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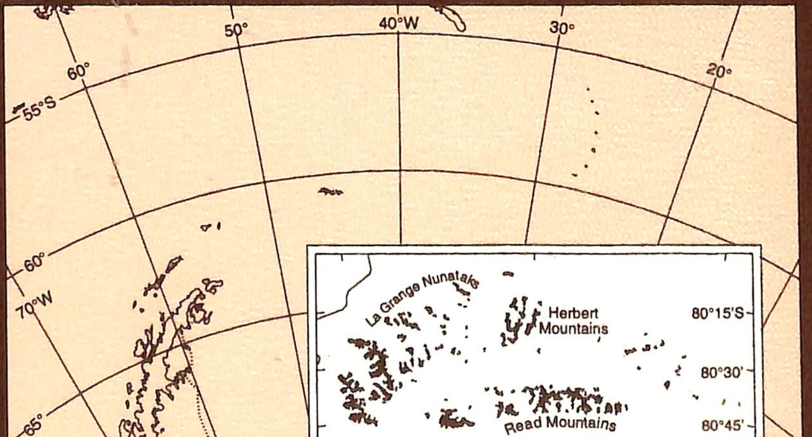
BAS GEOMAP Series
Geological Map and Supplementary Text

SHEET 4

Geological map of Shackleton Range, Antarctica

SCALE 1:250 000



CAMBRIDGE
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NATURAL ENVIRONMENT RESEARCH COUNCIL
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MAP COMPILED BY J.W. THOMSON

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GEOLOGICAL MAP OF SHACKLETON RANGE, ANTARCTICA
SUPPLEMENTARY TEXT

P.D. CLARKSON, F. TESSENSOHN, M.R.A. THOMSON, B. BELYATSKY, H.-M. BRAUN, W. BUGGISCH, G.E. GRIKUROV, J. HOFMANN, A. HÖHNDORF, E.N. KAMENEV, G.J. KAMENEVA, G. KLEINSCHMIDT, H. KREUZER, P.T. LEAT, M. OLESCH, H.-J. PAECH, R.J. PANKHURST, M. PETERS, N.W. ROLAND, W. SCHUBERT, I.A. SOLOVIEV, G. SPAETH, K.S. TECHMER, J.W. THOMSON, B. WEBER, K. WEBER, *and* S. KING

Abstract

The geological sheet map of the Shackleton Range represents the synthesis of numerous geological research programmes between 1967 and 1989. Such investigations have indicated that the ancient cratonic margin of East Antarctica apparently extended across the central part of the Shackleton Range, dividing it into two distinct belts, a cratonic southern and a non-cratonic northern part. All but the youngest stratigraphical units have been disrupted by a complex of thrusts and nappes during the Ross Orogeny, with movement directed toward the craton and orthogonal to the craton margin. In the north, supracrustal rocks, represented by the Pioneers Group (middle–late Proterozoic), are tectonically interleaved with high-grade metamorphic basement rocks belonging to the Stratton Group, probably the oldest rocks in the Shackleton Range (Archaean–middle Proterozoic). These metamorphic rocks are overlain in the north-western part of the range by undeformed sedimentary rocks of the Blaiklock Glacier Group (BGG). Apart from trace fossils there is no palaeontological evidence for the age of the BGG but it is believed to be between Cambrian and Devonian in age, possibly Ordovician. The southern belt comprises a basement of granitic orthogneisses and massive granitoids of the Read Group (early–middle Proterozoic), exposed in the Read Window anticline, upon which rest small remnants of an undeformed and unmetamorphosed Eocambrian platform cover, the Watts Needle Formation. At least three metamorphic events have been recorded in the Read Group: a relict early granulite-facies metamorphism, the main amphibolite-facies event (with its subsequent extensive retrograde stage) and a localized greenschist-facies metamorphism. The Watts Needle Formation has yielded stromatolites and acritarchs which are consistent with a Riphaean–Vendian age. Low-grade metasedimentary rocks of Lower–Middle Cambrian age (Mount Wegener Formation) in the east, and Late Precambrian–Palaeozoic age (Stephenson Bastion and Wyeth Heights formations) in the west overlie the Read Group and its cover. Mafic dykes are distributed throughout the range and intrude the oldest and the youngest rocks. They range from tholeiitic to alkaline in composition and are strongly discordant to the metamorphic foliation of the host rocks. Age determinations indicate several episodes of dyke intrusion; the metamorphosed dolerites of the Read Mountains are probably Late Proterozoic in age but most dykes were emplaced during the Palaeozoic and a few are Jurassic in age.

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Frontispiece. Aerial view of Read Mountains, southern Shackleton Range, looking eastward. Glen Glacier is in the foreground. (Photograph by M.R.A. Thomson)

1 Introduction

by P.D. Clarkson

The Transantarctic Mountains form an extensive sinuous escarpment across Antarctica, marking the ancient Pacific margin of the East Antarctic craton. This mountain chain extends unbroken from the ANARE Mountains on the coast of northern Victoria Land, south and south-eastward to the Horlick Mountains. From there it continues east and north-eastward as a less coherent chain of isolated groups of mountains toward the Pensacola Mountains and Coats Land (Fig. 1.1). How far the chain continues is a matter of geological, geomorphological and geographical debate; the Shackleton Range, in southern Coats Land, is one of these isolated groups of mountains.

The Shackleton Range (80°07'–80°50'S, 19°–31°W), located between Slessor and Recovery glaciers (Fig. 1.1), is an elongate mountain block about 240 km in length; its principal summits are 1500–1800 m in height. The range extends from an erosion scarp at the inland edge of the Filchner Ice Shelf eastward to where it is gradually submerged beneath the Antarctic ice sheet. To the north, across Slessor Glacier, are the Theron Mountains and to the south, across Recovery Glacier, are the Whichaway Nunataks; eastward there is no exposed rock before the coastal mountains of Enderby Land, 1800 km distant.

The following summary of exploration in the Shackleton Range covers the period until the end of the 1980s and Table 1.1 lists notable visits to the range, in chronological order, since 1955. Investigations under-taken since 1990 (USA in 1993–94 and the European Expedition to the Shackleton Range (EUROSHACK) in 1994–95) are not the subject of this report.

Early exploration of the Shackleton Range

The Imperial Trans-Antarctic Expedition (1914–16), led by Sir Ernest Shackleton, would probably have discovered the Shackleton Range on its planned traverse from Vahsel Bay (on the Filchner Ice Shelf) to the South Pole, although it is doubtful if there would have been time for any exploration. However, the expedition never reached land and its subsequent adventures are now a part of Antarctic history (Shackleton, 1919). Thus the Shackleton Range was not discovered until December 1955, well after the heroic age of Antarctic exploration was over, when an aircraft from the Argentine "Base Belgrano" observed the range from the air. The flight approached the Theron Mountains ("Montes Rufino"), turned south-west to cross the Shackleton Range ("Cordón Los Menucos"), and continued on to the northern Pensacola Mountains before returning to base (Pujato, 1977). The Argentines did not pursue their discovery and the Spanish names have not survived in the literature.

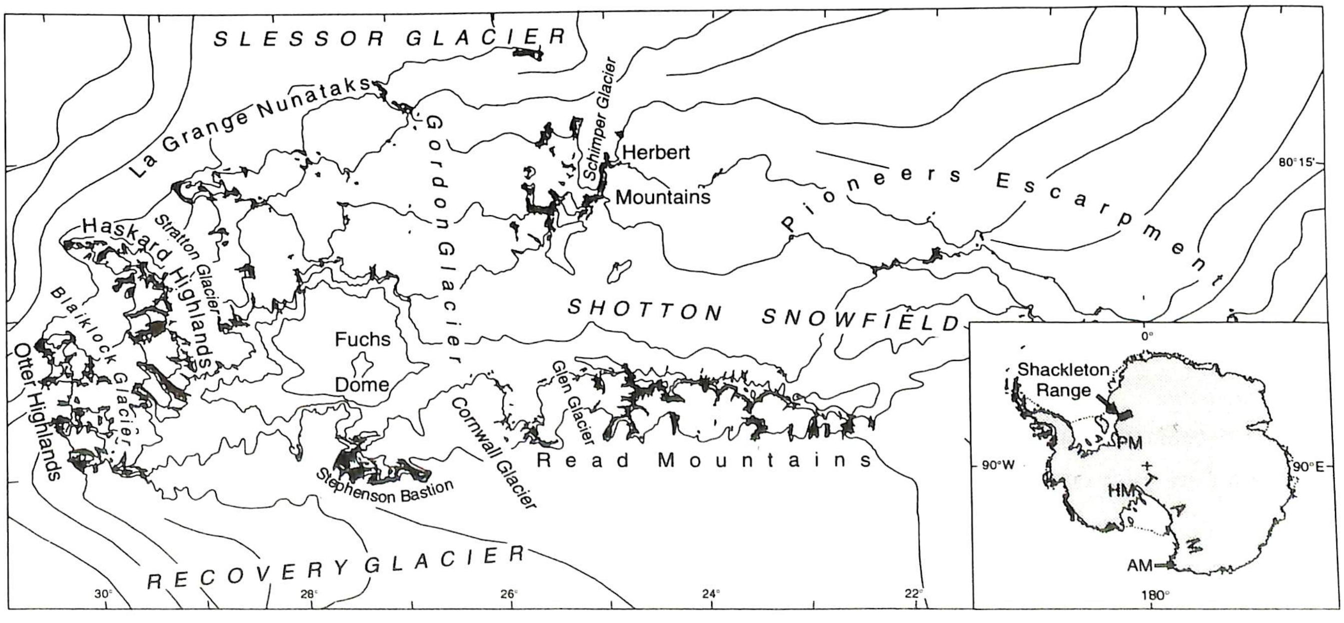

Fig. 1.1. Sketch map of the Shackleton Range showing the location of the principal place-names referred to in the text; black areas represent rock outcrop. Inset map of Antarctica indicates the geographical relationship of the Shackleton Range to the Transantarctic Mountains (TAM); AM, ANARE Mountains; HM, Horlick Mountains; PM, Pensacola Mountains.

Table 1.1. Chronology of exploration of the Shackleton Range before 1990

Date	*Nationality*	*Type of expedition*	*Work undertaken*	*Personnel*	*Reference*
Dec. 1955	Argentine	Air reconnaissance	Aerial observation only	Aircrew	Pujato (1977)
7 Feb. 1956	UK	Air reconnaissance	Aerial observation only	Aircrew	Fuchs and Hillary (1959)
20 Jan. 1957	UK	Air reconnaissance	Aerial observation and hand-held air photography	Aircrew	Fuchs and Hillary (1959)
Oct. 1957	UK	Ground traverse with two dog teams	Triangulation survey and geological reconnaissance	2 surveyors and 1 geologist	Blaiklock and others (1966); Stephenson (1966)
10 Feb. 1964	USA	Air reconnaissance	Aerial observation only	Aircrew	Anonymous (1964)
Dec. 1967	USA	Aerial survey	Trimetrogon air photography	Aircrew	Anonymous (1968*a*)
Nov. 1968	UK	Tractor traverse	Reconnaissance mapping, geomorphological observation and geological collecting	3 mechanics and 3 field assistants	Fuchs (1982)
Nov. 1968 to Jan. 1969	UK with US air support	Ground traverse with three dog teams	Triangulation and trilateration survey network and geological reconnaissance survey	2 surveyors with 2 field assistants, 2 geologists	Fuchs (1969)
Nov. 1969 to Jan. 1970	UK with US air support	Ground traverse with three dog teams	Triangulation and trilateration survey network and geological reconnaissance survey	2 surveyors and 1 geologist with 3 field assistants	Fuchs (1970)
Nov. 1970 to Feb. 1971	UK with US air support	Ground traverse with three dog teams	Geological reconnaissance survey	2 geologists with 2 field assistants	Clarkson (1971)
1975–76 season	USSR	Ground party with helicopter support	Geological reconnaissance	Grikurov and others	Soviet CAR (1976)
1976–77 season	USSR	Ground party with helicopter support	Detailed mapping of selected areas	Grikurov and others (2 US geologists)	Soviet CAR (1977)
Nov.1977 to Feb. 1978	UK	Ground traverse with two motor toboggans	Geological survey	2 geologists with 2 field assistants	BAS (1978*a*)
1977–78 season	USSR	Ground party with helicopter support	Detailed geological survey of selected sections	Kamenev and 4 other geologists (1 GDR)	Soviet CAR (1978)
1978–79 season	USSR	Ground party with helicopter support	Geological mapping with airborne reconnaissance	?	Soviet CAR (1979)
1981–82 season	USSR	Ground party with helicopter support	Detailed geological sections and mapping	?	Soviet CAR (1982)
1982–83 season	USSR	Ground party with helicopter support	Detailed geological sections and mapping; some aero-gravimetric survey in the vicinity	?	Soviet CAR (1983)
1987–88 season	FRG	Ground party with helicopter support	Detailed mapping in four main areas		Roland (1994)

The Trans-Antarctic Expedition

The Commonwealth Trans-Antarctic Expedition (1955–58), led by Dr (later Sir) Vivian Fuchs, planned to cross the continent via the South Pole and also to explore the region within aircraft range of its base "Shackleton" on the Filchner Ice Shelf, 38 km east of "Base Belgrano [I]". During a reconnaissance flight on 7 February 1956 the Shackleton Range was sighted. Nearly a year later, on 20 January 1957, the expedition's single-engined Otter aircraft flew across the range and various glaciological observations and geological speculations were made. In October of that year two survey parties were flown to the western end of the range and established a field camp at the base of Mount Provender. P.J. Stephenson, the expedition geologist, made a brief geological survey of the mountains flanking Blaiklock Glacier (Fig. 1.2). Meanwhile, the surveyors K.V. Blaiklock and D.G. Stratton established a triangulation network at the western

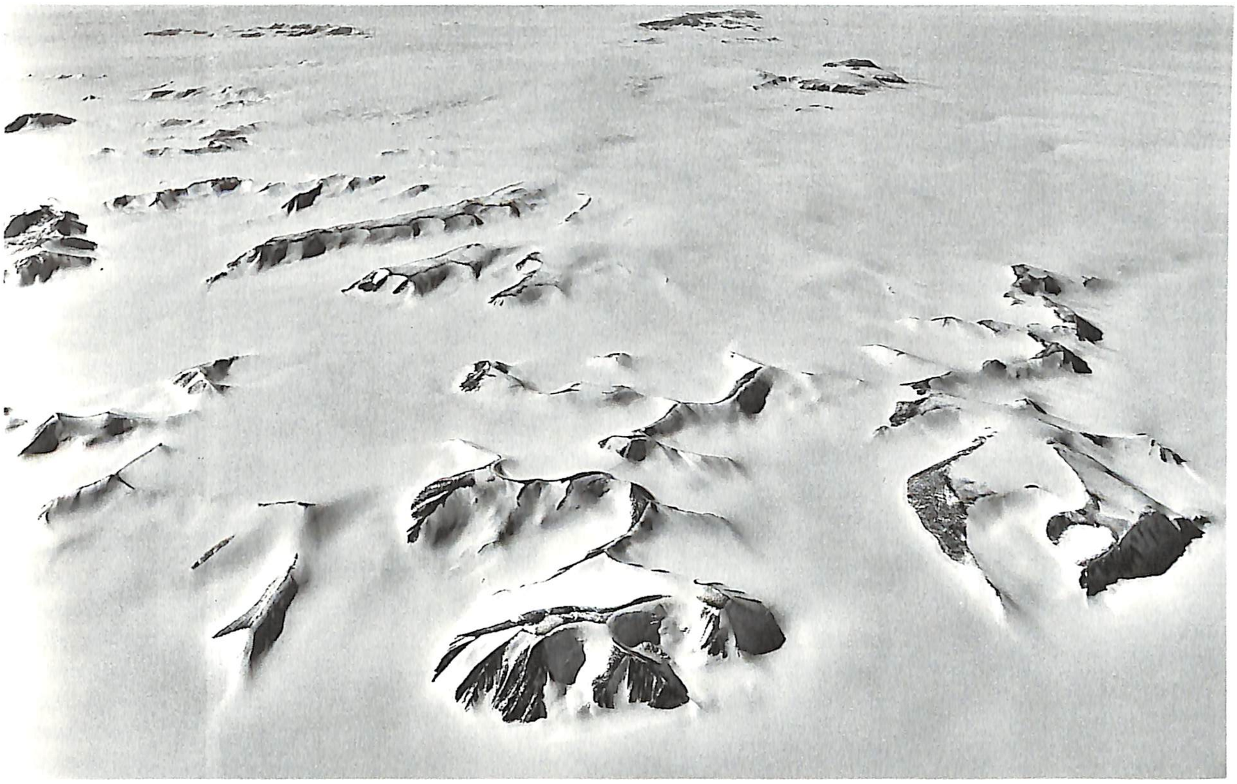

Fig. 1.2. Oblique aerial photograph of the Shackleton Range, looking east over the Otter Highlands (foreground) to the Read Mountains (centre, distance) and Herbert Mountains (far left). (US Navy photograph, TMA 2048 F31 054)

end of the range and extended this eastward while traversing around Fuchs Dome (Blaiklock and others, 1966). During their travels they collected many rock specimens, which enabled Stephenson to extrapolate the known geology farther east. Both the topographic and geological surveys were extended by using hand-held oblique air photographs of areas not visited on the ground and in just a few weeks sufficient data had been gathered to make very respectable reconnaissance topographic and geological maps of the western part of the Shackleton Range (Fuchs and Hillary, 1959).

The work by Stephenson proved to be remarkably comprehensive. The western end of the range includes representatives of each of the major rock groups exposed in the range and he was able to visit most of these. As a result he identified a Precambrian basement of medium- to high-grade schists and gneisses ("Shackleton Metamorphics"; see Appendix 1) overlain in the south by a distinct group of low-grade metamorphic slates and quartzites ("Turnpike Metamorphics") and in the north and west by undeformed sedimentary rocks ("Blaiklock Beds"). The last group he divided into upper and lower formations, and the brachiopod-bearing shales, observed as erratics on the moraine below Mount Provender, he assigned to unexposed intermediate strata hidden beneath Blaiklock Glacier (Stephenson, 1966). Stephenson had successfully established the broad stratigraphical framework for the range that is still the basis for modern geological interpretation, albeit with much revision and expansion of detail.

