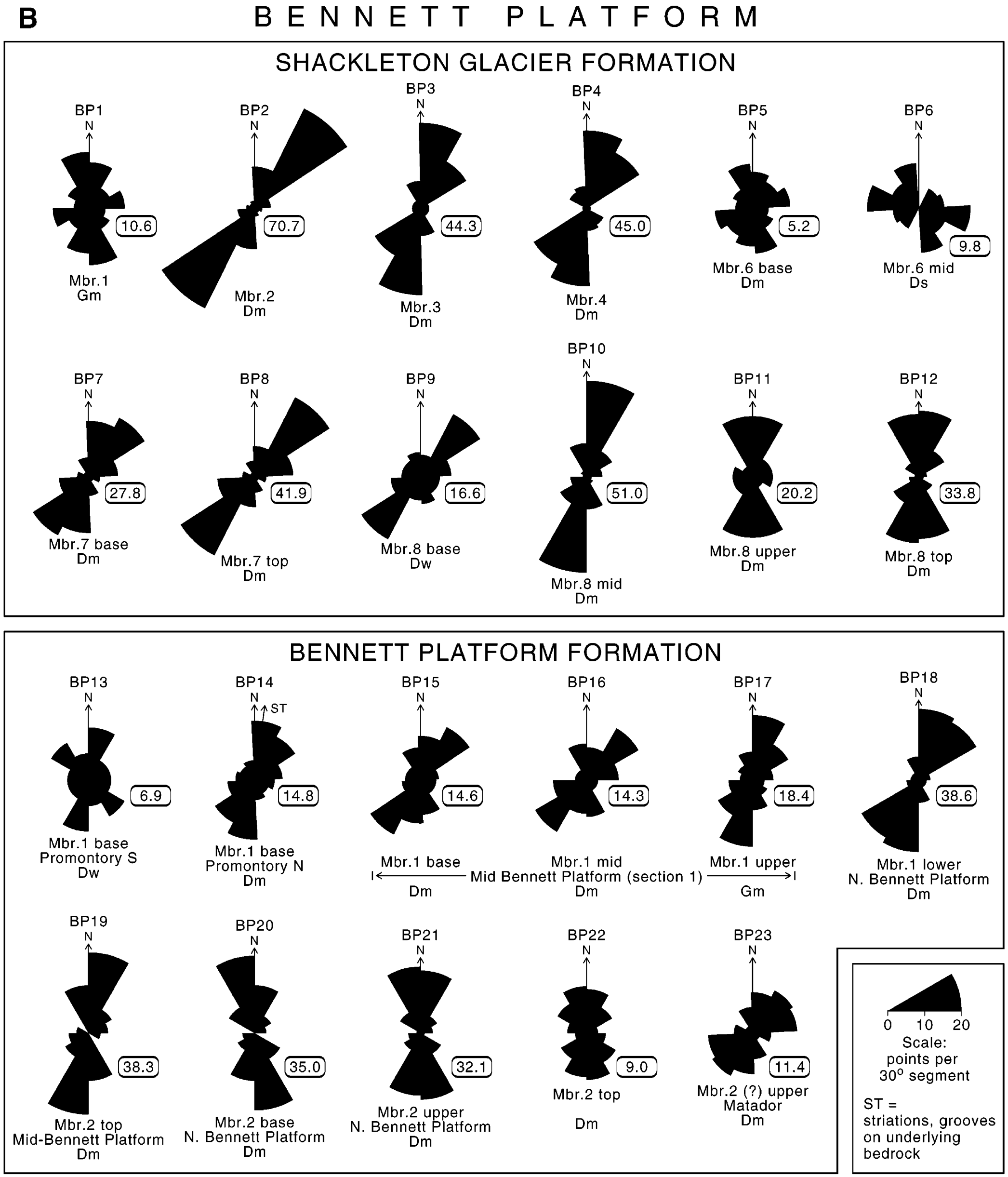


Figure 8. (*Continued.*)

Similar areas of gently washed diamicton with lag-gravel deposits on top of diamict beds are observable adjacent to the snouts of slowly receding polythermal glaciers in Svalbard (Glasser and Hambrey, 2001) and are formed as a result of supraglacial stream runoff. Reddish iron staining in the Shackleton Glacier gravel is also indicative of weathering and incipient soil development.

Of quite different origin is one bed of cross-stratified gravel in member 5 of the Shackleton Glacier Formation that, in view of its intimate association with laminite, is regarded as part of a grounding-line fan complex. Grounding-line fans are fed by sediment carried by large volumes of meltwater from subglacial conduits entering a lake or the sea (Powell and Alley, 1997); the best-known examples are associated with temperate glaciers in Alaska, although such fans are equally associated with polythermal glaciers in the Arctic (Bennett et al., 1999b).

Sandstone and sand beds are also of mixed origin. The majority, associated with diamicts and gravels, are probably of glaciofluvial origin. The subaerial origin of the sandy beds is indicated by yellow staining, which may represent oxidation just below the surface. Sand also occurs in wedge-like features just below the present-day surface, but these are unrelated to depositional processes at the time of formation of the Sirius Group. Rather, they represent frost-contraction features, filled with sediment possibly of eolian origin. They are intimately associated with salt, which is regarded as typical of long-term chemical weathering of bedrock and arid soil development in this part of Antarctica (Campbell and Claridge, 1987).

Reworking processes, particularly those resulting from gravity, such as slumping, are indicated by breccia beds near the base of the Shackleton Glacier Formation (member 1, Fig. 5); they show incomplete mixed contorted intraformational clasts and dolerite clasts.

The laminite beds with outsized clasts are interpreted as ice-contact lake sediments. The laminae, in the form of couplets, are inter-

TABLE 2. LITHOFACIES, THEIR PRINCIPAL CHARACTERISTICS AND INTERPRETATION, BASED ON OBSERVATIONS THROUGHOUT THE UPPER SHACKLETON GLACIER REGION