National investigations

US overflights: The range was not visited on the ground for another 11 years but during this interval a US Navy LC-130F Hercules aircraft overflew part of the eastern end of the range (Anonymous, 1964). One point in this flight can be established with certainty. In December 1977, E.J. Wright, sledging with P.D. Clarkson in the eastern nunataks of the range, saw a black object protruding from the snow in Nobleknausane. It proved to be a flagpole with a sharpened, weighted lower end. The remains of the "Stars and Stripes" were attached to the upper end, above the pennant of a US Navy admiral. Inside the top end of the pole was a note to the finder signed by "James R. Reedy, Rear Admiral, United States Navy, Commander, U.S. Naval Support Force, Antarctica" and the statement:

> "THIS FLAG AND MESSAGE WAS DROPPED FROM A UNITED STATES NAVY AIRCRAFT OVERFLYING THIS UNCHARTERED LAND BY REAR ADMIRAL JAMES R.REEDY, U. S. NAVY ON THE TENTH DAY OF FEBRUARY IN THE YEAR OF OUR LORD NINETEEN HUNDRED AND SIXTY FOUR."

The position of the flag was very close to 80°40'S, 19°46'W.

The next phase in the exploration of the Shackleton Range happened by accident, quite literally in one sense, during December 1967. Following a medical emergency at the British base "Halley Bay" (now referred to as Halley) on the Brunt Ice Shelf, a request for evacuation was sent to the US authorities. With astonishing speed

Fig. 1.3. Oblique aerial photograph looking east along the Read Mountains to Pioneers Escarpment (scattered eastern nunataks in distance, left). Glen Glacier is in the foreground and Watts Needle is at extreme right, with Recovery Glacier beyond. (US Navy photograph, TMA 2051 F33 294)

and great generosity the US Navy despatched two LC-130 Hercules from McMurdo Sound to effect the medical evacuation to New Zealand (Anonymous, 1968*b*,*c*; Fuchs, 1982). One aircraft acted as a com-munications relay and occupied its time by taking air photographs of the Shackleton Range, providing complete trimetrogon coverage (Anonymous, 1968*a*; see Figs 1.2–1.4).

British: In January 1968, two British Antarctic Survey (BAS) field parties from Halley used dog teams to find a safe route south from the Theron Mountains, where BAS geologists had completed their work, across Slessor Glacier and into the Shackleton Range. The parties reported having to make a long traverse eastward toward the head of the glacier before a crossing point could be found. One party had found a route and reached within 50 miles of the range before having to turn back and the other had attempted to reconnoitre a direct route back to the base; both parties eventually had to return via the Theron Mountains (Noble, 1968). Thus it was decided that the Shackleton Range was too far away from the British base to support mountain field parties overland.

British–US: At the X SCAR meeting in Tokyo in 1968, Sir Vivian Fuchs reached an agreement with the Americans whereby British surveyors would provide ground control for the US trimetrogon air photographs of the range in exchange for air transport of British personnel into the field. On 22 November 1968, two Hercules aircraft landed at Halley, loaded six men, three sledges, tents, equipment and supplies, together with 27 huskies, for a three-month season in the Shackleton Range. The air party comprised two surveyors (K.V. Blaiklock and A. True) who had flown in with the Americans via McMurdo Station and South Pole, two general assistants (N. Mathys and T.H. Wiggans) and two geologists (M.J. Skidmore and P.D. Clarkson). Blaiklock, who had started the survey work during the Trans-Antarctic Expedition, had been asked to return for the summer to provide continuity to the survey programme.

Meanwhile, a tractor party from Halley had been travelling overland for more than three weeks. BAS personnel (J.F. Carter, W.A. Etchells, J.M. Gallsworthy, A.S. MacQuarrie, P.H. Noble and N.W. Riley) with two tractors and two bulldozers towing 12 sledges, with a living caboose and 28.5 tonnes of supplies, had driven direct from the inland margin of the Brunt Ice Shelf to the point near the head of Slessor Glacier where the dog teams had made a safe crossing during the previous season (Fuchs, 1982). From there they had followed the route pioneered by the dogs and continued into the eastern nunataks of the Shackleton Range (Fig. 1.3), arriving on 22 November just ahead of the air party, after driving nearly 800 km. Their main purpose had been to prove a safe overland route and stock it with supply depots so that it could be used by dog teams forced to return overland to Halley. The members of the tractor party also explored their immediate surroundings, drew a sketch map of the area, made geomorphological observations, collected many rock specimens and made several first ascents of the local peaks. They had made a useful addition to geological knowledge of the eastern end of the range and the substantial depot of supplies left there was invaluable to ground parties in later seasons.

While the tractor party was celebrating its arrival in the eastern part of the Shackleton Range, the air party was making the one hour flight from Halley to the mountains. Commander Eugene van Reeth flew farther south into thickening weather and it began to look as though the aircraft would have to return to the South Pole to refuel when he managed to descend through the cloud on the south side of the range. The first attempted landing was incredibly bumpy but the second attempt was successful. The navigating officer reckoned from the radar that the landing site was about 13 km south-west of Mount Greenfield. After some 24 hours the visibility improved and the mountains loomed into view to the north, a long way away. True did a sunshot to establish the approximate position of the aircraft party; they were actually on Recovery Glacier, about 48 km from Mount Greenfield. Eight days were spent relaying the entire 5 tonnes of equipment some 30 km closer to Mount Greenfield. The two survey parties (Blaiklock and Wiggans, True and Mathys) traversed anticlockwise around Fuchs Dome, returning to survey points established by Blaiklock and Stratton during the Trans-Antarctic Expedition, to provide a link between the old and new survey networks. They consolidated the ground control network in the western part of the range and began a traverse eastward into the Read Mountains (Fig. 1.3). Skidmore and Clarkson made a rapid traverse around the area of Blaiklock and Stratton glaciers, revisiting localities described by Stephenson and extending the mapping coverage. Then they moved into the southern Herbert Mountains, western Read Mountains and the southern and western sides of Stephenson Bastion, breaking new ground and confirming some of the observations made by Stephenson on specimens collected by the survey party during the Trans-Antarctic Expedition (Fuchs, 1969).

In 1969–70, the Americans flew a second party to the range to complete the survey network and to extend the geology (Fuchs, 1970). C.A. Clayton and True (surveyors), Clarkson (geologist), and M.C. Guyatt, Wiggans and G.K. Wright (assistants), were established in a camp on Gordon Glacier, south of Lewis Chain, in a convenient position for continuing work to the east. Clarkson and Wiggans travelled eastward along the northern side of Pioneers Escarpment, to link the geology of the Herbert Mountains to largely similar rocks collected by the tractor party during the previous season. Further reconnaissance geological mapping was also undertaken in the Read Mountains, Herbert Mountains, the northern side of Stephenson Bastion, and at La Grange Nunataks. The surveyors circumnavigated Read Mountains, Shotton Snowfield and Pioneers Escarpment, establishing a firm link to the ground control in the western part of the range. By linking the triangulation and trilateration network to all the air photograph runs, the British–US collaboration enabled the US Geological Survey to produce an excellent 1:250 000 scale topographic map of the Shackleton Range (US Geological Survey, 1983).

During the 1970–71 season the Americans provided air support for a third BAS party to continue with the geological investigation of the Shackleton Range. Clarkson and R.B. Wyeth (geologists), accompanied by Wright and M.A. Warden (assistants) and three dog teams, were airlifted from Halley to a landing site on Stratton Glacier. Wyeth and Wright worked extensively in the western part of the range, consolidating the known geology and mapping many previously unvisited areas. Clarkson and Warden carried out similar work in the Herbert and Read mountains. This work completed the series of BAS–US field seasons on the Shackleton Range (Clarkson, 1971).

Soviet: In the 1975–76 season, the 21st Soviet Antarctic Expedition sailed into the Weddell Sea and established their base Družnaja-1 (77°34'S, 40°13'W), on the Filchner Ice Shelf. G.E. Grikurov led the geological reconnaissance programme that included flights to Touchdown Hills, Shackleton Range, Pensacola Mountains and Vestfjella (Kraulberga). On the ground, the party visited the area south and west of Mount Provender, mapping the angular unconformity between the early Precambrian basement rocks and the overlying sedimentary cover. The most important and exciting discovery was that of the trilobite fossils found on erratic shale blocks in the moraine below Mount Provender. These occurred in the general vicinity of the poorly preserved brachiopod specimens collected by Stephenson (1966), assigned by him to unexposed intermediate strata of the sedimentary sequence hidden beneath Blaiklock Glacier (Soviet Committee on Antarctic Research, 1976).

The 1975–76 Soviet expedition also served as a geological and logistic reconnaissance for planned future work from Družnaja-1. Accordingly, Grikurov led a second party to the Shackleton Range in 1976–77, visiting 40 different selected sites. Detailed sedimentary sections were constructed at many of these sites and at one of them, at the north-western extremity of Mount Wegener (in the Read Mountains), organic remains were collected. These later proved to be stromatolites, confirming a Precambrian age for the host limestones at this locality, and providing the first reliable age for any of the sedimentary rocks found *in situ* in the Shackleton Range (Soviet Committee on Antarctic Research, 1977).

The 22nd Soviet Antarctic Expedition (1976–77) included the American geologist E.S. Grew as a summer exchange scientist with the Soviet programme (Grew, 1977). He made petrological studies of the crystalline rocks, working from the camp at Mount Provender. Later in the season, A.B. Ford, another American geologist, joined Soviet field parties in the central Read Mountains and at La Grange Nunataks, working with them as part of his comparative study between the Pensacola Mountains and the Shackleton Range (Ford, 1977). Scientists from the German Democratic Republic frequently took part in the Soviet programmes and this

Fig. 1.4. Oblique aerial photograph of the western part of the Shackleton Range, viewed from the east. Herbert Mountains are in the foreground, Mount Sheffield is at extreme right, and the scattered nunataks of La Grange Nunataks and Haskard Highlands are in the distance; Slessor Glacier flows from right to left at right of photograph. (US Navy photograph, TMA 2052 F33 389)

year the geologist H.-J. Paech was a member of the Soviet field party.

In addition to the 1977–78 Soviet expedition (see below), the annual Soviet Antarctic Expeditions placed further geological field parties in the range in the 1978–79, 1981–82 and 1982–83 seasons. The principal activities of these parties were to continue the geological research, building on the work of previous seasons and selecting new areas for investigation, either where the geology was unknown or where there appeared to be value in revisiting areas of known geology. The last season also included aero-gravimetric surveys in the general vicinity of the Shackleton Range.

British and Soviet expeditions: During the 1977–78 season two national expeditions (British and Soviet) worked in the Shackleton Range. The *Soviet* party of five geologists and a radio operator was led by E. M. Kamenev and included J. Hofmann of the German Democratic Republic. The *British* geological party of Clarkson and P.D. Marsh (geologists), with their assistants G.A. Holden and E.J. Wright, used motor toboggans in place of dog teams for the first time; the British party was established on Gordon Glacier, just south of Lewis Chain, using a Twin Otter aircraft (British Antarctic Survey, 1978*a*). Clarkson continued to work in the eastern part of the range and in the southern Herbert Mountains (Fig. 1.4) while Marsh carried out detailed mapping in the northern areas between Blaiklock and Stratton glaciers, through La Grange Nunataks and into the northern Herbert Mountains. The two parties met first at La Grange Nunataks when the Soviet party, in an Antonov-2 bi-plane, made a courtesy call to Marsh and Holden. Later both British parties camped together with the Soviets below Sumgin Buttress, in the Herbert Mountains. The Soviet party worked mainly in the region of the Herbert Mountains and included a visit to Mount Sheffield, on the southern margin of Slessor Glacier. This visit was made by helicopter and Marsh was invited to join the party, an invitation he gratefully accepted.

German: The Shackleton Range is certainly not the most remote mountain area in the Antarctic in terms of its distance from the coast but the ability to work there requires a major logistic effort. It was only the Soviet Expeditions, working from Družnaja-1 with long-range MI-8 helicopters, that were able to support field parties in the range without too much difficulty. Other national expeditions had worked there at the limit of their logistic capabilities. Thus, although geologists from the Federal Republic of Germany began planning a field season in 1985, it was not until the 1987–88 season that they were able to mount their field programme.

The Geologische Expedition in die Shackleton Range (GEISHA) was transported by RV *Polarstern* to Antarctica, arriving at the British research station Halley early in January 1988 (Kothe and others, 1994). A group of 27 scientists and support staff, including four pilots and three engineers for the two Dornier 228-100 fixed-wing, ski-equipped aircraft and two twin-engined Bölkow 105 helicopters, was established in a base camp on the Brunt Ice Shelf. A second base camp was established by air in the Shackleton Range, in the long valley on the northern side of Stephenson Bastion, below Clayton Ramparts, at 80°44'S, 27°11.5'W. Satellite field camps were then emplaced by helicopter throughout the Read Mountains, in southern Otter Highlands, below Mount Provender and at Mount Skidmore. The combination of helicopters and motor toboggans was used to good effect so that even when weather conditions prevented helicopter flying, the geologists were able to travel on the ground using toboggans. A total of 41 days was spent in the range, carrying out stratigraphical correlation and lithological studies of the "Turnpike Bluff Group" (see Appendix 1) and Blaiklock Glacier Group, collecting samples of the crystalline basement rocks for petrological and geochronological work, and of the mafic dykes for geochemical and palaeomagnetic studies (Roland, 1994). Extensive structural investigations were made at all the sites visited, and glacial erratics and other glacial features were mapped.

Geological setting

Geological investigations of the Shackleton Range have indicated that the ancient margin of the East Antarctic craton apparently extended across the central part of the range, dividing it into two distinct belts, a cratonic southern and a non-cratonic northern part. All but the youngest stratigraphical units have been disrupted by a complex of thrusts and nappes during the Ross Orogeny, with movement directed toward the craton and orthogonal to the craton margin. In the northern belt, supracrustal rocks represented by the Pioneers Group (middle–late Proterozoic) are tectonically interleaved with high-grade metamorphic basement rocks belonging to the Stratton Group, these are probably the oldest rocks in the Shackleton Range (Archaean–middle Proterozoic). The metamorphic rocks are overlain in the north-western part of the range by undeformed sedimentary rocks of the Blaiklock Glacier Group (BGG). Apart from trace fossils there is no palaeontological evidence for the age of the BGG but it is believed to be between Cambrian and Devonian in age, possibly Ordovician.

The southern belt comprises a basement of granitic orthogneisses and massive granitoids (the Read Group (early–middle Proterozoic)), exposed in the Read Window anticline, upon which rest small remnants of an undeformed and unmetamorphosed Eocambrian platform cover, the Watts Needle Formation. The Watts Needle Formation has yielded stromatolites and acritarchs which are consistent with a Riphaean–Vendian age. Low-grade metasedimentary rocks of Lower–Middle Cambrian age (Mount Wegener Formation) in the east, and Late Precambrian–Palaeozoic age (Stephenson Bastion and Wyeth Heights formations) in the west overlie the Read Group and its cover.

Mafic dykes are distributed throughout the Shackleton Range and intrude the oldest and the youngest rocks. They range from tholeiitic to alkaline in composition and are strongly discordant to the metamorphic foliation of the host rocks. Age determinations indicate several episodes of dyke intrusion; the metamorphosed dolerites of the Read Mountains are probably Late Proterozoic in age but most dykes were emplaced during the Palaeozoic and a few are Jurassic in age.

The terminology adopted for the stratigraphical units of the Shackleton Range has changed as geological research progressed. A summary of all the old stratigraphical terms and those in current use in this volume are listed in Appendix 1.

Conclusions

The exploration of the Shackleton Range has been very largely related to geological investigations, in common with the exploration of many other areas of the Antarctic. However, the part played by the surveyors must not be forgotten, as they enabled the preparation of a variety of excellent maps, which scientists today may too easily take for granted. This brief introduction to the exploration of the Shackleton Range has inevitably concentrated on the early expeditons, when the whole area was *terra incognita*, but it is not intended to belittle the achievements of later expeditions. The character of each succeeding field party has gradually changed from a combination of geographical exploration and geological mapping to a focus on geological research. The early reconnaissance geological surveys laid the basic foundations of stratigraphy and structure that have pointed to specific research problems; these, in their turn, have provided some answers but have invariably posed further questions. The Shackleton Range lies at a geological crossroads between the craton of East Antarctica, the Transantarctic Mountains and the enigmatic tectonic provinces that together constitute West Antarctica. This volume relates the geological story to date; there is no doubt that the Shackleton Range holds further secrets that will be yielded in the future to enhance our understanding of the geology of the Antarctic continent as a whole.

2 Read Group

by M. Olesch, H.-M. Braun, E.N. Kamenev, G.I. Kameneva and W. Schubert

Synopsis

Short description: The Read Group is a sequence of high- to medium-grade metamorphic rocks intruded by predominantly granitic to granodioritic plutons and veins. This newly named group (Tessensohn and Thomson, 1990) is, in general, the equivalent of the older gneisses of the "Shackleton Range Metamorphic Complex" of Clarkson (1982*a*). Smaller ultrabasic and basic intrusions occur as relicts. These polymetamorphic gneisses, amphibolites and magmatic rocks form the basement in the central southern and south-eastern part of the Shackleton Range.

Geographical location: Read Mountains (80°37´–80°46´S, 22°20´–26°20´W), especially outcrops at (from west to east) Du Toit Nunataks, The Ark, Murchison Cirque, Beche Blade, Eskola Cirque and Mount Wegener.

Metamorphism and tectonics: The oldest metamorphic event is represented by upper amphibolite-facies and, locally, relict granulite-facies rocks; related deformation structures (pre-D_1) are commonly indistinct. The main metamorphic event is characterized by amphibolite-facies conditions, which were of sufficient grade to cause migmatization in some places. The deformational event D_1 correlates with this progressive metamorphism, D_2 with an extended retrogressive metamorphic event, possibly representing the Nimrod orogeny. Greenschist-facies metamorphism, corresponding to D_3, is attributable to the Ross orogeny, and is associated with shear zones.