Lithofacies (formation)	Abbreviation	Distinguishing characteristics	Interpretation
Massive diamict type 1[†] (SGF)	Dm	Sharply bounded beds up to 0.5 to 5 m thick; clast shapes predominantly SR and SA; clast concentration 5–20%; clasts up to 1 m common; strong preferred clast orientation	Lodgement till
Massive diamict type 2[†] (SGF)	Dm	Sharply bounded beds a few centimeters to 1 m thick; base commonly loaded; contorted intraclasts of laminite and slump structures; clast shapes predominantly SR and SA; clast concentration 20–40%; no clast-preferred orientation	Subaquatic glacigenic debris flows with rip-up clasts
Massive diamict type 3[†] (BPF)	Dm	Sharply bounded beds up to 15 m thick, with exceptionally large boulders, many >2 m; clast shapes predominantly SA and SR; clast concentration 30–50% (gradational with boulder gravels; preferred clast-orientation fabric; yellowish staining and sand wedges in upper BPF	Lodgement till, with weathering horizons
Weakly stratified diamict type 1 (SGF)	Dw	Sharply bounded beds up to 5 m thick; clast shapes predominantly SR and SA; clast concentration 5–30%; clasts up to 1 m common; strong preferred clast-orientation; stratification defined by thin gravel layers	Lodgement till
Weakly stratified diamict type 2* (SGF)	Dw	Wispy stratification, sometimes defined by single lamina; outsized clasts depress stratification; synsedimentary fold structures; clast shapes predominantly SR and SA; clast concentration 5–40%; clasts up to 1 m common; no preferred orientation	Ice-proximal glacigenic sediment, formed close to ice margin; some slumping
Massive muddy gravel type 1 (boulder-rich) BPF	bGm	A more clast-rich variety *of massive diamict type 1*; beds semicontinuous to lensoid with mainly sharp contacts; strong clustering of large boulders >2 m at specific levels; clast shapes predominantly SA and SR; clast concentration 50–80%	Large-scale gravity-flows derived from basal till sheets
Massive gravel type 2 (boulder/cobble beds)[†] BPF (top only)	bGm	Boulders/cobbles with minor sandy matrix or diamict matrix from adjacent beds; sharply defined beds up to 1 m thick, but irregular owing to size of clasts; clasts predominantly A and VA; clast concentration 80–100%; preferred orientation unknown	Supraglacial meltout till, derived from rockfall
Massive gravel type 3 (boulder/cobble beds) BPF (Dismal Buttress only)	bGm	Angular, coarse-grained crumbly dolerite boulder layer, 0.5–1 m thick; almost in situ, passing down into solid bedrock and with minor matrix from above	Weathered dolerite scree forming nonorganic paleosol
Massive gravel type 4 (pebble/cobble) SGF	Gm	Thin beds (up to 10 cm), internally massive with sandy matrix, interstratified with laminites; clast shapes SR and SA; clast concentration 60–90%. Alternatively, diffuse patches in laminite	Subaquatic debris flow or wash in of fluvial material into lake
Massive gravel type 5 (pebble/cobble beds) BPF	Gm	Sandy matrix and minor boulder; beds up to 0.5 m with uneven diffuse contacts at base; clasts mainly A; gravel concentration at least 60%	Supraglacial meltout till (rockfall derived)
Massive gravel type 6 (pebble/cobble) BPF	Gm	Beds and lenses up to several centimeters with sharp tops (sometimes rusty colored) and diffuse bases; clast mainly SR; clast concentration 50–90% and very variable in individual layers	Glaciofluvial, slightly reworked from lodgement till; affected by weathering
Massive gravel type 7 (pebble/cobble) BPF	Gm	Surface layer of heavily pitted, polished, and disintegrated dolerite gravel with rare boulders >3 m; near 100% gravel, but minor sand between boulders; clast shapes mainly SA and SR where not pitted	Lag deposit from diamicts and other boulder gravels resulting from wind deflation
Weakly stratified gravel[†] BPF and SGF	Gw	Decimeter-thick interbeds within diamicts (members 3 and 8 of SGF and 2 of BPF); boundaries mainly gradational but some sharp tops; beds relatively continuous; matrix mainly sandy; clasts similar to those in bounding diamicts (mainly SR and SA); clast concentration 50–80%, mainly pebble and cobble sizes but some boulders; in BPF yellow/rusty matrix with Fe layers	Winnowing of basal tillite by fluvial processes of limited efficacy; weathering associated with BPF gravels
Well stratified gravel and gravelly sand SGF, member 5b	Gs	Moderately well-sorted pebble/cobble gravel, forming continuous layers 1 cm to 0.5 m thick, sometimes with clast imbrication and inclined (<5°) cross-beds, and trough-fillings; clasts shapes mainly SA and SR; clast content 30–70%	Glaciofluvial, prograding into lake; moderate reworking of diamicts
Breccia SGF	B	Beds mainly centimeter- to decimeter-scale, sometimes contorted diffuse bedding; mainly angular clasts, both of bedrock (dolerite) and intraformational types (especially laminite rafts); texturally grades into diamict type 2	Resedimented glacial (lodgement till) and glaciolacustrine sediment
Sandstone SGF and BPF	S	Minor stratified and nonstratified beds (<5 cm thick) and centimeter- to decimeter-scale lenses; moderately well-sorted with pebbles; yellowish staining in BPF	Fluvial or glaciofluvial with evidence of subaerial weathering in BPF
Sand BPF (member 3)	S	Wide wedges of sand and gravelly sand up to 25 m deep and 15 cm wide; narrow irregular wedges as much as 1.5 m deep	Frost-contraction cracks or ice-wedge pseudomorphs, filled with wind-blown sand
Laminite* SGF (member 5a)	L	Millimeter- or submillimeter-scale couplets of sand/silt/mud, interbedded with thin Dm and Gm units; variable proportion of outsized clasts (granules to boulders); soft-sediment deformation structures including intraformational brecciation, convolute lamination, synsedimentary folding, load structures	Glaciolacustrine varves with ice-rafted debris; some slumping; interrupted by gravity flows
Mud SGF (member 6)	M	A few centimeters only of homogeneous (dark gray) mud	Distal glaciolacustrine; mud from bottom of basin
Salt (undifferentiated) BPF (member 3)	—	Layers of sandy salt up to 25 cm thick, just below surface boulder lag; also salt in fractures and around periphery of gravel clasts	Polar arid soil; salt accumulation associated with chemical weathering of clasts and in ice-wedge pseudomorphs

Note: SGF—Shackleton Glacier Formation; BPF—Bennett Platform Formation. Clast roundness (Powers, 1953) is abbreviated as follows: VA—very angular, A—angular, SA—subangular, SR—subrounded, R—rounded, WR—well rounded.

[†] Lithofacies marked * are illustrated in Figure 10.

preted as varves, whereas the clasts are dropstones released from icebergs. Diamict dropstones probably were derived from the basal debris layer of the glacier and lend support to the inference of iceberg rafting, rather than rafting by lake ice. The interbedded thin diamict and gravel beds represent pulses of subaquatic gravity flowage of previously deposited glaciogenic debris. Slump structures indicate sediment instability in the lake. The rare example of mud may represent lake-bottom sediment when glacial influence was minimal.

Facies Associations

Three main facies associations can be identified in the measured sections: a terrestrial glacial facies association, which achieves its greatest complexity near the top of Bennett Platform

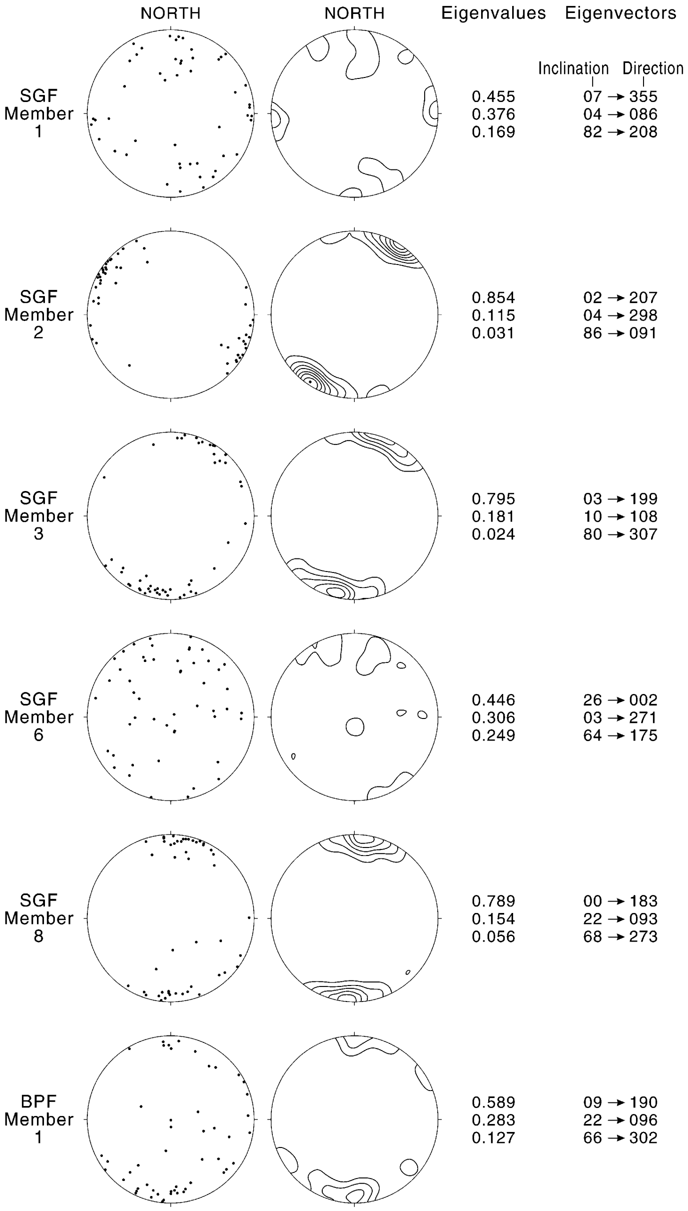


Figure 9. Three-dimensional clast orientation fabrics and statistics plotted on a lower-hemisphere Schmidt equal-area projection. SGF—Shackleton Glacier Formation; BPF—Bennett Platform Formation. All fabrics are from massive diamict, except Shackleton Glacier Formation member 6, which is weakly stratified diamict. For each fabric diagram, eigenvalues are listed in the order S_1, S_2, S_3, and eigenvectors are in the order V_1, V_2, V_3. S_1 gives a measure of fabric strength, the strongest fabrics approaching unity. V_1 is a measurement of the dominant clast orientation in degrees east of north.

Formation (member 2) and two ice-contact lake associations comprising an ice-proximal grounding-line fan association and an ice-distal bottomset association in members 6 and 5, respectively, of the Shackleton Glacier Formation. In comparison with modern Antarctic glacial environments, the geometry and sedimentological characteristics of the Shackleton Glacier and Bennett Platform Formations are quite different. Most data on modern glaciogenic sediment in Antarctica come from the surrounding continental shelves where, commonly, a compact diamicton (interpreted as basal till) that formed beneath ice streams is overlain by a variety of sand, mud, and diatomaceous lithofacies (Anderson, 1999). Few detailed field studies have been made of the sedimentology of onshore glaciogenic sediment, but our observations have invariably shown that sandy gravel, rather than diamicton, is the dominant lithofacies, especially around the margins of cold-based glaciers.

Terrestrial Glacial Facies Association

The bulk of Bennett Platform and Shackleton Glacier Formations comprises massive or weakly stratified diamicts and are interpreted as basal (lodgement) till on the basis of the textural and lithologic characteristics and clast-orientation fabrics. Except for gravel beds a few centimeters thick of inferred glaciofluvial origin, these diamicts are surprisingly uniform. The upper part of Bennett Platform Formation, however, shows a facies association typical of deposition of glaciogenic sediment in a terrestrial environment (Fig. 11). Massive diamicts are interpreted as lodgement till, massive angular gravels as supraglacial melt-out debris, and better-sorted sands and gravels as glaciofluvial sediment. Weathering horizons are also present, indicated by red/yellow iron oxide staining of certain horizons. Wedge-shaped sand or diamict features extending below some bed boundaries in diamict may represent filled frost-contraction cracks. All these lithofacies show marked changes over tens of centimeters, both vertically and laterally in the upper 10 m of Bennett Platform Formation. This facies association can be traced along much of the exposed Bennett Platform Formation section and indicates a strong interplay among glacial, fluvial, and rockfall processes.

Grounding-Line Fan Association

Grounding-line fans—a feature of glacier cliffs terminating in the sea or lakes—are generally associated with the complex interaction between subaquatic discharge of subglacial streams and rain-out of debris from icebergs, coupled with reworking by gravity-flow processes (Powell and Molnia, 1989). Member 6 of the Shackleton Glacier Formation (Fig. 12) is characterized by lithofacies indicative of a grounding-line fan, including (1) massive and weakly stratified diamict, interpreted as ice-proximal glaciolacustrine sediments, sometimes reworked by subaquatic gravity flowage and slumping; (2) laminite indicative of background sedimentation from suspension, sometimes with dropstones; and (3) minor sand and gravel, derived directly from the subglacial stream conduit. At the type section, member 6 rests on a northward-prograding wedge of well-sorted sand and gravel, which may represent an ice-contact delta. This delta was formed when subaquatic discharge was more dominant and may have built up to shallow water depths (member 5b; Fig. 12). On the basis of these facies alone, it cannot be determined whether deposition was in a lake or the sea, but the relatively high elevation above sea level and the presence of distinctive laminite in the underlying member suggest a lacustrine environment.

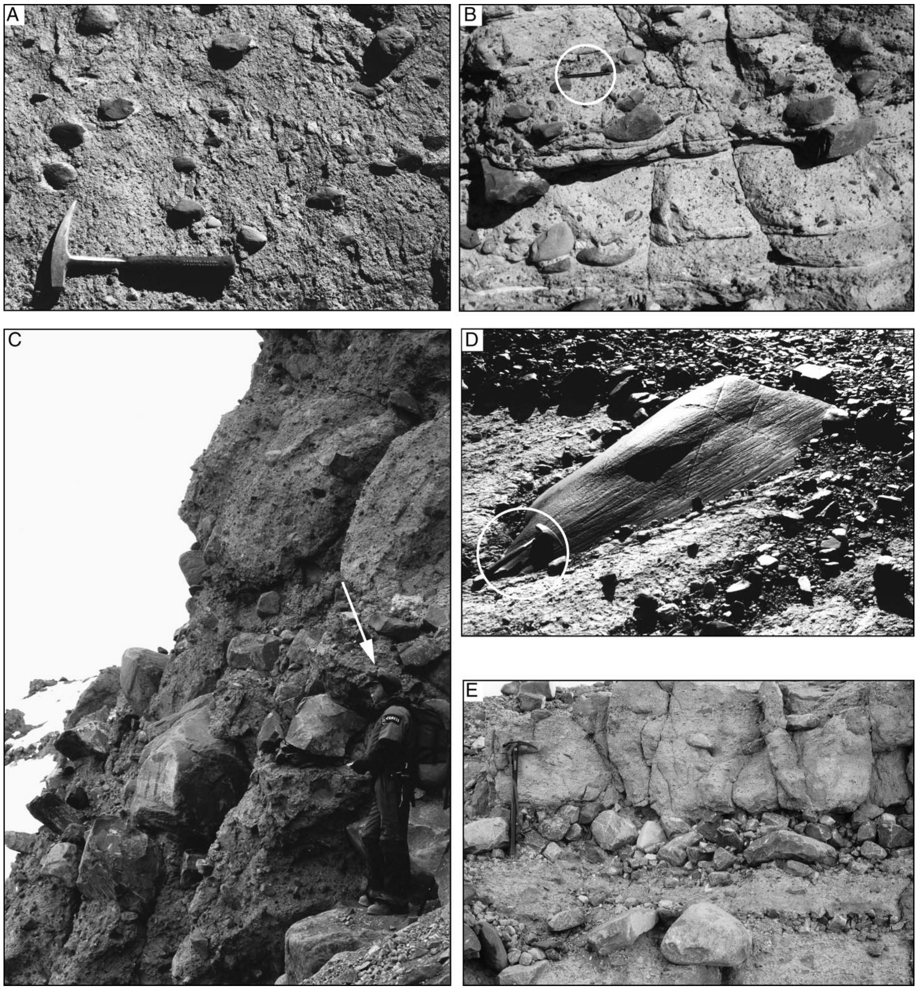


Figure 10. Representative lithofacies in the Sirius Group at Shackleton Glacier. (A) Exposed upper surface of massive diamict type 1 (cf. Table 2), the "Bowl," Roberts Massif; note preferred alignment of clasts parallel to shaft of hammer. (B) Weakly stratified diamict (type 2) of the Shackleton Glacier Formation (unit 6), Bennett Platform; pencil (ringed) for scale. (C) Massive diamict (type 3) (upper and lower parts of photograph) and boulder-gravel (middle) of Bennett Platform Formation (member 1), Bennett Platform; person (shown by arrow) for scale. (D) Streamlined and striated boulder of dolerite embedded in massive diamict (type 1), Roberts Massif, northern lowlands; ice-flow direction from lower left to upper right; hammer (ringed) for scale. (E) Massive cobble-boulder gravel (type 2) of mainly angular character, interbedded with diamict at the top of Bennett Platform Formation (member 2), Bennett Platform; ice axe at left for scale. (F) Weakly stratified pebble-gravel layers within diamict succession, Shackleton Glacier Formation (member 3), Bennett Platform; the pole is 1 m long. (G) Dolerite dropstone in interbedded laminite and thin diamict/gravel beds, Shackleton Glacier Formation (member 5); horizontal axis of boulder measures 40 cm; pencil at arrow tip for scale. (H) Laminite with dispersed dropstones consisting mainly of dolerite (black) and diamict (pale, mottled) clasts; Shackleton Glacier Formation (member 5), Bennett Platform. (I) Laminite with soft-sediment deformation (slump folds); Shackleton Glacier Formation (member 5), Bennett Platform.