Age and stratigraphical range: The Read Group consists of Archaean and Proterozoic basement. In the eastern part of the Read Mountains the basement is overthrust by the Watts Needle Formation and, in the western part, it is unconformably overlaid by the Stephenson Bastion Formation. The youngest reliably datable event in the Read Group is the intrusion of granodioritic dykes at *c.* 1300 Ma.

Introduction

Stephenson (1966) published the first geological sketch map of the Shackleton Range, showing "Turnpike Metamorphics" in the southern and south-eastern parts of the range, underlain by a group of rocks referred to as the "Shackleton Metamorphics". It was suggested that the two groups of rocks were separated by an unconformity. The age of the sequence was estimated to be pre-Permian. Later geological investigations proved that the "Shackleton Metamorphics" form the crystalline basement of the south-eastern Shackleton Range, in an area named Read Mountains. Clarkson (1972) redefined the "Shackleton Metamorphics" as the "Shackleton Range Metamorphic Complex" (SRMC) and suggested that it was middle Precambrian in age. More detailed work allowed a litho-stratigraphical division of the SRMC into two parts: the older gneisses and the younger schists (Clarkson, 1982*a*). The older gneisses cropping out in the Read Mountains generally correspond to the Read Group of Tessensohn and Thomson (1990) and they are described below. They probably form part of the Antarctic shield.

Marsh (1983*a*) renamed the crystalline basement of the Shackleton Range as "Basement Complex" and estimated that it was mid- to early Proterozoic or late Archaean in age. Paech (1986, p. 100 *et seq.*), confirming this age, revived the term SRMC ("Shackleton-Range-Kristallinkomplex") but made a regional division into "Read-Gruppe"/"Provender-Gruppe" and "Skidmore-Gruppe" for the southern and north-western parts of the Shackleton Range, respectively. This division was modified by Buggisch and others (1990), who created the term "Read Mountains Basement Complex" for basement rocks in the south. The variety of litho-stratigraphical terms used in the past to describe the Precambrian metamorphosed crystalline basement of the southern Shackleton Range (see Appendix 1) has now been rationalized, and the name Read Group (Tessensohn and Thomson, 1990) has been adopted for the infracrustal rocks described in this chapter.

The age of these infracrustal rocks is imprecisely known. Metasedimentary rocks of the Watts Needle Formation have yielded K-Ar ages of 580–720 Ma (peak of metamorphism) and were thrust over the Read Group at *c.* 500 Ma. K-Ar and Ar-Ar data indicate an age of c. 900–1200 Ma for the overlying Late Proterozoic Stephenson Bastion Formation and, based on Rb-Sr analyses, the emplacement of granites and granodiorites occurred at *c.* 1760 Ma. The intrusion of granodiorite dykes at *c.* 1300 Ma provides the youngest reliably datable event in the Read Group (Pankhurst and others, 1983).

Lithology and metamorphism

The Read Group comprises a wide variety of metamorphic and plutonic rocks: arenaceous and argillaceous to carbonaceous sedimentary facies are represented by quartzites, schists, amphibolites, gneisses and migmatites, and the plutonic rocks have alkali-granitic to tonalitic and dioritic compositions. There are rare occurrences of metabasaltic dykes (see Chapter 11).

The majority of outcrops assigned to the Read Group occur in the central part of the Read Mountains, between Watts Needle and Mount Wegener. A description of the

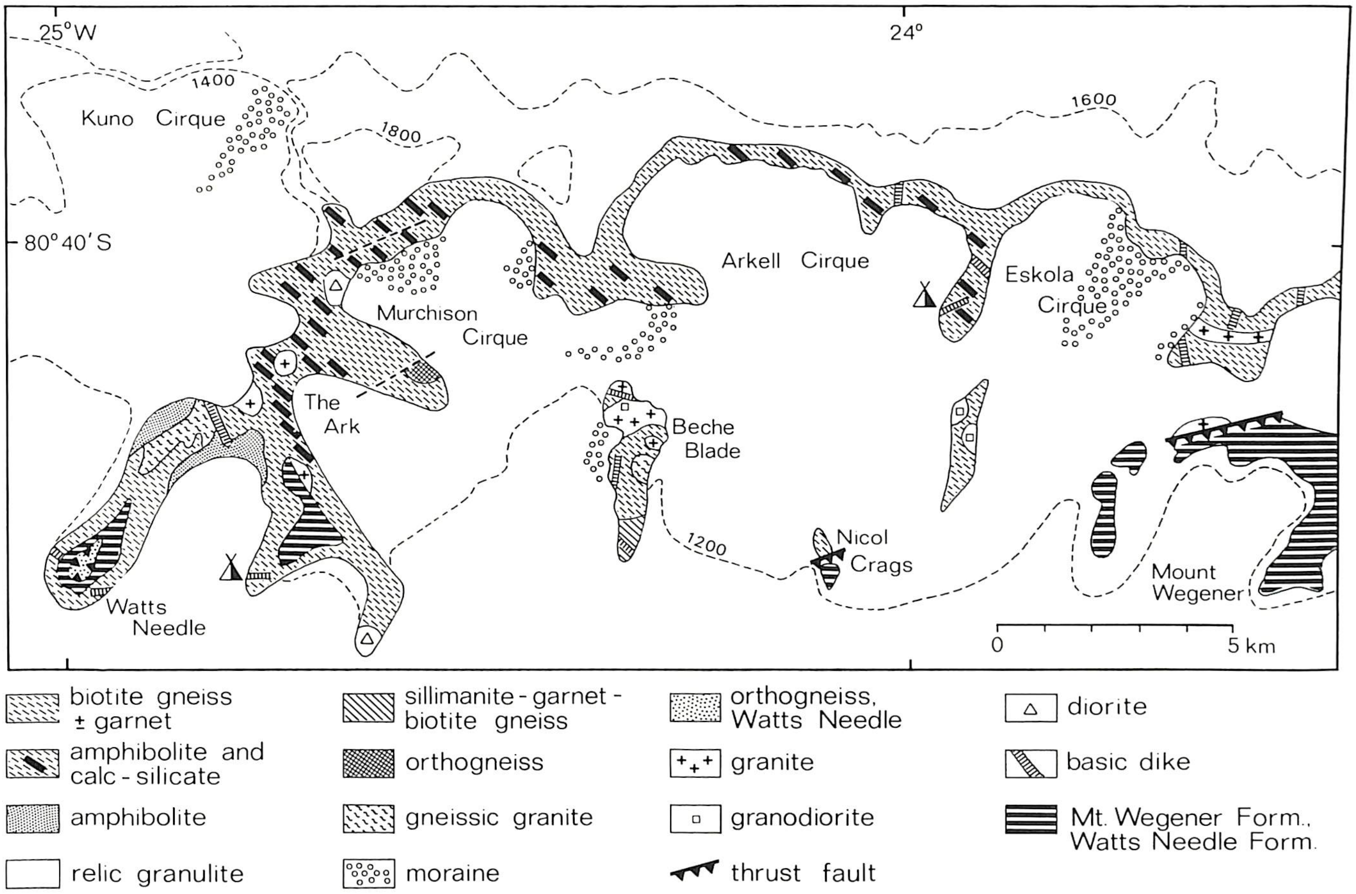

Fig. 2.1. Sketch map showing the distribution of lithofacies of the Read Group in central Read Mountains; tectonic boundaries are omitted.

different lithologies was given by Clarkson (1982*a*) and more detailed geological mapping by the 1987–88 German Geological Expedition to the Shackleton Range (GEISHA) has enabled the preparation of a simplified lithofacies map of the area (Fig. 2.1). The distribution of the different rock types shown is based primarily on the 1987–88 fieldwork; later petrographical investigations revealed the presence of relict granulites, especially in the amphibolites. Biotite-bearing gneisses, with or without garnet, are the predominant rock type of the Read Group. Layers of amphibolite and calc-silicate rock, up to several metres in thickness, are commonly intercalated with the gneisses, and amphibolites occur also in nearly homogeneous layers which are several tens of metres in thickness. These amphibolite bodies exhibit conformable as well as discordant boundaries against the host rock, indicating possible inherited intrusive contacts. Smaller areas, for instance the southern part of Beche Blade, contain higher-grade sillimanite-bearing gneisses.

Intrusive rocks occur as geothermally altered and structurally deformed orthogneisses (on the west side of Murchison Cirque), as deformed gneissic granites (e.g. west of The Ark and at the east side of Beche Blade; Figs 2.2 and 2.3), and as virtually unmetamorphosed granitic–tonalitic rocks. Diorite crops out on the west side of Murchison Cirque and it represents the most basic intrusive rock in the area, other than the mafic dykes and relicts of strongly altered gabbroic and small ultrabasic bodies.

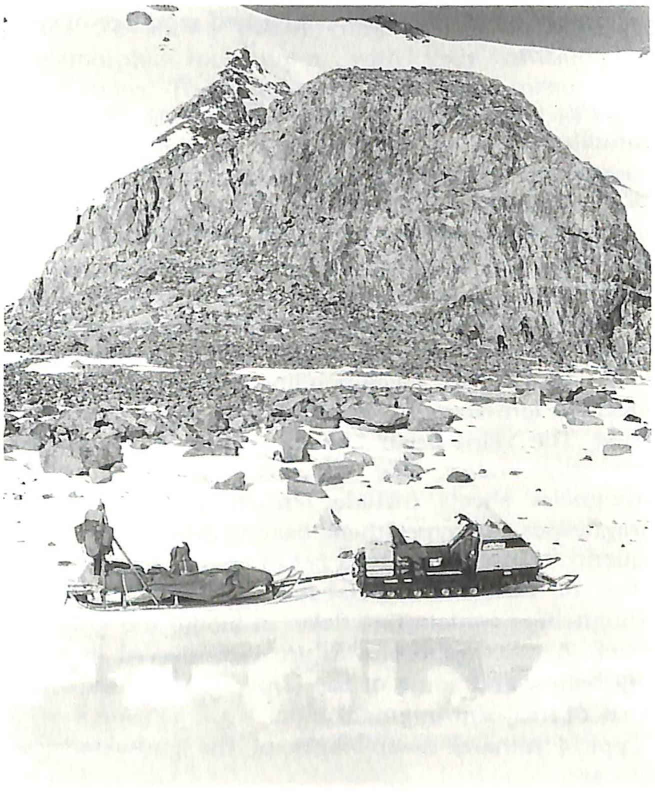

Fig. 2.2. Gneissic granite from the west side of Beche Blade, central Read Mountains.

Fig. 2.3. K-Feldspar porphyroblasts in foliated granite, Beche Blade, central Read Mountains.

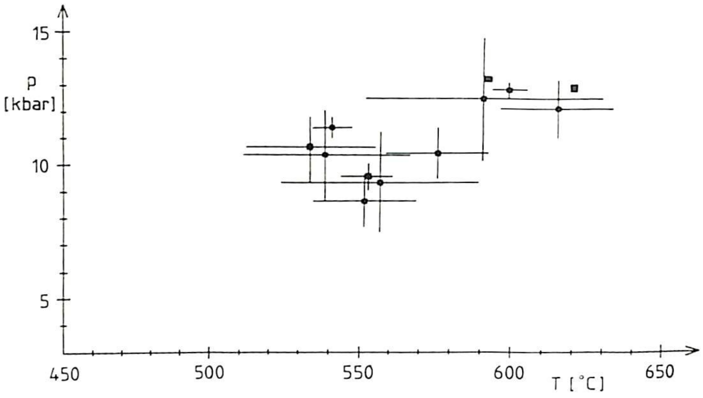

Fig. 2.4. Pressure–temperature estimate for gneisses from Beche Blade, based on the ternary feldspar geothermobarometer of Green and Usdansky (1986).

Sequence of metamorphic events: Granulite-facies rocks represent the oldest metamorphic event but typical phase associations have been recorded as relicts only. Pressure–temperature conditions have been estimated at 8–12 kbar and 540–580°C, respectively; this relatively low temperature range indicates a transition to the upper amphibolite facies. Amphibolite-facies conditions *sensu stricto* were reached during a younger event, followed by an extensive retrograde stage, both stages recording the main metamorphic event affecting the Read Group. Greenschist-facies conditions, observed locally in shear and fracture zones, represent the youngest metamorphic event in the region. These three metamorphic events (or four, if the extensive retrogressive stage of the amphibolite facies is considered to be a separate event) correlate perfectly with the established sequence of rock deformation.

Granulite-facies metamorphism: The most prominent granulite-facies rock sequence crops out at Eskola Cirque. It comprises monoclinal dipping sheets, 40–180 m in thickness, of leucocratic granitic orthogneisses, garnet-biotite-paragneisses, garnet-hypersthene- and biotite-hypersthene- (charnockitic) orthogneisses, and metabasites (biotite-pyroxene-andesine-, pyroxene-labradorite-andhornblende-pyroxene-labradorite-schists).

The sheets of gneisses include lenses or subangular blocks (similar to mega-boudins) of metabasite and deformed lens-shaped veins of granitic to granodioritic gneiss. The veins occur outside as well as within the metabasite bodies. The metabasite and charnockitic orthogneiss sheets include lens-shaped xenoliths of paragneisses and hypersthene-bearing orthogneisses. The sequence is intersected by a net of aplitic veins and rare dykes of Palaeozoic metabasalt. Leucocratic granitic orthogneisses contain rare flakes of biotite and grains of garnet. A relict gabbroic texture is preserved in some metabasites, and some of the (?)paragneisses show the effects of incipient migmatization.

Typical mineral assemblages of the granulite-facies rocks are:

(a) Hypersthene + plagioclase ($An_{47\text{-}52}$) ± K-feldspar ± quartz ± garnet ± biotite,
(b) Hypersthene + augite + plagioclase ($An_{49\text{-}62}$) ± hornblende ± biotite ± quartz,
(c) Garnet + hypersthene + plagioclase ($An_{35\text{-}45}$) + quartz ± K-feldspar ± biotite,
(d) Garnet + biotite + plagioclase ($An_{30\text{-}45}$) + K-feldspar + quartz, and
(e) Plagioclase ($An_{25\text{-}30}$) + K-feldspar + quartz ± garnet ± biotite.

This sequence of assemblages reflects increasing silica content in the rock chemistry.

In many instances these mineral assemblages have been altered by the younger amphibolite-facies metamorphic event. Newly formed minerals (hornblende, biotite, microcline, muscovite) are superimposed on the older assemblages and, as a result, the metabasites and garnet- and/or hypersthene-bearing gneisses are altered to biotite-amphibolites and biotite-garnet-microcline-gneisses, respectively.

Pressure estimates based on the ternary feldspar-geothermobarometer of Green and Usdansky (1986) indicate 8–12 kbar at temperatures of 540–580°C (Fig. 2.4). The relatively low temperatures are probably caused by the retrogressive alteration of the feldspar pairs. Temperatures estimated using a variety of biotite-garnet geothermometers yielded values that were too high due to the chloritization of biotite (Schulze and Olesch, 1990).

Amphibolite-facies metamorphism: Amphibolite-facies rocks are the most widespread rock types observed in the Read Mountains. Their mineralogical and chemical compositions are very variable. The four most abundant rock types are:

(a) layered or banded biotite- and garnet-biotite-paragneisses and migmatites (sometimes with fibrolitic sillimanite),
(b) banded hornblende-biotite- and clinopyroxene-hornblende-biotite-gneisses and migmatites,
(c) leucocratic granite orthogneisses (with rare biotite and garnet or hornblende), and
(d) clinopyroxene-(hypersthene)-hornblende-biotite-plagioclase-schists and amphibolites (metabasites).

Table 2.1. Modal compositions of gneiss *sensu stricto*, biotite-gneiss and amphibolite from Beche Blade, Read Mountains

Sample No.	*Gneiss 'sensu stricto'*			*Biotite-gneiss*				*Amphibolite*
	89	90	107	95	100	105a	99	88
Quartz	42	44	49	40	34	47	35	-
K-feldspar	32	33	29	17	4	12	-	-
Plagioclase	19	16	17	19	27	20	39	34
Biotite	7	7	4	22	34	19	25	-
Muscovite	-	-	1	-	1	-	-	-
Hornblende	-	-	-	-	-	+	-	64
Garnet	+	-	-	-	-	-	-	-
Clinozoisite	-	-	-	-	-	-	-	2
Zircon	+	+	+	+	+	+	+	-
Apatite	-	+	+	+	+	+	-	-
Opaque minerals	-	-	-	2	1	2	1	1
Anorthite mole component	30–35	n.d.	n.d.	35–41	36–39	38–42	31–37	n.d.

+, accessory minerals ‹1 vol.%; -, mineral species not observed; n.d., not determined (plagioclase highly altered).

The anorthite mole component (An) was determined on an universal stage by repeated measurement of the maximum symmetrical extinction angle. Additional biotite-gneiss samples gave An ranges of 32–39, 31–34 and 33–38. Alternative microprobe analyses yielded anorthite contents that equal the upper limit of the range measured optically.

Selected modal analyses of gneiss *sensu stricto* and biotite-gneiss are given in Table 2.1.

The rock types noted above form well-defined sheets that vary in thickness between 50 and 300 m. The sheets include lenses, boudins and/or layers of biotite-cordierite-gneiss, calc-silicate rock, quartzite, carbonatized meta-ultrabasite, metabasite and pegmatitic leucogneiss. Calc-silicate rocks, biotite-cordierite-gneisses and quartzites occur predominantly in the biotite-garnet-gneisses and migmatites; meta-ultrabasic lenses are restricted to the metabasites. Small lenses and boudins of metabasite or gneissic pegmatite may form part of all the different types of sheets. Some thick metabasite sheets display distinct gabbroic textures, proving an intrusive origin.

Typical mineral assemblages of the amphibolite-facies rocks are:

(a) Clinopyroxene + (hypersthene) + hornblende + biotite + plagioclase ($An_{50\text{-}60}$),
(b) Clinopyroxene + hornblende + biotite + plagioclase ($An_{35\text{-}49}$) + quartz,
(c) Hornblende + biotite + plagioclase ($An_{25\text{-}36}$) + quartz ± K-feldspar,
(d) Biotite + plagioclase ($An_{12\text{-}28}$) + K-feldspar + quartz,
(e) Garnet + biotite + plagioclase ($An_{27\text{-}34}$) + K-feldspar + quartz,
(f) Garnet + sillimanite + biotite + K-feldspar + quartz + plagioclase ($An_{25\text{-}27}$),
(g) Cordierite + biotite + plagioclase ($An_{23\text{-}30}$) + K-feldspar + quartz + garnet + sillimanite,
(h) Olivine + carbonate + tremolite + diopside,
(i) Carbonate + diopside + actinolite + olivine + scapolite + phlogopite,
(j) Carbonate + tremolite + phlogopite + quartz, and
(k) Quartz + plagioclase + K-feldspar + garnet + biotite.

Table 2.2 shows modal compositions of significant metamorphic rock types, with their critical phase associations. These indicate clearly that metamorphic conditions reached the higher temperature zone of the amphibolite facies.

The mineral assemblages described and the incipient partial melting observed locally provide evidence for the peak conditions reached during the amphibolite-facies metamorphic event. The higher temperature zone of the amphibolite facies is especially well developed in the rock sequence observed at Hatch Plain (Fig. 2.5). Extensive

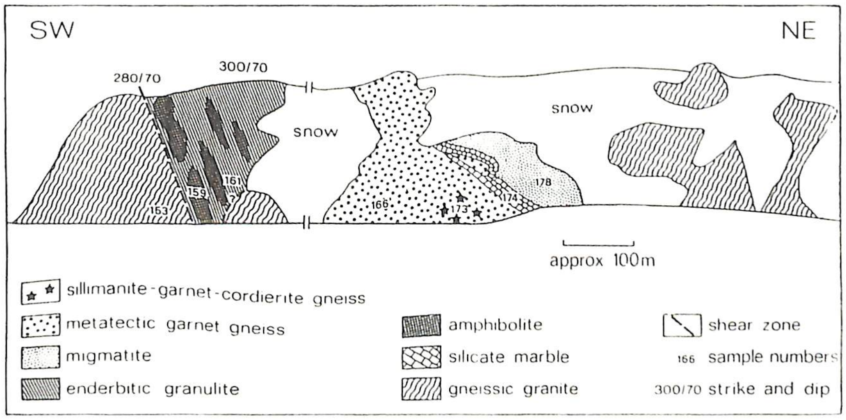

Fig. 2.5. Geological section across the western spur of Hatch Plain, Du Toit Nunataks, western Read Mountains; facing south-east.

Table 2.2. Representative modal compositions of amphibolite-facies rocks, partly superimposed on granulite-facies rocks, from Du Toit Nunataks, western Read Mountains

Sample No.	*158*	*159*	*160*	*162*	*164*	*168*	*171*	*111*
Quartz	-	-	-	-	2	4	15	57
K-feldspar	-	-	-	-	-	12	4	28
Plagioclase	38	44	42	34	51	11	4	2
Biotite	-	-	-	-	28	32	22	+
Muscovite	-	-	-	-	-	6	-	5
Clinopyroxene	-	-	6	-	-	-	-	-
Hornblende	61	31	51	57	-	-	-	-
Chlorite	-	21	-	7	16	2	1	3
Garnet	+	-	-		-	-	10	-
Cordierite	-	-	-	-	-	18	42	-
Sillimanite	-	-	-	-	-	13	2	5
Rutile	-	-	-	2	-	-	-	-
Zircon	+	-	-	-	-	+	+	+
Apatite	1	2	+	-	2	-	-	-
Opaque minerals	-	2	1	-	1	2	-	-

+, accessory minerals < 1 vol.%; -, mineral species not observed.

158. Amphibolite, fine-grained, most common rock type.
159. Amphibolite, dense; titanomagnetite is the predominant opaque phase, strongly chloritized.
160. Amphibolite with light schlieren (?meta-gabbro), magnetite is the opaque phase.
162. Amphibolite, dense, slightly chloritized.
164. Biotite-chlorite-gneiss.
168. Biotite-cordierite-sillimanite-garnet-gneiss with secondary muscovite.
171. Cordierite-biotite-garnet-sillimanite-gneiss.
111. K-feldspar-sillimanite-gneiss with garnet and secondary muscovite.

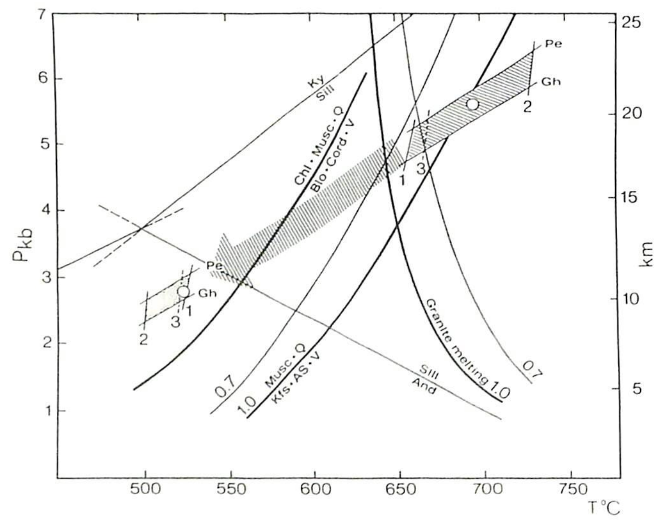

Fig. 2.6. Total pressure–temperature conditions of the amphibolite-facies metamorphic event, based on mineral assemblages and microprobe mineral data from representative sillimanite-garnet-cordierite-gneiss, Sample No. 173. Hatched area, peak conditions; stippled area, final retrogressive stage; hatched arrow, pressure–temperature path during uplift; temperatures (1) and (2) calculated using the biotite-garnet geothermometer of Perchuk and others (1985), and Ferry and Spear (1978), respectively; temperature (3) based on the cordierite-garnet geothermometer of Perchuk and others (1985); pressures (Gh) and (Pe) estimated according to Ghent and others (1979), and Perchuk and others (1985), respectively; circles, pressure–temperature calculations after Aranovich and Podlesskii (1983); chlorite + muscovite + quartz stability curve from Bird and Fawcett (1973); muscovite + quartz stability curves and granite melting curves with $X(H_2O)$ = 1.0 and 0.7 are from Kerrick (1972); aluminium silicate curves are from Holdaway (1971).

thermo-and barometric calculations indicate that peak conditions were reached at 5–6 kbar total pressure and about 690°C (Olesch, 1991; Schubert and Olesch, 1995). These peak conditions were continuously reduced to 2–3 kbar at about 520°C during a clockwise uplift path (Fig. 2.6). Retrogression is recorded by the formation of blue-green hornblende rims around brown-green hornblende or clinopyroxene, fibrolitic aggregates, pinitization of cordierite, and epidotization and saussuritization of plagioclase.

Numerous late- to post-orogenic granitoid bodies (stocks and sheets) intruded the metamorphic rocks of the Read Group (Fig. 2.7). The largest bodies crop out at Mount Wegener, Beche Blade, The Ark (Fig. 2.8) and Du Toit Nunataks. These granitoids consist of porphyritic biotite- and biotite-hornblende-granite, granodiorite, diorite, quartz-syenite and quartz-monzonite. Some granitoids include rare clinopyroxene or garnet crystals. An hypidiomorphic granular texture is common and, locally, a slight foliation of feldspars and/or dark minerals can be observed.

Greenschist-facies metamorphism: The last metamorphic event is represented most clearly by sheared or fractured rocks. These occur in shear zones varying in thickness from several tens to hundreds of metres. All rock types have undergone cataclasis and mylonitization during shearing, the recrystallized schists having the following mineral assemblages:

(a) Chlorite + epidote + albite ± carbonate,
(b) Muscovite + quartz, and
(c) Chlorite + quartz ± biotite ± carbonate.

Augen textures are common in the schists, the augen consisting of plagioclase porphyroblasts that have been completely albitized or sericitized.

Fig. 2.7. Leucogranite intruded into amphibolite, western side of Watts Needle. The bulb-shaped contact indicates emplacement in the lower crust.

Fig. 2.8. Biotite-gneiss with granitic intrusion and two generations of aplitic to pegmatitic veins, north-eastern slope of The Ark, central Read Mountains; height of the wall is *c.* 240 m.

Tectonics

A sequence of four deformation events has been established for the Read Group. Table 2.3 shows the correlation between the phases of deformation and the metamorphic events. Geochronological data mark either the peaks of metamorphic events or the ages of late- to post-orogenic intrusions. The predominant structural features are the result of D_1 and they are contemporaneous with the main phase of amphibolite-facies metamorphism. D_2 developed on a local scale only and was rather weak. Both these deformation events may be correlated to one (or possibly more) Proterozoic orogenies. Goodge and others (1992) suggested that the Nimrod orogeny affected the Read Group. Taking into account current palaeo-plate tectonic hypotheses concerning the configuration of Laurentia and Gondwana (e.g. Dalziel, 1991, 1992; Moores, 1991) D_1 and D_2 may reflect tectonic events of the Grenvillian orogeny. D_3 and D_4, the youngest deformation events, took place during the Ross orogeny. The structural and textural features observed are in accord with nappe formation, orthogonal tectonic transport and the lateral extent of thrusts (Kleinschmidt and others, 1992).

Table 2.3. Sequence of tectonic and metamorphic events

Deformation event	*Deformation structures*	*Metamorphic facies*	*Intrusive emplacement*	*Age (Ma)*
D_4	normal faulting, cleavage			
D_3	fracturing, shearing	greenschist facies (locally in shear- and fracture-zones)		490–530
D_2	folding of foliation (axes to W or E)	amphibolite facies (continued)	porphyroblastic granite	*c.* 1000 (?)
D_1	foliation (biot, chl, act) boudinage, stretching,		granodioritic dykes	1300
	lineation, folding, (intrafolded axes to N–NE)	amphibolite facies		1420–1640
			fine-grained granites, granitic and pegmatite veins	1760–1850
Pre-D_1	relict fabrics quartz veins	upper amphibolite to granululite facies		2200

act, actinolite; biot, biotite; chl, chlorite.

3 Stratton Group

by W. Schubert, H.-M. Braun, E.N. Kamenev and M. Olesch

Synopsis

Short description: The Stratton Group comprises the infracrustal crystalline basement within the northern and western Shackleton Range. Rocks of this newly named group, which were originally assigned to the "older gneisses with migmatites" of the "Shackleton Range Metamorphic Complex" (Clarkson, 1972; 1982*a*), are equivalent to the former "Provender Complex" of Hofmann and others (1982), and the "Charpentier Series" of Hofmann and Paech (1983); more recently the Stratton Group was referred to as the "Haskard Group" by Tessensohn and Thomson (1990). However, since the term "Haskard Group" had been used informally for a different rock sequence by Marsh (1984), this name has been abandoned now in favour of Stratton Group. The Stratton Group consists of medium- to high-grade gneisses, stromatic migmatites with a few basic layers, and small anatectic granitoids. It is tectonically overlain by the supracrustal metasedimentary unit of the Pioneers Group (see Chapter 4).

Geographical location: Haskard Highlands, and also at outcrops extending eastward from Mount Pivot (Otter Highlands) via Fuchs Dome and La Grange Nunataks to Charpentier Pyramid (Herbert Mountains).

Metamorphic facies: Medium- to high-grade, generally amphibolite facies; a younger, retrogressive low-grade metamorphic overprint is present in the south. The critical mineral assemblage (quartz–K-feldspar–sillimanite–plagioclase–biotite ± amphibole ± garnet) together with leucosomes in the migmatite (indicating partial melting processes) suggest metamorphic conditions of 660–680°C at 4–5 kbar pressure.

Age: Proterozoic; radiometric data are sparse but gneisses and pegmatites have yielded whole rock Rb-Sr ages of 2700 ± 100 Ma and Rb-Sr mineral ages of 1700 ± 50 Ma from pegmatitic muscovite (Pankhurst and others, 1983).

Introduction

Early reconnaissance geological investigations of the Haskard Highlands (Stephenson, 1966; Clarkson, 1972, 1982*a*,*b*; Hofmann and Paech, 1980; Kamenev and Semenov, 1980) led to the recognition of a mainly orthogneissic–gneissic–migmatitic infracrustal basement (hereafter referred to as the Stratton Group) underlying medium- to high-grade metasedimentary supracrustal basement rocks (Pioneers Group; see Chapter 4). The latter correspond to the lower part of the former "Shackleton Range Metamorphic Complex" of Clarkson (1972, 1982*a*). It is believed that the boundaries between the Stratton and Pioneers groups are tectonic, possibly thrust faults. In the western part of the Shackleton Range, rocks of the Stratton Group are separated from the overlying, unmetamorphosed Palaeozoic Blaiklock Glacier Group by a structural unconformity (Clarkson 1972; Clarkson and Wyeth, 1983; see also Chapter 10).

The geology, stratigraphy and structure of the area have been described by Hofmann and Paech (1980, 1983), Marsh (1983*a*,*b*, 1984) and Buggisch and others (1990), and radiometric data have been published by Grew and Halpern (1979), Grew and Manton (1980), Hofmann and others (1982) and Pankhurst and others (1983). This chapter summarizes these earlier investigations and also includes new data on the petrography, petrology and tectonics acquired during the German Geological Expedition to the Shackleton Range (GEISHA) in 1987–88 (Braun and others, 1988; Kleinschmidt and Roland, 1988; Roland and others, 1988; Buggisch and others, 1990). Geochronological data are summarized in Chapter 12.

Infracrustal basement

The exposed infracrustal part of the basement of western and northern Shackleton Range has been assigned to the Stratton Group. It comprises early–middle Proterozoic crystalline rocks, including intermediate to acid metamorphic rocks, associated migmatites, synkinematic and post-kinematic granitoids and ultramafic intrusive rocks.

The Stratton Group is equivalent to the lower portion of the "Shackleton Range Metamorphic Complex" of Clarkson (1982*a*), the "Provender Complex" of Hofmann and others (1982) and, partly, to the "Charpentier Series" of Hofmann and Paech (1983) (see Appendix 1). To a large extent, this chapter follows the suggestions of Marsh (1984) and the units or lithologies described below are: Mount Weston gneiss, Wedge Ridge gneiss, Fuchs Dome gneiss, Mathys gneiss, and Wiggans blastomylonite.

For the La Grange Nunataks and Herbert Mountains area it is somewhat difficult to decide whether or not infracrustal basement rocks exist in the northernmost outcrops: whereas Marsh (1984) included the Charpentier gneisses in the basement, others (Hofmann and Paech, 1980, 1983; Hofmann and others, 1982; Paech, 1985) apparently regarded all rocks in this area as supracrustal; the occurrence of blastomylonites in the lower part is due to a basement below the present-day erosion level.

Mount Weston gneiss (Marsh, 1983*b*): The Mount Weston gneiss crops out in the Mount Weston area, south-east of Mount Gass and in the western part of Williams Ridge.

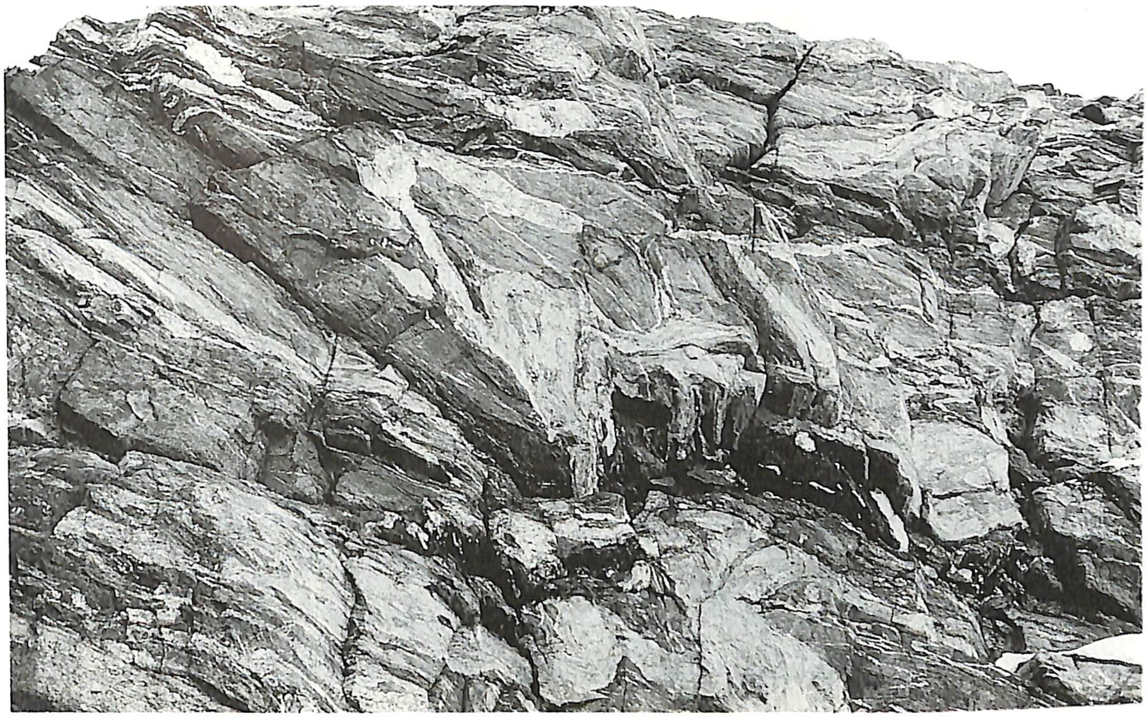

Fig. 3.1. Typical outcrop of Wedge Ridge gneiss on the ridge north-east of Pointer Nunatak. (Photograph by P.D. Marsh)

It is a coarse- or medium-grained leucocratic orthogneiss (quartz + plagioclase + perthitic K-feldspar ± garnet ± hornblende ± biotite ± sillimanite), locally with layers and boudins of basic rocks (up to 2 m thick), calc-silicate layers (up to 15 cm thick) and quartz-schists. To the south, the amount of strongly foliated mylonitic schists alternating with the gneiss increases. Unfoliated feldspar-pegmatites (up to 3 m thick, commonly 5–15 cm) cross-cut each other and the gneissose layering.