Ice–Distal Lake–Bottomset Association

A unit of laminite and diamict underlies the grounding-line fan association of the Shackleton Glacier Formation, the latter indicating encroachment of the glacier toward the depositional site (Fig. 13). Laminite comprises sand/mud couplets and is more typical of a lake varve succession than of tidal rhythmite. The laminite probably accumulated on the bottom of the lake basin. Alternatively, the laminite could be interpreted as a turbidite succession, but the laminae are not graded in the same way, nor do they have the same sedimentary structures as classical turbidites. The ice-contact nature of the lake is indicated by the presence of dropstones throughout, some of which are of diamict (''till clots''), indicative of reworking of older glacial sediment or the release of basal glacial debris from icebergs. Each couplet could thus represent a year's sedimentation, but this regular accumulation was periodically interrupted by the input of debris transported subaquatically by debris flows. The latter are indicated by sharp-bounded units of massive beds of diamict with rip-up clasts of laminite up to 10 cm thick. In addition, sporadic high-discharge fluvial events resulted in deposition of thin sand and gravel beds in the lake basin. Local slumping of laminite is also evident at several levels in member 5. The glacial-lake sequence, comprising the grounding-line fan and bottomset associations, is sandwiched between lodgement tills and represents a phase of major ice-sheet recession.

POST–SIRIUS GROUP TECTONICS

Several lines of evidence indicate large-scale faulting of the region after (or even during) Sirius Group deposition.

1. Relatively uniform distribution of facies irrespective of present-day local topography and at a wide range of topographic levels. The Shackleton Glacier Formation at both Roberts Massif and Bennett Platform is dominated by massive diamicts interpreted as lodgement tills. Ice-flow indicators (clast fabric, striated embedded boulders, and the underlying abraded pavement) demonstrate consistent orientations. Topographic highs did not divert ice flow, suggesting that they were formed subsequent to deposition.

2. Concordance of faults in the Sirius Group, Beacon Supergroup, and Ferrar Dolerite. Although the edge of Bennett Platform is characterized by a series of rotational fault scarps within the Sirius Group, many other faults along the flanks of Shackleton Glacier also extend down into the underlying Ferrar Group dolerite and Beacon Supergroup sandstone.

3. Normal faulting of the Shackleton ero-

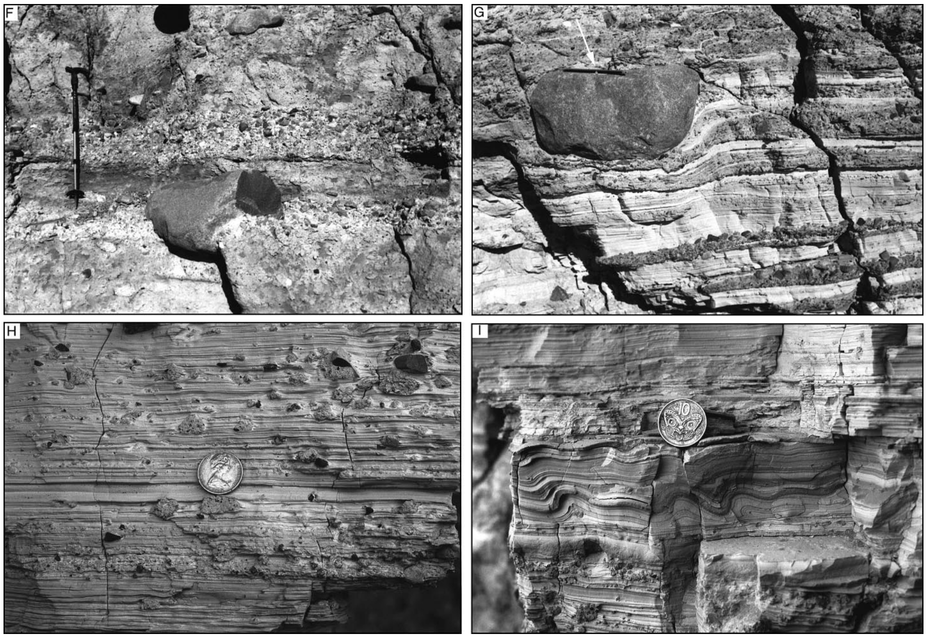
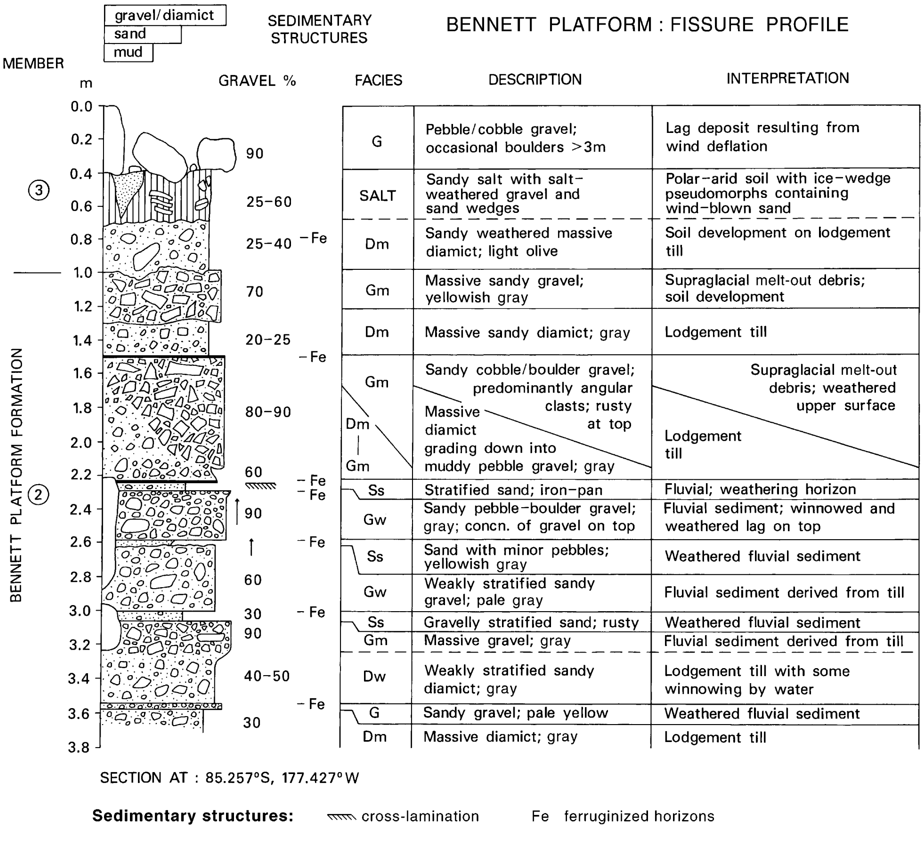


Figure 10. (*Continued.*)



FACIES	DESCRIPTION	INTERPRETATION
G	Pebble/cobble gravel; occasional boulders >3m	Lag deposit resulting from wind deflation
SALT	Sandy salt with salt-weathered gravel and sand wedges	Polar-arid soil with ice-wedge pseudomorphs containing wind-blown sand
Dm	Sandy weathered massive diamict; light olive	Soil development on lodgement till
Gm	Massive sandy gravel; yellowish gray	Supraglacial melt-out debris; soil development
Dm	Massive sandy diamict; gray	Lodgement till
Gm Dm | Gm	Sandy cobble/boulder gravel; predominantly angular clasts; rusty at top Massive diamict grading down into muddy pebble gravel; gray	Supraglacial melt-out debris; weathered upper surface Lodgement till
Ss	Stratified sand; iron-pan	Fluvial; weathering horizon
Gw	Sandy pebble–boulder gravel; gray; concn. of gravel on top	Fluvial sediment; winnowed and weathered lag on top
Ss	Sand with minor pebbles; yellowish gray	Weathered fluvial sediment
Gw	Weakly stratified sandy gravel; pale gray	Fluvial sediment derived from till
Ss	Gravelly stratified sand; rusty	Weathered fluvial sediment
Gm	Massive gravel; gray	Fluvial sediment derived from till
Dw	Weakly stratified sandy diamict; gray	Lodgement till with some winnowing by water
G	Sandy gravel; pale yellow	Weathered fluvial sediment
Dm	Massive diamict; gray	Lodgement till

Figure 11. Terrestrial glacial facies association with lodgement tills, supraglacial melt-out debris, and glaciofluvial sediment, influenced by weathering at several horizons showing development of polar soil; upper Bennett Platform Formation, rift zone at Bennett Platform. See Table 2 for details of facies.

sion surface and overlying Sirius Group. At Roberts Massif, the erosion surface on dolerite is grooved, striated, and dissected by normal faults (Fig. 4A). At least one fault, marked by a 5-m-high scarp, dissects the Sirius Group. Elsewhere, faults displace a deeply weathered dolerite land surface. Overall, faults occur on all scales, with individual displacements ranging from a few millimeters to 100 m or more. As observed in the erosional pavement (Fig. 4A), there are at least three crosscutting fault systems, although a systematic analysis of their orientation remains to be undertaken.