Samples of garnet-sillimanite-gneiss from Mount Weston were described by Stephenson (1966) and Pankhurst and others (1983); high-grade paragneiss with garnet, sillimanite and (?)kyanite, from near Mount Weston, have given whole-rock Rb-Sr ages that have a crude alignment close to 1550 Ma and an initial Sr ratio of 0.707 (Pankhurst and others, 1983). The contact of the Mount Weston gneiss with the supracrustal "Mount Gass Formation" (Marsh, 1983*b*) is not a clear tectonic one but it is marked by a broad shear zone, with apparent muscovite on the shear planes (Braun and others 1988; Braun, 1995).

Wedge Ridge gneiss (Marsh, 1983*b*): This type of gneiss covers the largest area in the Haskard and Otter highlands, extending westward from Pointer Nunatak, via Wedge Ridge, Guyatt Ridge and Mount Homard, to Mount Pivot. The rock is a grey and pink, mesocratic, medium- to coarse-grained gneiss (quartz + K-feldspar + sodic plagioclase + biotite ± secondary epidote, chlorite, muscovite) with deformed quartz-feldspar segregations (Fig. 3.1). In the field, the Wedge Ridge gneiss has structural features indicative of magmatic origin (e.g. around Mount Pivot), and compositional layering is typically indistinct. Rb-Sr whole-rock age determinations on orthogneisses from around Wedge Ridge resulted in a moderately good errorchron, corresponding to 2700 ± 100 Ma and 1700 ± 50 Ma for pegmatitic muscovite from the same locality (Pankhurst and others, 1983).

Layers of mica-schists and siliceous schists are partly interfingered with flattened Wedge Ridge gneiss. In the northern part of Wedge Ridge, at the contact with the Blaiklock Glacier Group, there is a narrow zone of blastomylonitic mica-schist (the "Wedge Ridge schist" of Marsh (1983*b*)) with biotite + muscovite + quartz + oligoclase ± garnet; this rock type indicates local strong shearing of the gneiss.

Fuchs Dome gneiss (Marsh, 1984): A migmatitic, coarse-grained, mesocratic gneiss which covers the area of Fuchs Dome, from Lister Heights in the west, via Flat Top and Petersen Peak, to Clarkson Cliffs in the east. Most of the outcrops show large-scale partial-melting features, which are best exposed on the ridge 6 km south-south-east of Flat Top (Marsh, 1984, fig. 4). The millimetre- and centimetre-scale layering of the overall grey gneiss grades into sheets and irregular bodies of granitic material, with disrupted layers and schlieren derived from the palaeosome. Marsh (1984) also described blocks of gneiss surrounded by more leucocratic migmatite, and sheets of more homogeneous granite (up to 10 m thick), with sharp boundaries.

The mineral assemblage of the grey migmatitic gneiss comprises quartz + plagioclase + K-feldspar + biotite ± amphibole ± garnet, and sillimanite as prisms or as fibrolite. Local transitions from normal gneiss to cataclastic blastomylonite are visible, leading to the development of mylonitic schists with cracked relict feldspar, quartz, chloritzed biotite and secondary muscovite. Cross-cutting garnet-bearing leucocratic veins or diffuse patches of quartzo-feldspathic material are present in the biotite-gneisses.

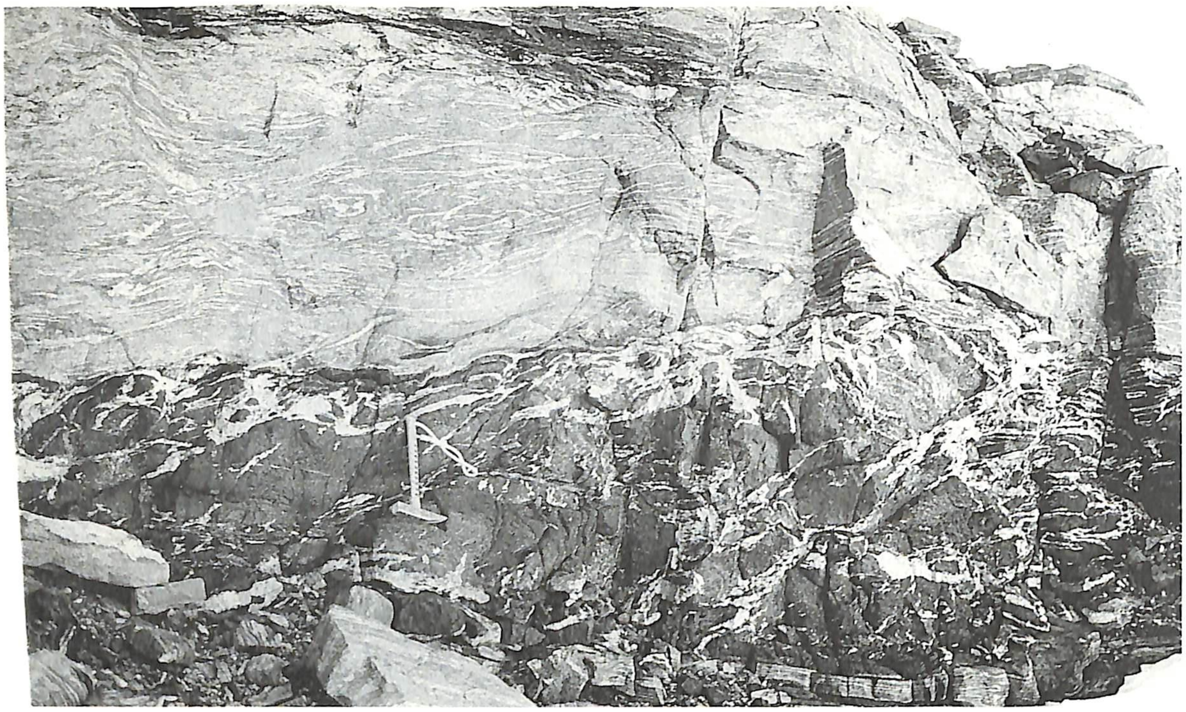

Fig. 3.2. A net-veined basic layer in typical feldspathic gneiss, Mathys gneiss on the peak 4 km east of Mount Skidmore. (Photograph by P.D. Marsh)

Mathys gneiss, Charpentier gneiss and Wiggans blastomylonite (Marsh, 1984): Within the La Grange Nunataks, to the north of outcrops of the Fuchs Dome gneiss, the infracrustal basement is partially in contact with younger, metasedimentary supracrustal rocks of the Pioneers Group; there is possibly some interleaving of the two rock types (Marsh, 1984, fig. 3). The infracrustal basement gneiss itself was subdivided by Marsh (1984) into the Mathys gneiss, Charpentier gneiss and Wiggans blastomylonite. They are lithologically uniform, mesocratic and leucocratic, medium-grained granoblastic varieties with quartz + K-feldspar + plagioclase + amphibole and/or biotite ± garnet with diffuse cm-scale layering.

Mathys gneiss, which was dated at 2310 ± 126 Ma by Pankhurst and others (1983), crops out at Mathys Bank, Mount Etchells, Butterfly Knoll, Mount Beney, Morris Hills, and in the two northernmost nunataks of Lewis Chain. It is characterized by the occurrence of basic layers, from 1 cm to several metres in thickness, which are locally abundant. The thicker layers are commonly net-veined by feldspathic material (Fig. 3.2). All basic and acid layers and veins have been flattened and the thicker basic layers are boudinaged.

The Charpentier gneiss at Charpentier Pyramid, Kendall Basin, and Charlesworth Cliffs in the Herbert Mountains, corresponds to the "Charpentier Series" of Hofmann and others (1982). It is a sequence of migmatized biotite-gneiss, biotite-amphibole-gneiss and amphibolite with a well-defined parallel foliation. A blastomylonitic overprint, combined with the growth of megablasts of microcline and biotite, appears to be typical (Hofmann and others, 1982, fig. 23). In the Wiggans blastomylonite, there is clear evidence of cataclasis in the mesocratic hornblende-gneiss and amphibolite layers but the medium-grained mineral fabric is a result of recrystallization following deformation.

In the Mount Provender area, medium-grained leucocratic, migmatitic granoblastites (the "Stratton gneiss" of Marsh, 1983*b*, and the migmatites of "unit a" in Grew and Halpern, 1979), and small, late-tectonic, intrusive granitic stocks (up to 200 m in diameter) may represent infracrustal basement that can be assigned to the Stratton Group. Members of this unit are interleaved with, and embedded in, Pioneers Group rocks, and in places agmatitic migmatites (Fig. 3.3) mark the contact zone between both units. However, the actual structural relationship between the infracrustal basement rocks and the metasedimentary rocks is difficult to interpret.

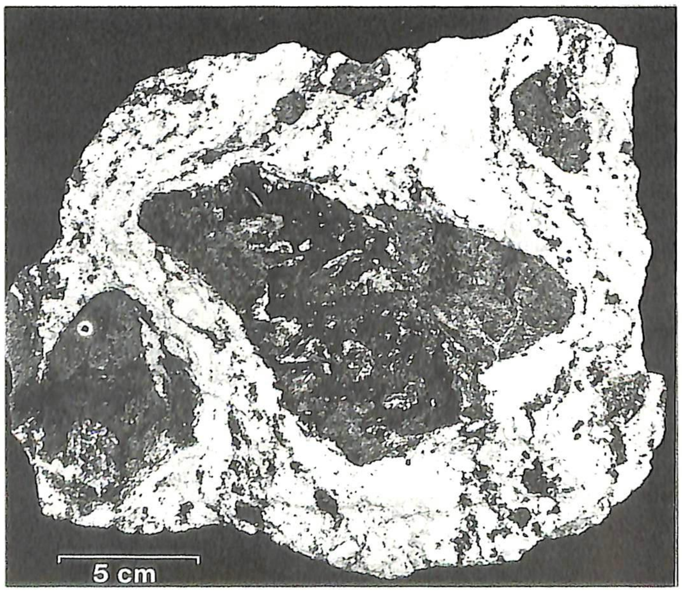

Fig. 3.3. Mafic rock fragments (melanosome) in a tonalitic granite leucosome; agmatitic migmatite from the border zone between the Pioneers Group and the infracrustal basement, at 620 m a.s.l. on the mountain 6 km east of Mount Provender.

Fig. 3.4. Unfoliated biotite-pyroxenite cut by leucocratic pegmatite veins, Pratts Peak intrusion. (Photograph by P.D. Marsh)

Intrusive Rocks

Pratts Peak intrusion: 12 km east of Mount Provender a complex, probably multiphase pluton of ultrabasic–basic rocks crops out in the Pratts Peak area. It appears to have an incomplete ring structure. The width of the inner zone, mostly outcrops of unfoliated biotite-pyroxenite (Marsh, 1983*b*; Fig. 3.4), is about 300 m. The structure of the coarse-grained ultramafic rock is dominated by sheets of biotite and crystals of diopsidic clinopyroxene and amphibole, each up to 5 cm in length. Biotite has Fe/(Fe+Mg+Mn) of between 0.32 and 0.40 and a negligible fluorine content; the proportion of biotite varies between 5 and 60 vol%. Zoned green amphibole occurs either as individual crystals or it has replaced clinopyroxene. The chemical zonation of amphibole crystals is represented by selected microprobe analyses.

The brecciated part of the inner zone comprises carbonate-rich rocks with serpentinite xenoliths and apatite-rich rocks. The apatite, present as individual prisms (Fig. 3.5) or radiating clusters of stout needles up to 3 cm in length, locally accounts for 20 vol% of the rock. The apatite is intergrown with quartz and is a pure Ca-apatite with a fluorine content of 1.06–1.70 wt%. Additional minerals are weakly serpentinized olivine, titano-magnetite, rutile rimmed by sphene, secondary calcite with <2 mol% magnesite and <1% siderite; there are also pegmatitic veins containing 50–70% of biotite crystals up to 20 cm in diameter. The outer zone of the pluton (400 m in width) is formed by intensively crushed and brecciated syenite-porphyries. The contact between the margin of the body and the adjacent blastomylonitic orthogneiss is exposed and shows 3–5 m of alternating layers of either foliated or massive biotite-amphibolite and striped calc-silicate amphibolite. As Marsh (1983*b*) pointed out, these rocks seem to represent a marginal shear zone with a recrystallized amphibolitic mineral assemblage.

The pyroxenite is cut by basic dykes and, in the south of the outcrop, by leucocratic granitic veins that vary from a single vein (1 m thick) to a zone of veins (3 m wide) following joints. The mafic body appears to post-date most of the deformation in the surrounding rocks but it has suffered local shearing and has a medium-grade metamorphic overprint.

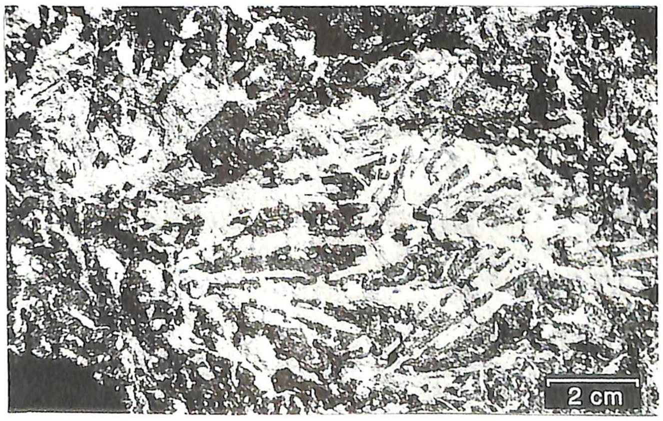

Fig. 3.5. Prismatic radiating crystals of apatite intergrown with quartz in an unfoliated biotite-pyroxenite; Pratts Peak, Haskard Highlands.

Critical mineral assemblage

In general the Stratton Group, as the exposed infracrustal part of the basement of northern Shackleton Range, exhibits a relatively uniform compositional character. The dominant leucocratic and mesocratic gneisses described above represent medium- to high-grade gneisses of either igneous or igneous and sedimentary origin, with granitic–granodioritic–tonalitic bulk-rock compositions. Gradual transitions from gneissic textures into more homogeneous, irregular bodies of granitic material (indicative of an anatectic origin) are present locally.

The most widespread stable primary mineral assemblage in these gneissic rocks is quartz + perthitic K-feldspar + plagioclase (sodic oligoclase) + sillimanite + biotite ± amphibole (e.g. Mount Weston gneiss, Wedge Ridge gneiss). Associated layers of basic composition have the following major mineral phases: plagioclase (andesine) + quartz + calcic amphibole + sphene ± biotite. Sporadic calc-silicate bands within the basic layers have calcic amphibole + diopsidic pyroxene + plagioclase (andesine) + sphene ± biotite ± quartz as the main constituents.

There is evidence that anatexis and high-grade metamorphism affected the rocks of igneous and sedimentary origin, resulting in the formation of migmatites, mostly with a layered structure (Fuchs Dome gneiss, Charpentier gneiss). Cross-cutting leucocratic veins or diffuse patches of granitic composition, partly garnet bearing, seem to represent eutectic aplitic melts from deeper crustal levels. The light-coloured granitic leucosomes of the migmatites are composed of quartz + K-feldspar + plagioclase ± garnet, but biotite-rich selvedges were not observed. The migmatitic melanosomes are composed of biotite + garnet + sillimanite/fibrolite and minor amounts of plagioclase, K-feldspar and quartz. Migmatites of the Charpentier gneiss are described in detail by Hofmann and others (1982). They were able to recognize a two-step process of migmatization: the leucosomes and melanosomes both exhibit an older mineral association of plagioclase (An_{10-23}) + K-feldspar 1 + quartz + garnet + Ca-amphibole + Fe-rich biotite 1 ± cummingtonite that differs only in its modal ratio. A second, younger mineral generation in the migmatites is characterized by advanced biotitization of Ca-amphibole and (in part) of garnet, albitization of former plagioclase and blastesis of twinned microcline associated with intense blastomylonitization. Growth of muscovite and epidote/clinozoisite has only been identified in strongly deformed and retrogressed samples.

Metamorphism

Since a proncounced zonation of critical mineral assemblages is lacking in the Stratton Group area, the position of the metamorphic isograds relative to the present land surface must be assumed to be rather flat. To date, relict granulite- facies rocks have not been recorded. During the main metamorphic event, pressure and temperature conditions of the upper amphibolite facies were attained, presumably with minor regional differences in temperature and/or pressure.

The absence of muscovite in the presence of quartz in gneisses of suitable bulk rock chemistry, together with the presence of K-feldspar and sillimanite at several places, indicates that the muscovite dehydration equation of muscovite + quartz = K-feldspar + sillimanite + vapour (Chatterjee and Johannes, 1974) was crossed. As migmatitic structures are virtually present, the formation of the leucosomes can be attributed partly to melt-producing reactions; the mineralogy of these leucosomes indicates granitic-granodioritic but also leucotonalitic compositions.

In the P-T grid the experimentally determined solidus curves of granitic to leucotonalitic composition (Thompson and Algor, 1977; Lappin and Hollister, 1980; Johannes, 1984), together with the stability curve of K-feldspar plus sillimanite, allows the minimum conditions of metamorphism to be estimated at about 660–680°C at 4–5 kbar.

In restricted areas (e.g. in the Wedge Ridge schists) equilibria of the greenschist facies were either approached or reached locally by a younger retrogressive metamorphism. Biotite and garnet were partly or completely replaced by chlorite, amphibole by chlorite + actinolite and feldspars by sericite (Marsh, 1983*b*, 1984; Hofmann and others, 1982).

Tectonics

Rocks of the Stratton Group generally have a medium- to coarse- grained granoblastic fabric, formed under medium- to high- grade metamorphic conditions. Schistosity is defined by the orientation of micas and amphiboles, feldspar augen, and elongated quartz grains, but curving and anastomosing surfaces are more common than straight foliation planes (Stephenson, 1966; Grew and Halpern, 1979; Marsh, 1983*b*, 1984). At Mount Weston, quartz inclusions in garnets indicate syntectonic growth, and pressure shadows round garnet and rigid blasts contain a felty mixture of biotite and sillimanite (Stephenson, 1966; Braun, 1995). At the same location, hazy streaks of angular magnetite fragments are overgrown by garnet cores and old biotite flakes, indicating an earlier tectonic activity (Braun, 1995).

In the northern Haskard Highlands (Mount Weston area), the early foliation dips mainly NW, but this direction may change to a N–NE dip due to later tectonics. The latter is also the orientation of an early stretching lineation. At Wedge Ridge and in the southern Otter Highlands, northerly dipping foliation planes show lineations plunging NE–E (see Marsh (1983*b*) for orientation diagrams). Lithological layering which roughly parallels the early foliation has been observed locally at La Grange Nunataks; pegmatites and basic layers are flattened and show boudinage. In the Fuchs Dome area, migmatitic melts formed under upper amphibolite-facies conditions locally obscure older structures (Marsh, 1984).

Flattening and cataclasis led to secondary, medium- to fine-grained fabrics, which are restricted to distinct zones within the Mount Weston gneiss in the north, but are more pervasive, if not dominant, in the south (Otter Highlands and southern Haskard Highlands) and in the east (La Grange Nunataks, Fuchs Dome). Kinked kyanite, fractured feldspars, fragmentation of garnet blasts, and the formation of new biotite and chlorite are evidence for deformation under retrogressive conditions (Marsh, 1983*b*, 1984; Braun, 1995); quartz is strongly recrystallized whereas garnet and oligoclase are locally stable. Foliation planes, as well as a strong stretching lineation, dip NW or NE. At Mount Weston, shear indicators point to NW-directed downglide of the hanging rocks (Braun, 1995). Isoclinal to close folds deflect the first foliation with W- or E-plunging axes.

In the southern Otter Highlands, close examination of the boundary between the Stratton Group (Wedge Ridge gneiss) and the Wyeth Heights Formation confirmed thrusting of basement upon sedimentary rocks, as originally suspected by Marsh (1983*a*). In a narrow zone of extreme shear deformation and tectonic interleaving, a large variety of structures indicates southbound movement of the hanging crystalline rocks (Braun and others, 1988; Kleinschmidt and others, 1991). Similar southbound thrusting has been suggested for the area north of Stephenson Bastion (Hofmann and Paech, 1980; Marsh 1983*a*; Braun and others, 1988; Kleinschmidt and others, 1991), and for the boundary between Mount Weston gneiss and "Williams Ridge Formation" (Marsh, 1983*b*). SE-vergent thrust planes in basement rocks at La Grange Nunataks were assigned by Paech (1985) to the second, retrograde deformation event.

Although in the south there are no noticeable signs of subsequent tectonics, large-scale folding in the northern Haskard Highlands created the so-called "Mount Weston anticline" (Marsh, 1983*b*) with a NNE-striking axial plane. Since this antiform has roughly the same orientation as the "Mount Gass fold" in the Pioneers Group, and similar folding has also been found within the "Williams Ridge Formation", these late structures are regarded as contemporaneous (Marsh, 1983*b*). Farther east, axes of open to close folds dip N or S. Within hinges of minor folds, a new retrograde planar fabric may be formed.

In the Otter Highlands, the northern boundary of the crystalline basement has been interpreted as a major fault plane by Clarkson (1972) and Marsh (1983*b*). Its maximum age is given by the fact that clastic rocks belonging to the Blaiklock Glacier Group are downthrown by several hundreds of metres to the north of the fault. Marsh (1983*b*) speculated that the Wedge Ridge schist, situated between the Wedge Ridge gneiss and the "Williams Ridge Formation", may represent a similar zone of faulting. For the Herbert Mountains, Hofmann and Paech (1983) suggested a block structure caused by faulting on planes striking N–S and W–E, respectively.

4 Pioneers Group

by N.W. Roland, H.-M. Braun, J. Hofmann, E.N. Kamenev, G.I. Kameneva, G. Kleinschmidt, M. Olesch and H.-J. Paech

Synopsis

Short description: The supracrustal rocks of the Pioneers Group are represented by a metasedimentary sequence of metapelite, metaquartzite and metacarbonate, and by amphibolite, metavolcanic intercalations of hornblende-schist, and felsic pyroclastic rocks. The rock sequences are pervasively affected by amphibolite-facies metamorphism, and they are intensely folded, commonly isoclinally, and with local intense penetrative shear; E–W-trending axes and lineations prevail. Tectonic duplication by folding and thrusting is widespread. In general the Pioneers Group seems to be in tectonic contact with the apparently underlying Stratton Group, both groups being tectonically interleaved. The new term Pioneers Group (Tessensohn and Thomson, 1990) replaces the former "Shackleton Range Metamorphic Complex" (Clarkson, 1972, 1982*a*), "Skidmore Group" (Paech, 1977, 1985; Hofmann and Paech, 1980, 1983), "Skidmore Complex" (Kamenev and Semenov, 1980), "Herbert Series" (Hofmann, 1982), and the "Haskard Group" and "Schimper Group" (Marsh, 1983*a*,*b*, 1984).

Geographical location: Pioneers Escarpment and adjacent nunataks; also crops out in northern Haskard Highlands, La Grange Nunataks and southern Herbert Mountains.

Stratigraphical range: Probably Upper Precambrian; assumed to be younger than the gneisses of the Stratton Group.

Introduction

The metamorphic rocks referred to as the "Shackleton Metamorphics" by Stephenson (1966) and renamed the "Shackleton Range Metamorphic Complex" (SRMC) by Clarkson (1972, 1982*a*), have now been subdivided into the Read, Stratton, and Pioneers groups (Tessensohn and Thomson, 1990; this volume). These metamorphic rocks are widespread throughout the Shackleton Range, except in its north-western part (where most of the rocks belong to the Blaiklock Glacier Group) and along the southern flanks of the range (predominantly Watts Needle and Mount Wegener formations). Clarkson (1972) envisaged that further field investigations of the SRMC would lead to new subdivision of the complex and, in due course, several new formation and sequence names were created by different authors working independently, e.g. the Herbert Mountains terminology of Marsh (1983*b*, 1984) and Hofmann (1982). To avoid further confusion, the participants of the Shackleton Range Workshop, held at Hannover in April 1990 (Tessensohn and Thomson, 1990), proposed a single new name, the Pioneers Group, for the supracrustal metamorphic rocks of the Shackleton Range.

The new name Pioneers Group (see Appendix 1) replaces the former stratigraphical terms of:

- "Skidmore Group" (Paech, 1977, 1985; Hofmann and Paech, 1980, 1983) and "Skidmore Complex" (Kamenev and Semenov, 1980) in the La Grange Nunataks,
- "Herbert Series" in the Herbert Mountains, including the "Venetz Peak sequence", "Bonney Bowl sequence", "Sumgin Buttress sequence"/ "Jamieson Ridge sequence", "Shaler Cliffs sequence" (Hofmann, 1982),
- "Haskard Group" (Marsh, 1984), to which the "Williams Ridge Formation", "Hollingworth metasediments" and "Butterfly Formation" belonged, and
- "Schimper Group", including the "Nostoc Lake Formation", "Mount Gass Formation", "Maclaren Formation" and "Bonney Formation" (Marsh, 1983*a*,*b*, 1984).

Lithology

The supracrustal rocks of the Pioneers Group are lithologically varied, ranging from metasedimentary to metavolcanic rock types. The metasedimentary sequences, in which primary sedimentary structures are preserved locally (e.g. cross-bedding), include:

i. Metapelitic rocks, represented by garnet-mica-schist and quartz-feldspar-schist containing variable amounts of high alumina minerals (kyanite, garnet, sillimanite, andalusite, staurolite, cordierite), mica (biotite and/or muscovite) and iron-oxides (magnetite or hematite),
ii. Metacalcareous rocks (calcitic and dolomitic) as marble, metalimestone and calcareous schist (with tremolite and rare diopside, forsterite, chondrodite, phlogopite, graphite, corundum, and epidote),
iii. Metaquartzite, mostly micaceous but locally ferruginous and even magnetite-bearing; partly green in colour due to their fuchsite content.

The carbonate rocks and the fuchsite-bearing quartzite, especially, form obvious marker beds within the Pioneers Group. Metavolcanic rocks are represented by mafic rocks such as hornblende-schist, amphibolite (mostly garnet-bearing and rarely containing titanite) and hornblendite, and by rocks of intermediate composition, including pyroclastic metasedimentary rocks. Chemical analyses of selected metasedimentary and meta-volcanic rock types are given in Appendix 2.

The lithology of the Pioneers Group sequences is described below on a geographical basis (from west to east), and refers to the terminology adopted by Clarkson

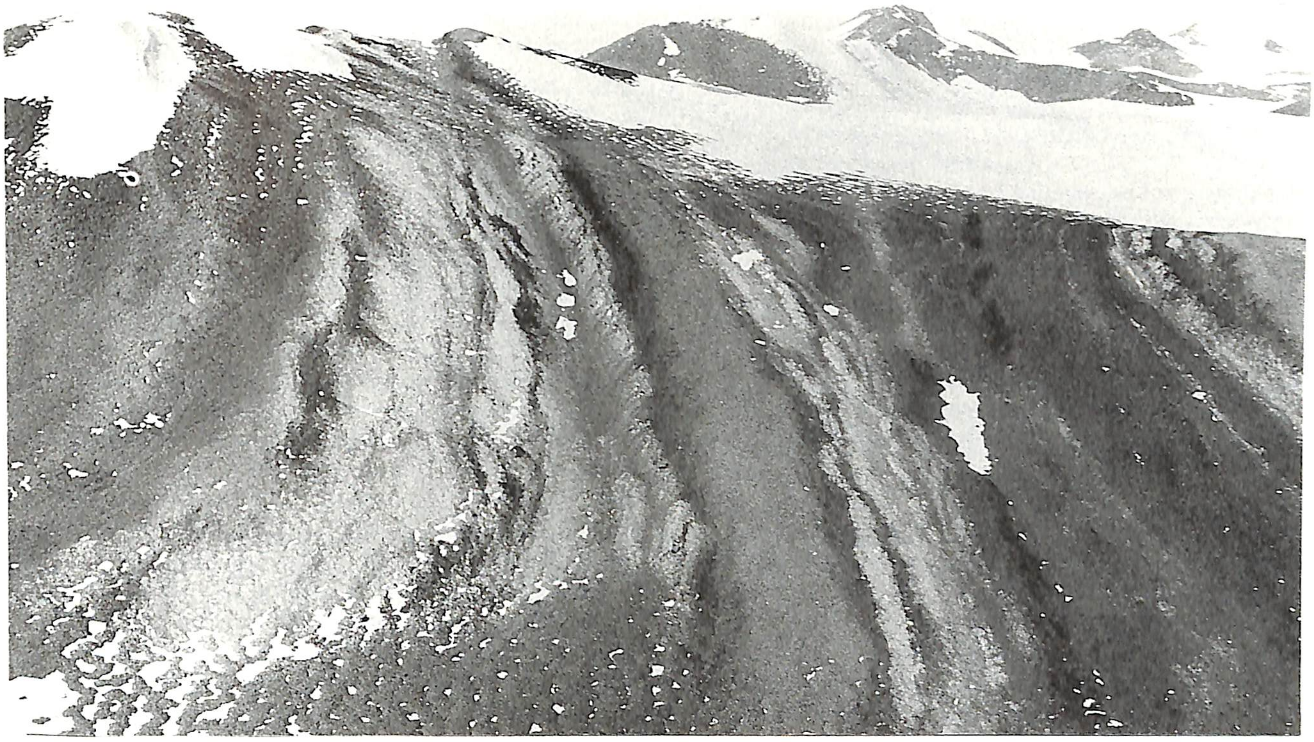

Fig. 4.1. Section of Pioneers Group supracrustal rocks showing several layers of carbonate rocks, east of Mount Provender, northern Haskard Highlands.

(1982*a,b*), Hofmann (1982), Hofmann and Paech (1983), Marsh (1983*a,b*, 1984), Paech (1985), and Roland and others (1995).

Haskard Highlands: In the Haskard Highlands the supracrustal rocks are adjacent to, and interleaved with, migmatitic Stratton gneiss and mylonitic Mount Weston gneiss of the Stratton Group (see Chapter 3). In contrast to the Pioneers Group supracrustal rocks exposed farther east, those in the west seem to be more affected by quartz–feldspar blastesis; the lithological associations observed at the different western outcrops are described below.

The carbonate rocks, and garnet- and kyanite-schists of the *Mount Provender* area (the "Nostoc Lake Formation" of Marsh (1983*a*)) are divisible locally into three belts, named "units a, b and c" by Grew and Halpern (1979, fig. 2). The "migmatites" of "unit a" are equivalent to the Stratton gneiss of Marsh (1983*a*). The subdivisions are:

i. A belt adjacent to the Stratton gneiss that consists mainly of layers (up to 8 m thick) of white, cream, pink and grey striped marbles (Fig. 4.1), quartzo-feldspathic (sometimes clinopyroxene-bearing) granoblastite, garnetiferous gneiss and schists, kyanite-schists, and quartzites. A kyanite + K-feldspar association was reported by Grew and Halpern (1979).
ii. A central belt of richly garnetiferous coarse- and medium-grained gneisses, mainly alternations of amphibole-bearing and biotite-bearing gneiss.
iii. A south-western belt which differs from (ii) by the addition of marble and layers of more variable composition.

The sequence of quartzites, carbonate rocks, and amphibolites in the *Mount Gass* area (the "Mount Gass Formation" of Marsh (1983*b*)) includes muscovite-bearing quartzites (locally pale-green fuchsite-quartzite), white metalimestone (up to 7 m thick), grey metadolomite, mica-schists, possibly metaconglomerate, amphibolite with relict clinopyroxene, and feldspathic granoblastite; the sequence lies adjacent to the Mount Weston gneiss. The mica-schists have the following mineral assemblage: biotite + muscovite + quartz + andesine ± staurolite ± kyanite ± K-feldspar. Semenov (1985) described an orthoclase + kyanite association, and a high-pressure facies (7–8 kbar, >740°C) determined by mineral thermometry and inclusion studies.

Metalimestone, calcareous schist and mica-schist (the "Williams Ridge Formation" of Marsh (1983*b*)) are exposed in the core of a N–S-trending syncline on *Williams Ridge*. Marsh (1983*b*) described the lithologies as:

i. cream or grey, medium- and fine-grained metalimestone (up to 10 m in thickness), partly dolomitic and containing quartz grains,
ii. calcareous schist (Fe-calcite + white mica + biotite + quartz ± oligoclase ± clinozoisite/epidote ± diopside),
iii. mica-schist (biotite + muscovite + quartz + oligoclase + epidote ± calcite ± magnetite), and
iv. white to yellow quartzite.

Excluding possible tectonic duplication, unproven at this locality, Marsh (1983*b*) estimated the thickness of the supracrustal rocks as (from top downward): marble (>300 m), quartzite (20–30 m), magnetite-bearing mica-schist (1.5–2 m).

A mica-schist with thin metalimestone layers exposed on *Wedge Ridge* (the "Wedge Ridge schist" of Marsh

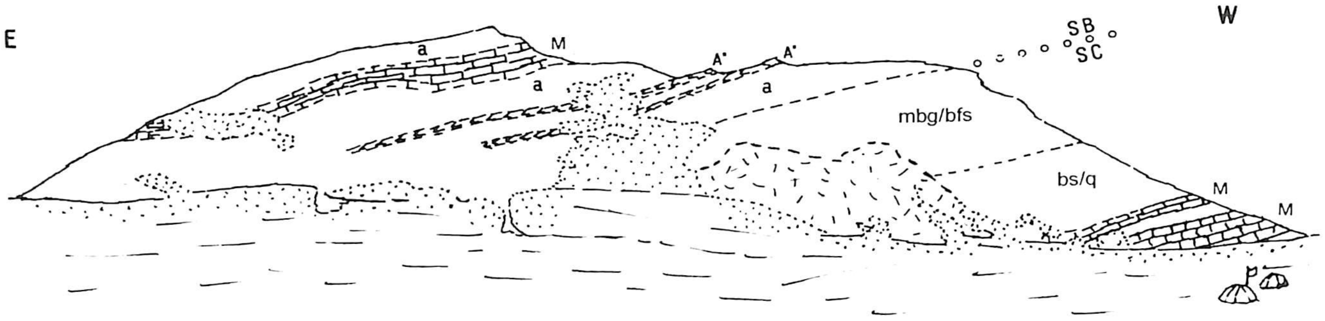

Fig. 4.2. Pioneers Group metasedimentary rocks, including marble, at Sumgin Buttress. Dotted line: boundary between "Shaler Cliffs sequence" (SC) and "Sumgin Buttress sequence" (SB) *sensu* Hofmann (1982). M, marble associated with fuchsite-quartzite; bs/q, biotite-quartz-schists and quartzites; mbg/bfs, muscovite-biotite-gneisses and biotite-feldspar-schists; a, partially banded garnet-amphibolites; A', massive amphibolites.

(1983*b*)), has a mineral association which is similar to that of the schists at Williams Ridge, i.e. biotite + muscovite + quartz + oligoclase ± garnet.

La Grange Nunataks: Contacts between the supracrustal rocks of the Pioneers Group and the Mathys gneiss and Fuchs Dome gneiss of the Stratton Group (see Chapter 3) have been observed in the La Grange Nunataks and northern Fuchs Dome area. Marsh (1984) subdivided the metasedimentary rocks into two units, which he named the "Haskard Group" (with the "Butterfly Formation"), and the undifferentiated "Schimper Group".

The flat-lying metasedimentary carbonate sequence exposed on Butterfly Knoll, southern La Grange Nunataks, and referred to as the "Butterfly Formation" by Marsh (1984), overlies granitic gneiss and has a foliation parallel to the bedding. Marsh (1984) described the sequence (from top to bottom) as:

saccharoidal metalimestone, with radiating clusters of tremolite	? m
muscovite-bearing quarzite, calcareous at lower part	>10 m
cream calcareous metasandstone, cross-bedded, right-way-up	1 m
calcareous biotite-schists	2–3 m
calcareous schists, containing varying proportions of muscovite, biotite, tremolite	12 m

A similar sequence of quartzite–white metalimestone–grey metalimestone is exposed to the south-east. Tremolite is conspicuous at most outcrops and it is believed to be a typical mineral in the calcareous sequences of the Pioneers Group. Metalimestone, calcareous schists and kyanite-bearing mica-schists on the southern nunatak of *Lewis Chain* were grouped with the "Butterfly Formation" by Marsh (1984).