4. Block-like nature of the terrain and tilted horsts. Much of the higher parts of Roberts Massif consist of fault-bounded blocks with scarps of up to 100 m. Remnants of striated surfaces and Sirius Group diamict have been observed in a few places on top of these blocks. At Bennett Platform, major steps in the topography and slope-parallel gullies several meters deep, up to a few hundred meters away from the cliff that overlooks Shackleton Glacier, are also interpreted as faults.

5. Style of faulting, including closely spaced fractures. In places, numerous near-vertical faults, with a spacing of tens of centimeters, intersect the dolerite and diamict. In the latter, the fractures penetrate through the diamict matrix into the clasts, sometimes accompanied by displacements of a few centimeters. Good examples occur in the ''Bowl'' on Roberts Massif.

6. Presence of fissure fills of Sirius Group material in Beacon Supergroup sandstone. Above the ''Bowl,'' adjacent to a small perched lobe of ice flowing from the Polar Plateau, is a major fault scarp. Normal faults, cutting the Sirius Group, dolerite, and sandstone, fan out away from the edge. Locally, diamict matrix has penetrated some of these cracks to form dike-like features. Diamict was probably injected under pressure as ice flowed over the bed and deposited lodgement till.

7. Relative degrees of weathering at dolerite fault scarps. The larger fault scarps, capped by dolerite in some places, are characterized by unweathered rock faces and fallen blocks, as well as progressively more weathered material. Many blocks are less weathered than the boulders in the Quaternary moraines that are commonly ferruginized, suggesting that these less weathered blocks were emplaced more recently. This interpretation implies that the fault scarps may still be active, although surface-exposure dating is necessary to confirm this hypothesis.

Faulting suggests significant post–Sirius deposition tectonic activity associated with continued rifting and uplift in the Beardmore block

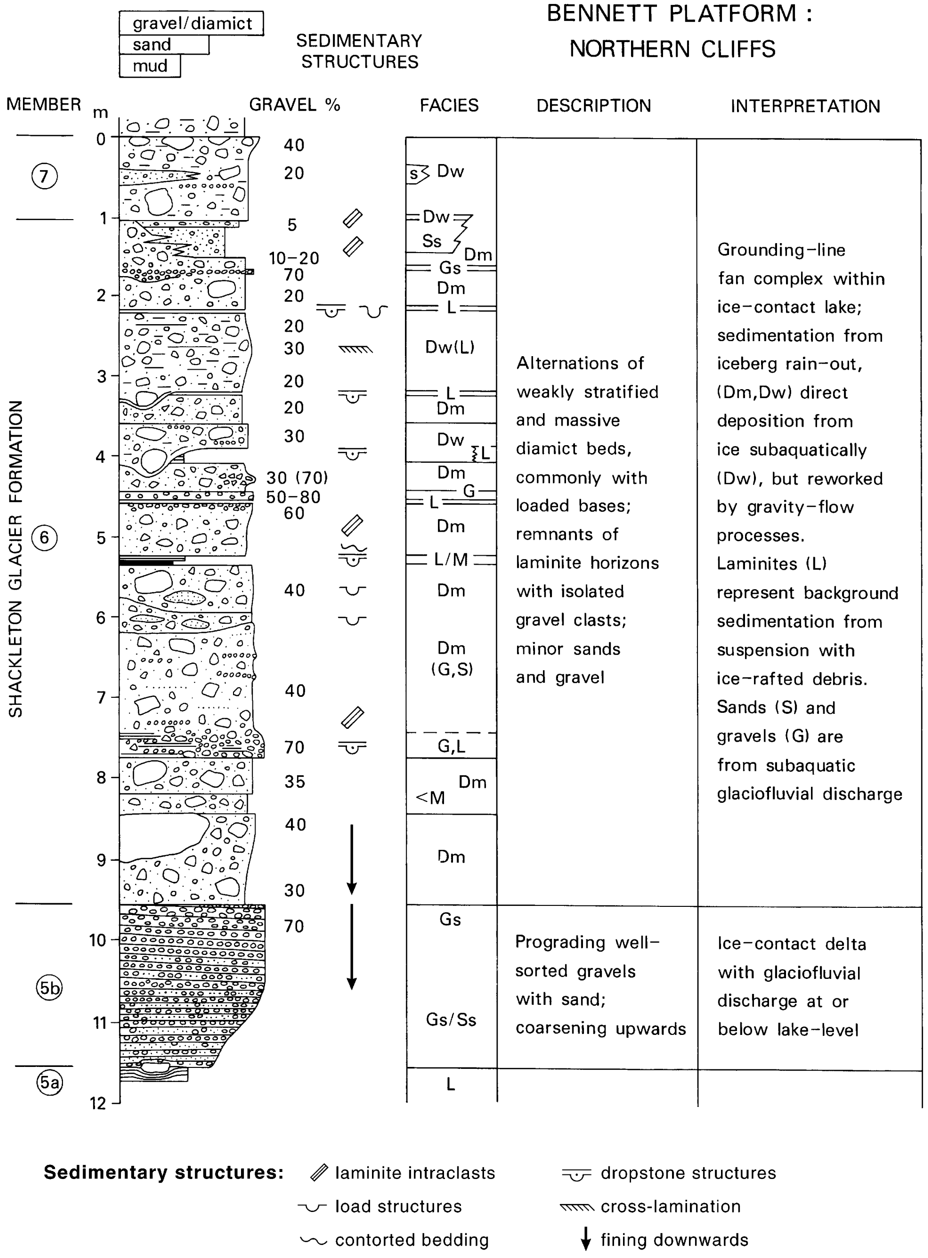


Figure 12. Grounding-line fan facies association, with alternations of iceberg rain-out sediment, debris flows, and minor rhythmite with ice-rafted dropstones, Shackleton Glacier Formation (unit 6). See Figure 2 for details of facies.

of the central Transantarctic Mountains (Webb et al., 1994; van der Wateren et al., 1999), to which the Shackleton Glacier region belongs. The character of faulting and its relationship with the Sirius Group resembles that on the Dominion Range (Beardmore Glacier), where one fault appears in aerial photographs to cut parallel lines of slightly curved "drift" on top of the Sirius Group (Fig. 4 of Mercer, 1972). Other faults in the Dominion Range resemble those along the outer edge of Bennett Platform that intersect both the Sirius Group and the underlying rocks. Crustal uplift has had the effect of largely damming the East Antarctic Ice Sheet and forcing discharge into the Ross Ice Shelf to be much more strongly channeled, as through the modern Shackleton Glacier.