Quartzites and garnetiferous schists, included in the "Schimper Group" by Marsh (1984), crop out at several localities in the La Grange Nunataks. At the nunatak west of Butterfly Knoll and on the one west of *Mathys Bank*, Mathys gneiss (of the Stratton Group) is in thrust contact at both the top and bottom of the metasedimentary sequence. The Pioneers Group sequence here includes: garnetiferous schists and gneisses of varied mineralogy (muscovite and/or biotite + quartz + garnet + plagioclase ± kyanite ± staurolite), kyanite-schist, garnetiferous quartz-rich layers and amphibolite layers (up to 15 cm thick), muscovite-rich schists with 20 cm thick grey metalimestone layers, and pale green quartzite (5 m) (Marsh, 1984).

An 800 m thick sequence of metapelites (garnet-mica-schist, garnet-amphibole-schist and staurolite-schist) with intercalations of marble, metaquartzite (containing magnetite) and mafic metavolcanic rocks crops out on the south-eastern ridge of *Mount Skidmore*, and on adjacent nunataks; these rocks were referred to the "Skidmore Group" by Paech (1985). From this same area, Paech (1985) reported gneisses with blastic feldspar growth, due to anatexis, that are lithologically transitional between the rocks of the Pioneers and Stratton groups.

Garnet-kyanite-bearing mica-schist, amphibole/biotite-schist, metaquartzite (locally green in colour), metacarbonate series and mafic metavolcanic rocks exhibit recumbent folds with a southern vergence in the north-eastern part of the NW–SE-trending ridge between Mount Skidmore and Mathys Bank.

A thick sequence of white calcareous rock exposed on *Mount Etchells* has been tentatively assigned to the Pioneers Group. However, the nature of its boundary to the migmatic rocks, which have yielded K-Ar ages of 390 and 460 Ma, is unclear. Most of the smaller outcrops in the La Grange Nunataks can also be assigned to the Pioneers Group. Quartzites (commonly pale green due to fuchsite), marble or metalimestone and muscovite-schists are typical lithologies at these outcrops; fibrolite co-exists with kyanite and staurolite.

Herbert Mountains: The geology of the Herbert Mountains has been studied mainly by Hofmann (1982), Hofmann and Paech (1983) and Marsh (1984). The rocks at most exposures, except at the northernmost ones, are supracrustal rocks belonging to the Pioneers Group. They are represented by a varied sequence of metapelite, metaquartzite and amphibolite together with calcareous rocks. The contemporaneous but independent lithological studies of Marsh (1983*a*,*b*, 1984) and Hofmann (1982) led to different lithostratigraphical terminology for the supracrustal rocks in this area. However, to prevent further confusion the following descriptions are based on lithological terms only and will neither refer to existing formation names nor introduce new ones.

The most notable feature of the Pioneers Group in the

Herbert Mountains is the occurrence of thick carbonate rock sequences that probably represent the lower part of the succession. These rocks crop out at the lowermost part of *Sumgin Buttress* (Fig. 4.2), at *Shaler Cliffs*, *Hollingworth Cliffs* and *Mount Absalom*. They are characterized by thick cream to white marble layers that are several metres thick near the base of the northern face of Sumgin Buttress (Fig. 4.2), and have a total exposed thickness of about 300 m at Hollingworth Cliffs. Marly limestone and marly schist are intercalated to varying degrees, and sedimentary structures, such as cross-bedding, are preserved locally. A varying amount of quartz grains is embedded in the carbonate layers. Carbonate intercalations occur also in the thick metapelite sequences at *Bernhardi Heights* and even in mylonites of the Stratton Group at *Charlesworth Cliffs*.

Another characteristic lithology of the area is fuchsite-bearing metaquartzite, the fuchsite content giving a pronounced pale green colour to the quartzites and making them useful marker horizons. The quartzites at Mount Absalom show dm-scale cross-bedding, indicating shallow-water sedimentation (Kleinschmidt, 1989).

The more common rock sequences observed in the Herbert Mountains, however, are metapelites, and pelitic metasandstones alternating with amphibolite and hornblende-schist (basic tuffite as protolith?); magnetite is widespread in the metapelites. The following mineral associations have been described:

i. garnet + muscovite + quartz,
ii. kyanite + garnet + muscovite + biotite + plagioclase (oligoclase) + K-feldspar + quarz,
iii. staurolite + kyanite + garnet + biotite + muscovite + plagioclase (oligoclase) + quartz,
iv. kyanite + sillimanite (fibrolite) + garnet + muscovite ± biotite + quartz.

Metamorphic mobilisates occur only as synkinematic quartz lenses or streaks, orientated parallel to the foliation and commonly folded. Migmatites are absent but blastomylonite fabrics are common (Charpentier Pyramid, Shaler Cliffs). Cracked and broken crystals of garnet, staurolite and kyanite, drawn out along the schistosity, provide evidence of an earlier coarse-grained amphibolite-facies fabric (Marsh, 1984).

Pioneers Escarpment: All the rock types described so far from the western and central parts of the northern Shackleton Range are present also along the Pioneers Escarpment, which gave its name to the Pioneers Group.

The Pioneers Escarpment is the easternmost and remotest part of the northern Shackleton Range, and outcrops are sparse. During the 1987–88 GEISHA expedition, this area was visited and sampled intensively for the first time. Most of the rock types observed represent amphibolite-facies metamorphic rocks of sedimentary and bimodal volcanic origin; the easternmost outcrop of the Pioneers Escarpment, at Vindberget, is of unmetamorphosed shales, sandstones and greywackes.

The supracrustal rocks exposed along the Pioneers Escarpment form a varicoloured succession of the following rock types (see Fig. 4.3):

i. quartzites: muscovite-quartzite, sericite-quartzite, fuchsite-quartzite, garnet-quartz-schists, etc.,
ii. pelites: mica-schists and plagioclase- or plagioclase-microcline-gneisses, alumina-enriched schists,
iii. marls and carbonates: grey metalimestones, carbonaceous quartzites, but also pure white, often fine-grained, saccharoidal marble of different varieties,
iv. ortho-amphibolites:amphibolite,amphibolite-schist, garnet-amphibolite, and
v. felsic to intermediate volcanic rocks: garnet-biotite-schist,epidote-biotite-plagioclase-gneiss,microcline-gneiss.

Metalimestones, marbles and quartzites are the typical lithologies. The marbles are partially impure, with quartzitic intercalations; the occurrence of single, rounded quartz grains in some samples may have been derived from beach sands and coastal dunes.

Roland and others (1995) have described the following varieties of marble: tremolite marble, olivine-tremolite marble, chondrodite-olivine marble, graphite-bearing tremolite-muscovite marble, diopside-clinopyroxene-tremolite marble, pure white, Carrara-type marble, and silicate marble. The high amount of strontium (up to nearly 2000 ppm) detected in samples from south-south-west of Blanchard Hill was probably concentrated in the calcite (strontio-calcite).

The metasedimentary rocks are intercalated with metavolcanic rocks. Amphibolites normally consist of hornblende (some with quartz inclusions), and biotite with inclusions of zircon, rutile/sagenite and leucoxene. An amphibolite collected at Lord Nunatak was probably originally either a lamprophyre or a basic ash layer; geochemical analysis has shown high values of chromium (up to 1972 ppm), nickel (581 ppm) and iron (12.37%). Another sample from Lord Nunatak is a garnet-amphibolite, with idioblasts of garnet and amoeboid opaque minerals, and an iron content of 14.51%. Hornblende in an amphibolite from Meade Nunatak has a relict structure which may be inherited from earlier clinopyroxene; the protolith of this amphibolite may have been a basic intrusive or volcanic rock. The amphibolites all plot in the ortho-amphibolite field on an MgO-Cao-Fe_2O_3 diagram (after Walker and others, 1960) and they

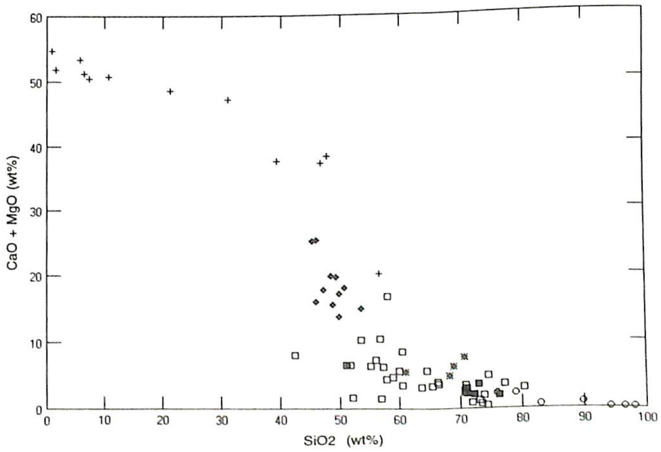

Fig. 4.3. CaO+MgO–SiO_2 plot showing the variety of rock types present in the Pioneers Group. Diamonds, marbles; asterisks, quartzites; solid triangles, ortho-amphibolites; squares, feldspathic gneisses; solid squares, feldspathic gneisses partly of volcanic origin; circles, samples of shales and greywacks from the Vindberget area (for comparison).

are of tholeiitic and calc-alkaline compositions (Roland and others, 1995). Pale-coloured gneisses of rhyolitic composition must also have been derived from volcanic protoliths since geochemical analyses have revealed higher amounts of the immobile, incompatible high field strength elements (HFSE) Nb, Ti, Y, and Zr (Fig. 4.4).

Depositional environment

The sedimentary associations described in the preceding section on lithology provide evidence of the depositional environment of the Pioneers Group protoliths.

The *carbonate rocks* range from grey calcareous schists and limestones to pure, white marble. Several calcareous units have been observed and, although tectonic repetition cannot be totally excluded, they seem to represent carbonate shelf cycles; such cycles would indicate a regressive phase during the geological evolution of the region (Wilson, 1975). The repeated occurrence of carbonate sequences indicates shallow-water marine deposition, possibly including slightly evaporite conditions. Cross-bedding proves high-energy transport (?tidal flats). Rounded quartz grains in the marbles are best explained by coastal dune or beach sand that has been reworked in a shallow marine environment (Roland and others, 1995). The existence of olivine (forsterite) marble proves the availability of magnesium and thus their protoliths were probably dolomitic limestones containing little quartz.

The *metapelitic rocks* are predominantly biotite-schists but garnet-, kyanite- (partly as kyanitite) and staurolite-bearing rocks are present also. The staurolite- and kyanite-schists and kyanitite were derived probably from high-alumina sediments or tuffites but the Al_2O_3 content (up to 26%) was not enriched by weathering (Roland and others, 1995).

The *quartzites* were derived from nearly pure quartz sands (up to 97.99 % SiO_2) which are in part cross-bedded. They are indicative of shallow-water sedimentation, including braided streams, but dune and beach sands may have been present during part of the deposition history since rounded quartz grains occur in the calcareous sedimentary rocks.

Because the sedimentary rocks occur together with bimodal volcanic rocks, the Pioneers Group can be assigned to two possible associations (Roland and others, 1995): the "quartzite-pelite-carbonate (QPC) association", and the "bimodal volcanics-arkose-conglomerate (BVAC) association". The latter comprises immature terrigenous clastic sediments (arkoses, feldspathic quartzites and conglomerates) as well as bimodal volcanic rocks, but they may also be composed of pelites, massive mature quartzites, banded iron formation (BIF), and carbonates according to Condie (1989); ferruginous quartzites are present in the Shackleton Range but there are no BIFs *sensu strictu*.

The QPC association is typical of Proterozoic sedimentary sequences, indicating that deposition took place on a stable shelf, i.e. on the submerged rim of a craton. Marine shallow-water sedimentation, possibly with coastal beach and dune sands, and (?)terrestrial alumina-enriched sediments and/or tuffites, formed the protoliths of most of the metasedimentary rocks. Contemporaneous tectonic/orogenic activity is unlikely as uplift would have caused a higher influx of terrigenous material. The QPC protoliths of the Pioneers Group probably represent an original, well-stratified sequence deposited on a stable shelf or in the marginal cratonic basin of a continent; this would have been located at the present-day position of the northern and north-western rim of the Shackleton Range. The initial $^{87}Sr/^{86}Sr$ ratio of the mica-schists, which in most samples is >0.710, indicates an extended prehistory for the metasedimentary protoliths. They may be derived from an early Proterozoic–late Archaean crustal complex (Hofmann and others, 1981) which is older than the homogenization event, dated at (?) 1400 Ma.

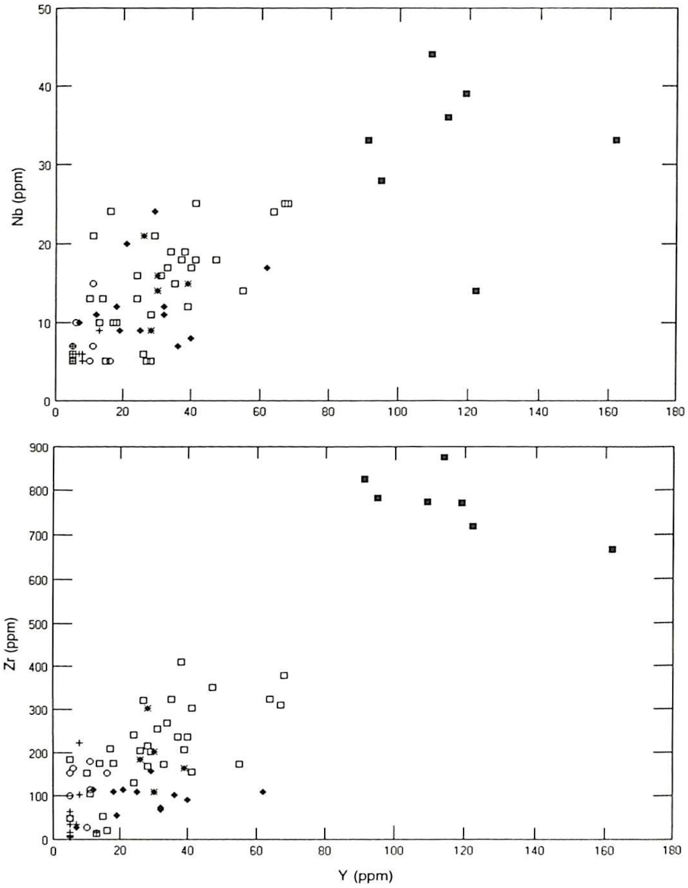

Fig. 4.4. Niobium–yttrium and zircon–yttrium plots. The higher amounts of Nb, Y, and Zr (see solid squares) provide evidence for a volcanic origin for some gneisses of the Pioneers Group. The samples are from the Meade Nunatak area and Mount Beney.

The QPC association is confined to three stable tectonic settings: rifted continental margins, cratonic margin of back-arc basins, and intracratonic basins (Condie, 1989). The Pioneers Group protoliths do not fit the intracratonic basin model because of the BVAC association, including calc-alkaline volcanic rocks. The latter can occur in both island arcs and continental margin arcs, and the QPC and BVAC associations are best combined near a cratonic margin, in a back-arc basin situation (Roland and others, 1995).

Metamorphism and tectonics

The metasedimentary rocks of the Pioneers Group have been subjected to multiple phases of metamorphism and deformation. Amphibolite-facies metamorphism prevailed, with the highest grade being reached, as indicated by mineral assemblages containing kyanite, sillimanite, staurolite, orthoclase and garnet. The P–T conditions varied and there seems to have been a distinct P–T increase from west to east, and possibly from south to north. The rocks at Williams Ridge probably suffered the lowest P–T conditions. Estimates based on garnet-biotite and garnet-staurolite geobarometry (after Glebovitski and others, 1977; Perchuk, 1977) for samples from La Grange Nunataks (4.4–4.9 kbars at 520–540°C) and Herbert Mountains (4.5–4.8 kbars at 600–625°C) indicate intermediate pressure, epidote-amphibolite-facies metamorphism.

Mineral analyses and P–T estimates carried out on garnet-kyanite-staurolite-mica-schists from southern Meade Nunatak, Pioneers Escarpment, have been described by Roland and others (1995). They used the paragenesis "quartz - plagioclase - biotite - kyanite - garnet - staurolite" as well as the stability fields of Al_2SiO_5 polymorphs, the P–T diagram of the KFMASH-system (K_2O-FeO-MgO-Al_2O_3-SiO_2-H_2O) of Spear and Cheney (1989), and the Fe/Mg-ratio in solid solutions, to deduce that the outer rim of garnet crystals developed at temperatures of 570–580°C and approximately 6 kbar pressure (X(Fe) $\approx$ 0.85), whereas the cores had a lower X(Fe) value ($\approx$ 0.73) and developed at 600–670°C and 6–10.5 kbar. They concluded that garnet growth started at temperatures of 600°C and a pressure of about 10.5 kbar. Zoning (pyrope-rich core, almandine-rich outer rim) indicates growth under retrograde conditions, i.e. during a phase of uplift. The relict cores provide good evidence that granulite-facies conditions were reached, at least in the rocks exposed along Pioneers Escarpment. The temperature of 600°C would have been too low for anatexis to occur, despite the high pressure conditions, and this has been confirmed by field observations.

Retrograde alteration of rocks in all areas is expressed locally by the partial recrystallization of cataclastic rocks; newly formed albite, chlorite and epidote indicate greenschist-facies conditions. It is assumed that this retrograde metamorphism is related to thrusting or nappe tectonics (see below). Throughout most of northern Shackleton Range, the tectonic structures in the Pioneers Group (fold axes and lineations, foliation(s) and thrust planes) trend predominantly E–W. Equivalent structures are reported from the migmatitic and blastomylonitic rocks of the Stratton Group adjacent to exposures of the Pioneers Group. Flat-lying structures are widespread. They are recognized by a schistosity mostly parallel to the axial planes of recumbent folds. Flat-lying sequences in the Herbert Mountains (lower part of the north-western corner of Sumgin Buttress, Charpentier Pyramid and surrounding outcrops), as well as in La Grange Nunataks, have complicated structures characterized by recumbent folding and tectonic stacking during multiple phases of deformation. Tectonic duplication and thickening is widespread. Rarely, the primary sedimentary superposition is still preserved.