DISCUSSION

Glacial Succession, Associated Climate, and Tectonic Uplift

Three main phases of glacial deposition are recorded in Sirius Group strata and erratics in the upper Shackleton Glacier area. The oldest are represented by erratics of lithified sandy diamictite, conglomerate, and sandstone, some of which contain wood fragments and occur in lateral moraines at the margins of the glacier and as clasts within the two documented formations. The lithified nature of these erratics probably suggests that they represent an earlier phase of glaciation in the Shackleton Glacier region. No direct evidence of age is available, but conceivably they could be as old as similar lithified glaciogenic sediments cored in the Ross Sea (Fig. 1A) at the MSSTS, CIROS (Barrett, 1989, 1996; Hambrey and Barrett, 1993), and CRP drill sites (Cape Roberts Science Team, 1998, 1999, 2001; Hambrey et al., 1998; Barrett et al., 2000, 2001), from which upper Eocene, Oligocene, and Miocene strata were recovered. If the erratics observed are representative of the succession that has been eroded, then a climatic regime with wet-based temperate or polythermal glaciers with abundant meltwater is envisaged. The presence of wood fragments implies the presence of shrubs or woodland growing along or above the flanks of the glacier, a condition that today is associated with glaciers in temperate regions such as Alaska, Patagonia, and the Alps or in Arctic regions such as southern Greenland, where polythermal glaciers prevail.

The other two phases of deposition by polythermal ice are well documented in Bennett Platform sections. The Shackleton Glacier Formation represents intervals dominated by deposition of stacked sheets of lodgement till (Fig. 14, stages 1 and 3), punctuated by glaciogenic-sediment flowage and glaciofluvial and glaciolacustrine deposition (Fig. 14, stage 2). Little, if any, of the sediment is derived from rockfall, such as one would expect if the ice mass were constrained in a valley (similar to the situation of today). Rather, the bulk of material was initially carried in the zone of traction at the base of the glacier. Glaciolacustrine processes, involving deposition from icebergs, form a distinct horizon, whereas glaciofluvial reworking of tills affected only a minor part of the succession. The presence of weakly weathered horizons at the top of some diamict beds suggests that subaerial conditions prevailed between depositional episodes. The dominance of diamict in the succession suggests that the closest modern analogue in terms of glacier thermal regime is found in the High Arctic (e.g., the Canadian Arctic or Svalbard), rather than in temperate regions such as Alaska or the Alps, or in frigid regions with little meltwater, as represented by Antarctica today.

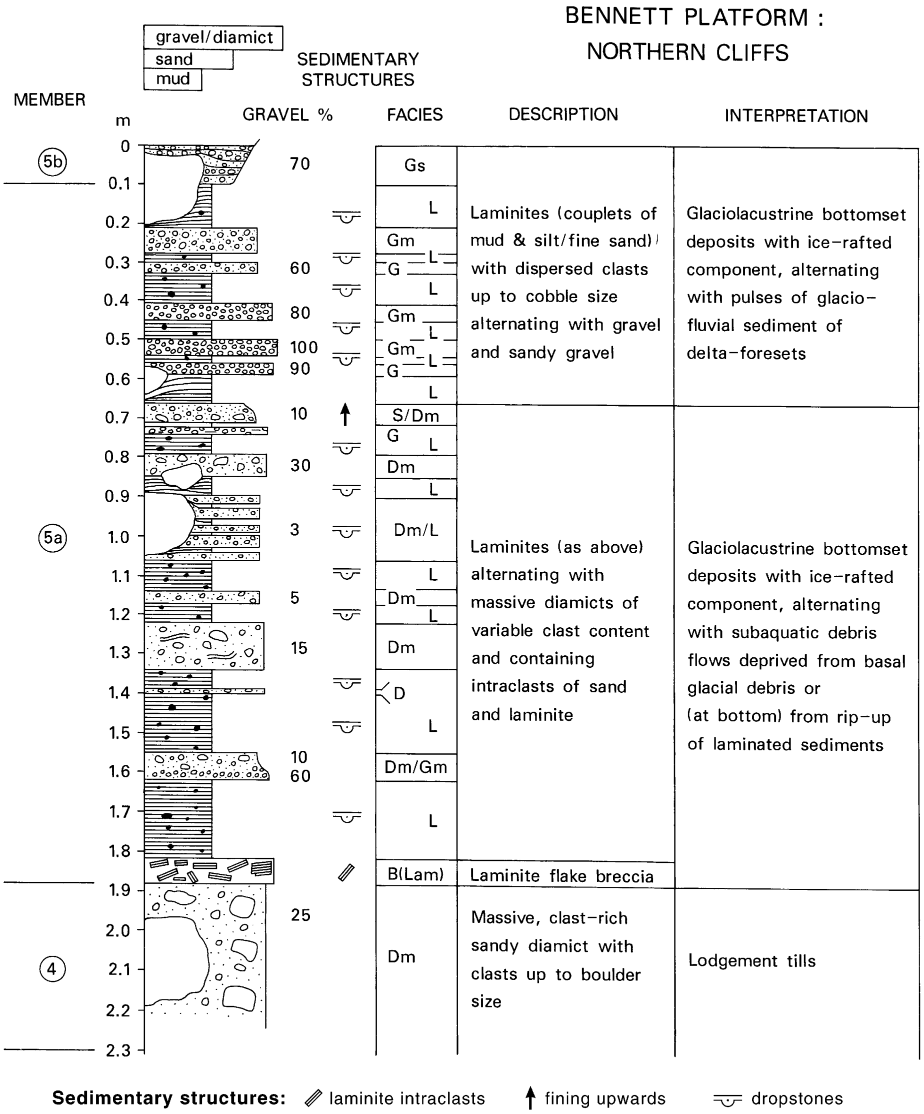


Figure 13. Ice-contact glacial-lake association showing bottomsets comprising rhythmite with ice-rafted dropstones and subaquatic gravity flows, Shackleton Glacier Formation (unit 5), Bennett Platform. See Table 2 for details of facies.

Bennett Platform Formation is texturally different from the Shackleton Glacier Formation in containing thicker beds of more boulder-rich diamict. These beds also indicate basal glacial transport, but the final depositional process is uncertain (lodgement till, mass flow, or both) (Fig. 14, stage 4). Toward the top of Bennett Platform Formation, however, a fluctuating ice margin in a terrestrial setting is indicated. Rocky terrain above the glacier under the influence of frost weathering is indicated by the presence of angular material, representing layers of supraglacial melt-out debris. Again, a polythermal regime is suggested.

The relief on the unconformity between the two formations and the contrast in lithofacies suggests that a considerable time interval may separate them. The unconformity may represent the first signal of tectonic uplift and Bennett Platform Formation deposition in a setting that begins to resemble that of today.

No direct evidence of age has yet been obtained from the Shackleton Glacier sediments. However, despite the 150 km separation, tentative comparisons with the Dominion Range in the Beardmore Glacier region may be made. Both regions have similar structural histories, belonging to the same fault-bounded block in the Transantarctic Mountains. The Shackleton Glacier Formation displays a relatively uniform ice-flow pattern that suggests ice-sheet–scale glaciation, with little topographic relief at the time of deposition, as indicated by the absence of supraglacial material. Given the similarity of the setting of the Sirius Group in the Shackleton Glacier region to that in the Dominion Range of the upper Beardmore Glacier, where biostratigraphic data have been obtained (Francis and Hill, 1996; Webb et al., 1996d; Ashworth et al., 1997), we suggest that, as a working hypothesis, the Shackleton Glacier and Bennett Platform Formations have an age in the range Miocene to Pliocene. A Pliocene age is further supported by age estimates from paleosols in the Dominion Range (Retallack et al., 2001).

Correlation with other areas of the central Transantarctic Mountains, such as Reedy Glacier (Mercer, 1968; Wilson et al., 1998), 400 km southeast of the Shackleton Glacier, is less secure. Longer distance correlation, notably with the well-studied Sirius Group sites in Victoria Land (e.g., Denton et al., 1993; Barrett et al., 1997; Stroeven and Prentice, 1997; Wilson et al., 2002), is inappropriate, given the different uplift and downcutting histories of each structural block in the Transantarctic Mountains (van der Wateren et al., 1999).

Following deposition of the Sirius Group, the upper Shackleton Glacier region was subjected to extensional faulting and uplifted. According to the flexural-uplift model of Stern and Ten Brink (1989), this positive tectonic response inland of the shoulder of the Ross Sea rift system resulted from a combination of lithosphere end-load and thermal and erosional effects. In the Beardmore Glacier region, Fitzgerald (1994) has demonstrated that ~7–10 km of uplift has occurred since early Cenozoic time. It has been proposed that this uplift was rapid (Behrendt and Cooper, 1991), and from dating the Sirius Group, some 3 km of this uplift has occurred since late Pliocene time (Webb et al., 1996d). Because the Beardmore and Shackleton Glacier regions belong to the same structural block, it may be suggested that the structural histories are similar. This contrasts with the lack of significant late Cenozoic uplift in Victoria Land (Sugden et al., 1995).

Following faulting and uplift, much of the Sirius Group was removed (Fig. 14, stage 5), and the landscape acquired approximately its present configuration. This stage represents the closing period of wet-based glaciation and was followed by the transition to modern cold-polar climatic conditions.

Finally, Quaternary phases of glaciation (stage 6) produced a quite different record from that of the Sirius Group: thin sheets of sandy, mainly angular gravel resulting from deposition from dry-based ice; low multiple sets of blocky moraines; and an absence of any indications of meltwater deposition.

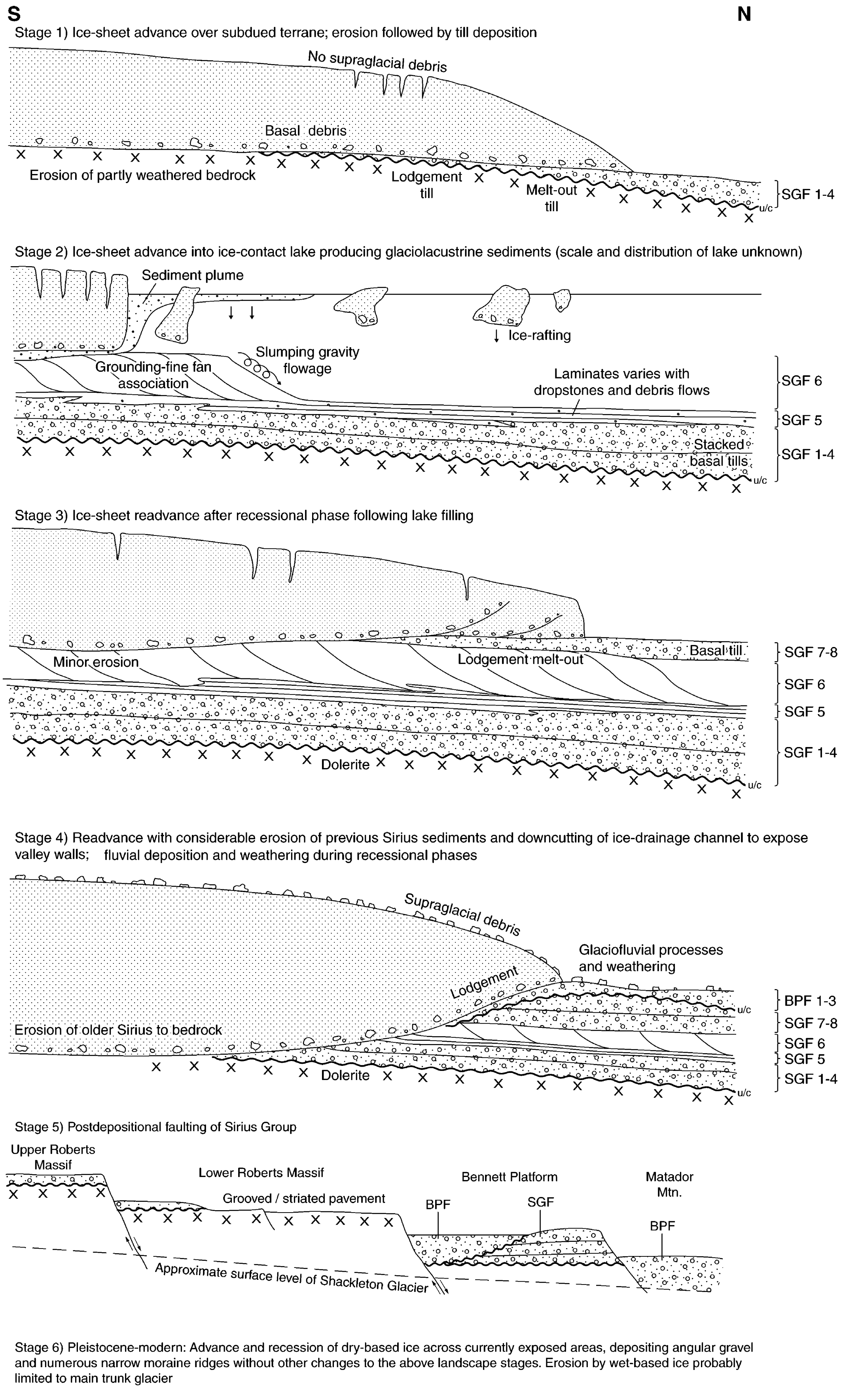

S
N
Stage 1) Ice-sheet advance over subdued terrane; erosion followed by till deposition
No supraglacial debris
Basal debris
Erosion of partly weathered bedrock
Lodgement till
Melt-out till
u/c
SGF 1-4
Stage 2) Ice-sheet advance into ice-contact lake producing glaciolacustrine sediments (scale and distribution of lake unknown)
Sediment plume
Ice-rafting
Slumping gravity flowage
Grounding-line fan association
Laminates varies with dropstones and debris flows
Stacked basal tills
u/c
SGF 6
SGF 5
SGF 1-4
Stage 3) Ice-sheet readvance after recessional phase following lake filling
Minor erosion
Lodgement melt-out
Basal till
Dolerite
u/c
SGF 7-8
SGF 6
SGF 5
SGF 1-4
Stage 4) Readvance with considerable erosion of previous Sirius sediments and downcutting of ice-drainage channel to expose valley walls; fluvial deposition and weathering during recessional phases
Supraglacial debris
Glaciofluvial processes and weathering
Lodgement
Erosion of older Sirius to bedrock
Dolerite
u/c
BPF 1-3
SGF 7-8
SGF 6
SGF 5
SGF 1-4
Stage 5) Postdepositional faulting of Sirius Group
Upper Roberts Massif
Lower Roberts Massif
Grooved / striated pavement
Bennett Platform
Matador Mtn.
BPF
SGF
BPF
Approximate surface level of Shackleton Glacier
Stage 6) Pleistocene-modern: Advance and recession of dry-based ice across currently exposed areas, depositing angular gravel and numerous narrow moraine ridges without other changes to the above landscape stages. Erosion by wet-based ice probably limited to main trunk glacier

TABLE 3. COMPARISON OF SEDIMENTOLOGICAL CRITERIA FOR THE SHACKLETON GLACIER AND BENNETT PLATFORM FORMATIONS WITH BASAL-TILL AND LATERAL-MORAINE SEDIMENT FROM MODERN GLACIAL ENVIRONMENTS

Criteria	Shackleton Glacier Formation	Modern low-relief basal till[†]	Bennett Platform Formation	Modern alpine lateral moraine or moraine wall[‡]
Dominant facies	Clast-rich diamict	Clast-rich diamict	Muddy boulder gravel	Muddy/sandy boulder gravel
Stratification	Massive/weakly stratified; follows bedrock contours	Massive/weakly stratified; follows bedrock contours	Weakly stratified; parallel to underlying unconformity; slight dip toward valley side	Weakly stratified; moderate dip toward valley sides, parallel to outer slope of moraine
Morphology	Sheet-like geometry; truncated at Bennett Platform	Sheet-like geometry, smoothing out uneven topography	Sheet-like form parallel to high-relief unconformity	Sharp-crested ridge; steep unstable inner face; moderate stable outer face
Clast size	Most clasts < 1 m	Most clasts < 1 m	Clasts > 2 m common	Clasts > 2 m common
Clast surface	Striations and facets common; embedded boulders (some bullet-shaped) with striations defining regional ice flow	Striations (depending on lithology) and facets common; embedded boulders (some bullet-shaped) defining regional ice flow	Striations and facets present, but generally $<10\%$	Striations and facets present, but generally rare
Clast fabric	Strong preferred orientation	Strong preferred orientation	Weak to strong preferred orientation	Weak preferred orientation
Relationship to faults	Postdepositional normal faulting, including underlying bedrock	Not generally present	Postdepositional normal faulting, including underlying bedrock; rotational failure	Faulting following removal of ice support from moraine wall; rotational failure excluding bedrock

[†] Wide range of data sources from polythermal and temperate glaciers (e.g. Boulton, 1978; Glasser and Hambrey, 2001).

[‡] Few data sources available (but see Boulton and Eyles, 1979; Roethlisberger and Schneebeli, 1979); other unpublished data obtained by M. J. Hambrey from modern glaciers in New Zealand, Cordillera Blanca in Peru, and James Ross Island and Dry Valleys in Antarctica.

Reconstruction of Land Surface Associated with Sirius Group Deposition

As indicated in Figure 2, the Shackleton Glacier and Bennett Platform Formations in the upper Shackleton Glacier area span an altitudinal range of over 800 m, yet the bulk of the lithofacies and ice-flow indicators are suggestive of an area of subdued relief. Faulting has reconfigured the head of Shackleton Glacier, so that land nearest the Polar Plateau has been uplifted more than to the north around Bennett Platform. However, the relationship between faulting and the exceptionally high relief north of McGregor Glacier (Mount Wade, 4084 masl) (Fig. 1C) is not known. Faulting at Roberts Massif is rather chaotic, and at least three sets are observable in oblique aerial photographs. Faulting has produced irregular elevated blocks, depressions, and tilted surfaces. In addition, a series of normal faults has resulted in a stepped profile spanning an altitudinal range from 2000 to 2400 m from north to south (Fig. 14, stage 5). At least some of these faults may be the result of reactivation of megajoints associated with dolerite injection during the Jurassic Period.

The lithofacies of the Shackleton Glacier Formation at Roberts Massif, combined with ice-flow indicators (grooved pavements and clast-orientation fabrics), indicate that ice flowed in a broad regular sweep, moving southwest to northeast near the Polar Plateau and south-southeast to north-northwest in the Roberts Massif lowlands. Uplifted blocks show no deviation of this general ice-flow pattern, which would have been the case if today's substantial relief were present when ice flowed across the area. Small fault scarps are evident, not only within the Sirius Group, but also in the grooved pavement.

At Bennett Platform, sections through Sirius Group strata are exposed in fault scarps and rifts. Although these scarps could have formed as a result of the lowering of the Shackleton Glacier, the faults appear to penetrate bedrock and therefore are not simply a superficial feature. Furthermore, the lithofacies (except near the top of Bennett Platform Formation) are indicative of subglacial, lowland-style glaciation.

An alternative view concerning the nature of the topography that existed when the Sirius Group was deposited has been expressed by Denton et al. (1991). The study area of these authors was the Beardmore Glacier, and their interpretation also has implications for the Shackleton Glacier. This view is in contrast to that of Webb et al. (1987, 1994), who interpreted the present landform morphology and disposition of the Sirius Group essentially to reflect postdepositional faulting and erosion. Denton et al. (1991) envisaged two distinctly different types of glacial deposit on the basis of morphological setting: subglacial and ice-marginal. On ‘‘old’’ surfaces, deposits were interpreted as ‘‘ground moraines’’ (i.e., basal tills), whereas sedimentary wedges in valleys cut into the old surface were considered to be lateral moraines. However, neither view was supported by sedimentological observations from modern glacial environments. For Shackleton Glacier, therefore, comparisons are made with modern glacial settings, in particular comparing the characteristics of lateral moraines and basal tills (Table 3). From these criteria, it is clear that the Shackleton Glacier Formation is a basal till, rather than a lateral-moraine remnant. For Bennett Platform Formation, there are some similarities with lateral moraines, but not in terms of morphology, which may have been modified by Quaternary glacial events. The abundance of angular clasts near the top of the formation does indeed suggest proximity to the walls of a glacier trough, although the morphology may not have been as pronounced as that of today.

From all these observations, we conclude that the faulting history, which has continued sporadically since the initiation of uplift of the Transantarctic Mountains on the shoulder of the Ross Sea rift system (Behrendt and Cooper, 1991; Fitzgerald et al., 1986; Fitzgerald, 1992), shows marked rejuvenation since deposition of the Sirius Group in the Shackleton Glacier region. This interpretation has impor-

Figure 14. Conceptual model illustrating the development of the Shackleton Glacier Formation (SGF, members 1–8), followed by erosion and then deposition of Bennett Platform Formation (BPF, members 1–3). The final stage illustrated here, after Sirius Group deposition, is faulting and stripping of most debris by supposed Quaternary glacial events. The present time is characterized by cold ice and the development of superficial moraines. Each stage is described in the text.

tant implications for the nature and scale of the East Antarctic Ice Sheet. The uplift history implies that, at the time of deposition, the glaciogenic sediment was deposited on a landscape that was much lower and had a more uniform elevation than that of today, but the deposits have now become dislocated over an altitudinal range of at least 800 m.

Implications for Ice-Sheet Fluctuations and Scale

The pre-Quaternary history of Antarctica in the upper Shackleton Glacier area is shown to have involved two main glaciations (represented by the Shackleton Glacier and Bennett Platform Formations), each revealing several advances and recessions. A third older glaciation is indicated by diamictites and other lithofacies in boulders in modern supraglacial debris and within the Sirius Group in the Shackleton Glacier area. The Sirius Group in outcrop can be divided into two main stratigraphic successions, represented by the Shackleton Glacier and Bennett Platform Formations, separated by a major unconformity. Multiple events suggest that caution should be applied in correlating Sirius exposures throughout the Transantarctic Mountains.

The postfaulting history affecting the glaciogenic sediment of the Shackleton Glacier and Bennett Platform Formations is significant in interpreting the scale of the ice sheet. From evidence presented herein, the former land surface was probably affected by lowland-style glaciation. This surface, therefore, would not have provided the same barrier to ice flow that the Transantarctic Mountains do today, which may suggest that the ice sheet was substantially (possibly hundreds of meters) thinner and at a lower elevation. Facies analysis suggests that the ice sheet that deposited the two formations was more temperate than that occurring in today's frigid arid environment. Climatic conditions of high-Arctic type are suggested by the proportions of basally deposited glacigenic facies and fluvial and lacustrine facies within the Shackleton Glacier and Bennett Platform Formations. Temperate conditions may have prevailed during deposition of the older glacial erratics, because the glaciers would have had to transport substantial woody vegetation. However, the wood fragments await detailed examination.

CONCLUSIONS

Several conclusions may be drawn concerning glacier thermal regime and dynamics, sedimentary environments, paleogeography, and tectonics from our investigations of the Sirius Group in the Shackleton Glacier area:

1. Neogene glaciogenic sedimentary deposits (the Shackleton Glacier and Bennett Platform Formations) near the head of the Shackleton Glacier (south of 85°S) exhibit evidence for multiple wet-based glaciations by earlier phases of the East Antarctic Ice Sheet. The principal lithofacies—diamict, gravel, sand, and laminite—form two principal stratigraphic units, the Shackleton Glacier and Bennett Platform Formations that are separated by a major unconformity. An older glaciogenic unit is represented by gravel clasts in the modern moraines and within the two formations. Underlying the succession is a glacially striated and grooved pavement. The glaciogenic strata were deposited primarily as lodgement tills on the bed of a wet-based ice mass, but mass-flow processes are also in evidence. In the middle of the Shackleton Glacier Formation, a glaciolacustrine succession is present. There are no indications of glaciomarine sedimentation.
2. Although no biogenic material has been found in the Shackleton Glacier and Bennett Platform Formations, the presence of silicified wood in the erratics of older glacial facies suggests that the ice sheet of that time was associated with a significantly warmer regime than that of today.
3. Following the deposition of the Sirius Group, the Shackleton Glacier region was affected by considerable faulting and cumulative uplift in excess of 800 m. The prefaulting surface was one of subdued and lower relief; it was affected by rather uniform ice-flow direction and glacial erosion. Thus, the Transantarctic Mountains did not form such a pronounced barrier to ice flow. It could therefore be argued that the East Antarctic Ice Sheet did not need to grow to the thickness it has today to deposit these strata.

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