In the Herbert Mountains the Pioneers Group is intensely folded along E–W axes. The folds plunge gently either eastward or westward (Marsh, 1983*a*; Hofmann and Paech, 1983; Braun 1995) but investigators differed in their interpretations of the vergence and intensity of folding: Hofmann (Fig. 4.5, lower part) prefers upright folds characterized by relatively gentle undulations whereas Paech (Fig. 4.5, upper part) favoured intense folding, mostly with a northward vergence. The structural trends observed elsewhere in the Pioneers Group are more uniform, with the exception of the Haskard Highlands, where there is no regular structural pattern. The ~ N–S-trending syncline at Williams Ridge, which has a core of Pioneers Group rocks, is apparently a simple, nearly isoclinal synform with an eastward vergence and an axial plane dipping at ~ 280°/50°. However, there are at least two phases of folding: B_1-axes (e.g. 210°/10°) are wrapped around B_2-axes (000°/00°). Moreover, the zone between the Pioneers Group and the basement has mylonitic structures, especially in the upper part of the basement; intrafolial and (?) sheath folds, *s-c* fabrics, phacoids, and shear bands indicate tectonic transport toward the south-west and a stretching lineation varies between 235°/05° and 225°/30°.

During amphibolite-facies metamorphism, prograde minerals formed a granoblastic texture with anastomosing foliation planes parallel to the bedding (Marsh, 1983*a*,*b*; Paech, 1985; Braun, 1995). Garnet, plagioclase, and kyanite crystals up to 1 cm in size are common, the latter showing a preferred orientation parallel to the foliation planes. Garnet porphyroblasts include parallel streaks of quartz or opaque minerals, most of which indicate passive rotation during or after crystal growth (Clarkson, 1972; Braun, 1995; Roland and others, 1995). Tectonic lineation is common in the metasedimentary rocks, attaining rod-like features in some metaquartzites particularly.

Deformation under retrogressive conditions resulted in mylonitic fabrics more or less parallel to the prograde foliation and compositional layering (Marsh, 1983*b*). Shear zones contain brittle fragments of garnet and feldspar, embedded in a matrix of recrystallized quartz grains and small mica flakes. The orientation of the mica defines a second schistosity parallel to the axial planes of minor, mostly isoclinal, folds. Thin-section investigations indicate that strain effects in minerals are common and varied. All structures and fabrics have been deformed by several generations of later folds. In the northern Haskard Highlands, tight folds, with axial planes parallel to the main trend of the earlier foliations, dip SW or W at medium angles (Marsh, 1983*b*; Braun, 1995). Locally, biotite flakes that are smaller than the earlier generations of mica, form a new planar schistosity. Crenulation within the fold hinges, a strong *b*-lineation, and rodding are common features in the exposures at Mount Gass ("Mount Gass Fold" of Marsh (1983*b*)). The *s*-planes in the Mount Gass–Mount Weston area dip mainly NW, but north of Mount Weston they are nearly vertical and strike E–W. A strong NW-W-plunging stretching lineation and westward shearing are indicated by phacoidal and bookshelf shear structures and sheath folds.

Late, large-scale folding produced mappable changes of strike. Typical examples have been observed in the northern Haskard Highlands ("Mount Gass Fold" of Marsh (1983*b*)) and Herbert Mountains ("Bonney Bowl Syncline" of Hofmann (1982) and Marsh (1984)). Calcareous layers close to basement rocks apparently served as preferential shear horizons (Braun, 1995)

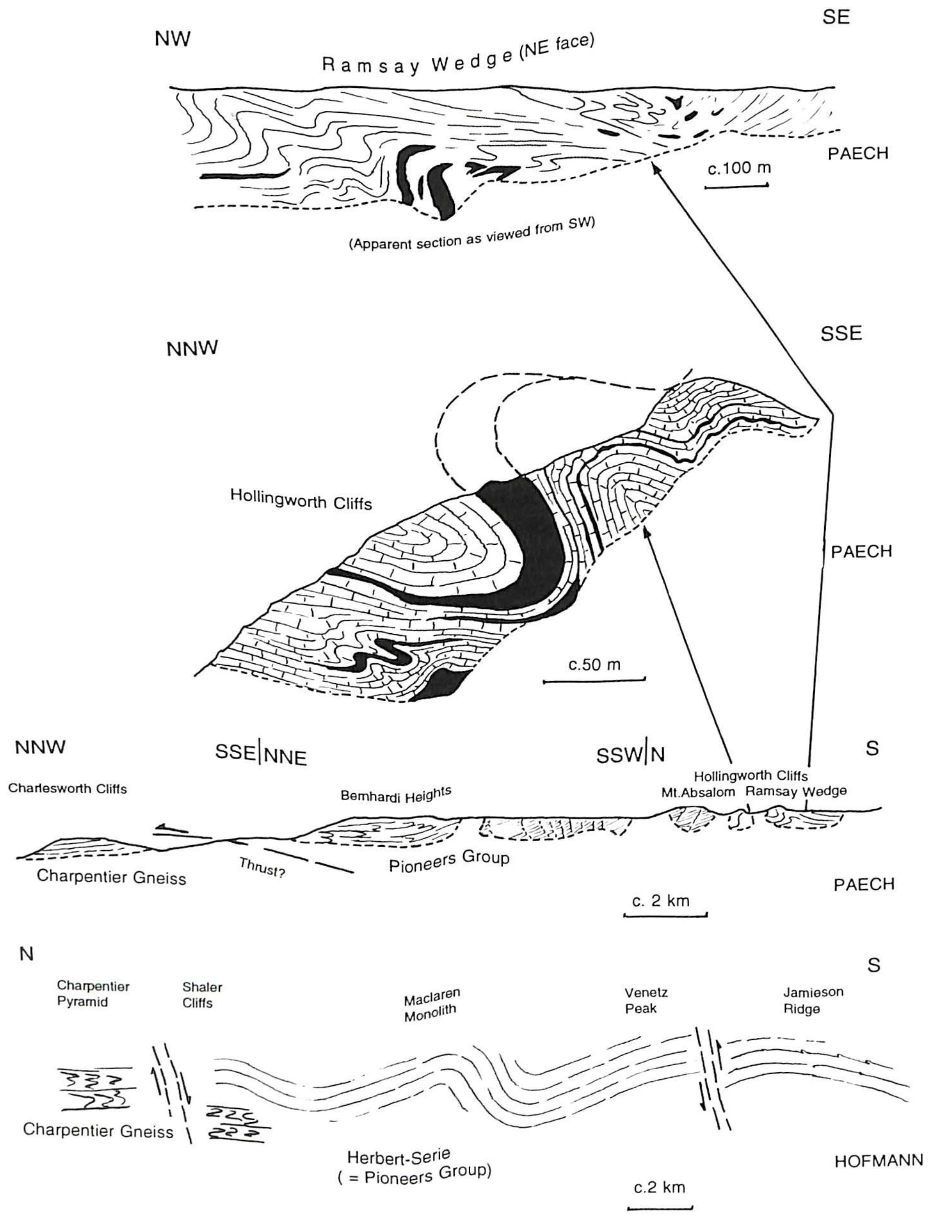

Fig. 4.5. Geological cross-sections through the Herbert Mountains showing two interpretations of the tectonic style. Black, amphibolite; brick pattern, marble.

although some unit boundaries may represent original unconformities (Marsh, 1984). Nappe tectonics are obvious in the southern part of the Shackleton Range (Roland and others, 1988; Buggisch and others, 1990) but there is evidence for thrust/nappe tectonics in the northern Shackleton Range as well:

i. Stephenson (1966) considered that thrusting was an important tectonic feature in the Shackleton Range and his theory was adopted to explain the structures of La Grange Nunataks (thrusting of basement gneisses over the "Butterfly Formation"; Marsh, 1984) and northern Haskard Highlands (thrusting of the so-called "La Grange Nappe", where (from bottom to top) Mount Weston gneiss, "Mount Gass Formation", and "Nostoc Lake Formation" were thrust over "Williams Ridge Formation" and the underlying basement; Marsh, 1983*a*). The sequences are partly interfolded and/or interleaved. According to Marsh (1983*a*) the structure of the Shackleton Range can be interpreted as a complex of nappes between a high-grade terrain to the north and a foreland to the south. The structures in the northern Haskard Highlands, La Grange Nunataks and Herbert Mountains seem to be analogous.

ii. On the northern face of Sumgin Buttress and at Charpentier Pyramid, north-western Herbert Mountains, Hofmann and Paech (1980, 1983) and Hofmann (1982) observed intense shear deformation with internal folding, boudinage and rodding. An extreme divergence of fold axes, as has been observed in this zone, is common in thrust planes.

iii. Overthrusts of unknown displacement are conspicuous on the north-eastern part of the ridge between Mount Skidmore and Mathys Bank, where they border tectonic slivers several hundred metres in thickness.

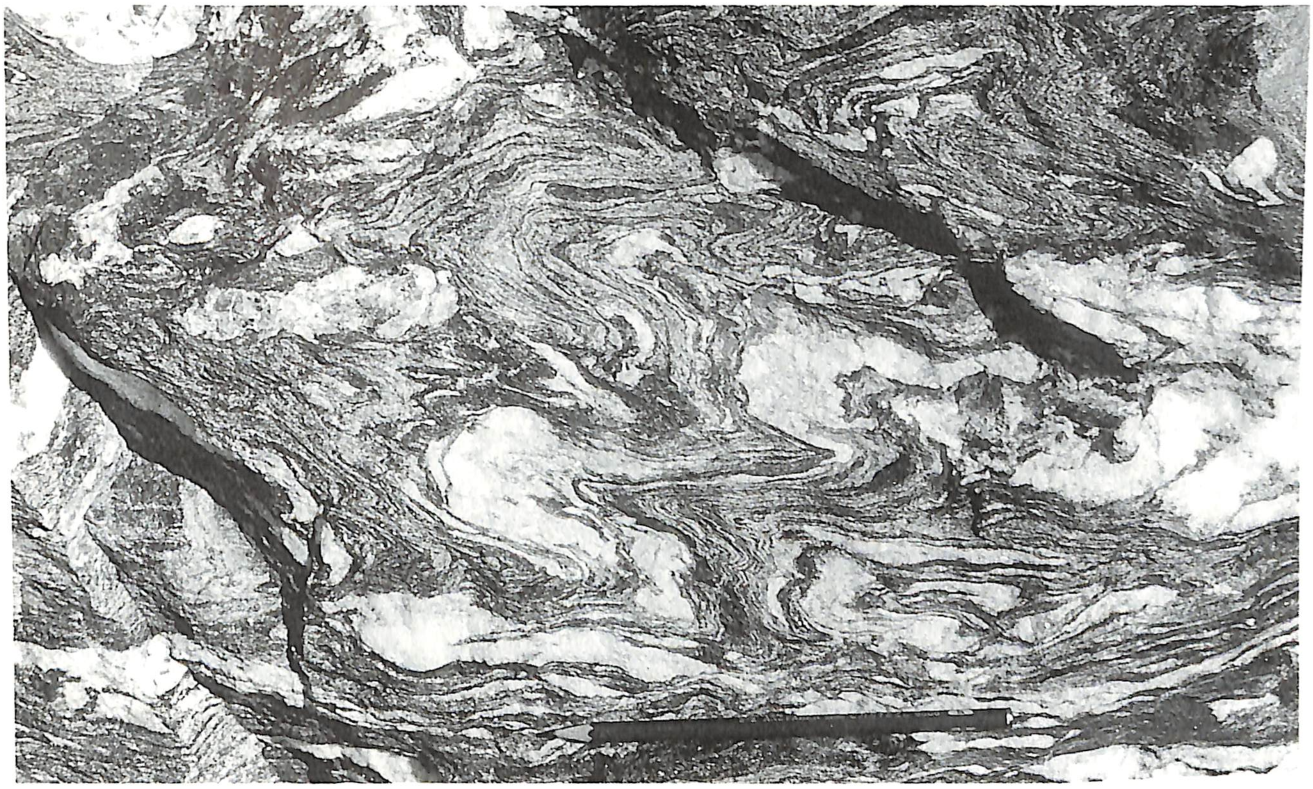

Fig. 4.6. Pioneers Group rocks at Whymper Spur are well stratified; marker horizons (especially fuchsite-quartzite) can be traced throughout northern Shackleton Range. Height of the cliff is >50 m.

iv. The Wiggans blastomylonite on True Hills has layers of carbonate rocks which possibly belong to the Pioneers Group. The incorporation of slivers of the overlying metasedimentary rocks into basement units can be explained by thrusting.
v. Pioneers Group metasedimentary rocks are structurally overlain by gneiss near Butterfly Knoll.
vi. Mount Weston gneiss alternates with strongly foliated mylonitic schists. Relicts within these mylonitic schists show that their precursor was gneissose, probably the Mount Weston gneiss.

Thus there are sufficient arguments in favour of thrust tectonics. If the allochthonous character of these units can be accepted, the structures could be called nappes. Future field investigations by the 1994–95 EUROSHACK expedition should provide new evidence for nappe tectonics.

Age and lithostratigraphical relationships of the Pioneers and Stratton groups

There are few reliable indicators for the age of the Pioneers Group. No fossil remains have been reported from either of the metasedimentary sequences, and their relative age cannot be ascertained in the field because the geological contacts seem to be mostly tectonic. The Stratton Group is assumed to be the older of the two groups on the basis of radiometric data.

Radiometric age determinations on the Pioneers Group and the adjacent, or interleaved, Stratton Group indicate only the age of their metamorphism. The age data have a broad scatter but 400–600 Ma dates predominate. There are no great differences between the radiometric dates obtained for the two groups although the Mount Weston gneiss, assigned to the Stratton Group, has yielded ages of >2000 Ma (Pankhurst and others, 1983). Grew and Halpern (1979) reported Rb-Sr ages for feldspathic augen-gneiss of 583 ± 48 and 519 ± 15 Ma, and 656 ± 66 Ma for a granitic gneiss. U-Pb ages of 500—550 Ma were reported for the same area by Grew and Manton (1980). For further details see Chapter 12.

It is probable that the Proterozoic–early Palaeozoic rock sequences assigned to the Stratton and Pioneers groups were intensively reworked during the Beardmore–Ross tectogenesis (= Pan-African thermo-tectonic orogeny widespread within the Gondwana supercontinent), thus resetting the radiometric clock. There is evidence for this in the similar tectonic pattern of both groups and in the mineral blastesis affecting the Pioneers Group, particularly in the Mount Provender area (Marsh, 1984), where both groups are closely interleaved.

Although the supracrustal rocks are well stratified (e.g. at Whymper Spur; Fig. 4.6) and some marker horizons (especially the fuchsite-quartzite) can be traced throughout northern Shackleton Range, it is neither possible to correlate between all the different sequences of the Pioneers Group, nor has it been possible to make a subdivision of the Pioneers Group that can be applied to all areas. This is mainly due to:

i. Poor exposures, especially in the Pioneers Escarpment area,
ii. Possible repetition of sequences due to thrusting (and (?) nappe) tectonics,
iii. Different P–T conditions,
iv. Structural differences, and
v. Effects of subsequent thermo-tectonism.

Paech (1985) observed incipient feldspar blastesis in the

Fig. 4.7. Migmatitic and intensely folded garnet-biotite-gneisses at Oleschnunatak, Pioneers Escarpment are referred to the Pioneers Group rocks, but they may be equivalents of the Stratton Group gneisses.

supracrustal rocks at Mount Skidmore, the blastesis increasing to the south-east, where granite-gneisses occur. This was interpreted as a gradational effect of anatexis, which was more intense in the Stratton Group. Post-depositional thermal events recognized in the Pioneers Group can be linked to the Stratton gneiss, which is interpreted as an intrusive body (Braun, 1995).

Gneisses, such as those at Oleschnunatak, Pioneers Escarpment (Fig. 4.7), have been assigned to the Pioneers Group but they could be equivalents of the Stratton Group. Younger tectonic events, e.g. thrusting and the development of mylonite zones, can simulate higher-grade metamorphism and/or an older structural stage, thus masking the true character of the Pioneers Group rocks. The lack of well defined boundaries and unambiguous correlations make it difficult to establish lithostratigraphical relationships between the two groups. Alternative correlations are discussed below.

Affinity between the Pioneers Group and parts of the Stratton Group: The calcareous intercalations within the Stratton Group may be the equivalents of carbonates in the Pioneers Group. Two explanations are possible:

i. The intercalations are tectonically emplaced by thrusting and/or nappe tectonics. The Pioneers Group supracrustal rocks are in contact with migmatic granite-gneiss of the Stratton Group (Mathys gneiss, Mount Weston gneiss, (?)Stratton gneiss, etc.) and blastomylonite lithologies ("Charpentier series"; Hofmann, 1982). The nature of these metamorphic rocks, which are mostly interleaved sequences within the Pioneers Group, is still under discussion; they have been correlated with the Read Group, and an age which is older than the supracrustal rocks is therefore assumed.

ii. Parts of the Stratton Group at least represent intensely deformed, partly mylonitic and gneissose Pioneers Group metasedimentary rocks. Marsh (1984) interpreted the occurrence of carbonate layers in the Wiggans blastomylonite as evidence of their sedimentary character, thus indicating their possible inclusion in the Pioneers Group. Equivalent calcareous intercalations are also known at Mount Etchells and Charlesworth Cliffs.

Affinity between the Pioneers Group and the Watts Needle Formation: Marsh (1983*a*) suggested the possible correlation of parts of the Pioneers Group with the Precambrian sedimentary formations exposed along the southern flank of the Shackleton Range, and Kleinschmidt (1989) also assumed that lithologies of the Pioneers Group (the "Williams Ridge Formation") were equivalent to the Watts Needle Formation. These sedimentary rocks were deformed during approximately the same period as the Pioneers Group (500–550 Ma; Buggisch and others, 1990), and both the Pioneers Group and the Watts Needle Formation cover basement rocks and consist of similar protoliths, e.g. limestone, quartzite, and Al-enriched sedimentary rocks.

It is hoped that more detailed field work by the 1994–95 EUROSHACK expedition will resolve the problems of interpretation discussed above and lead to a fuller understanding of the tectonic history of the Shackleton Range.

5 Watts Needle Formation

by W. Buggisch, A. Höhndorf, H. Kreuzer, H.-J. Paech and B. Weber

Synopsis

Short description: The Watts Needle Formation rests unconformably on deeply weathered basement rocks of the East Antarctic craton. It consists of sandstones, limestones, marls and shales, and represents a transgressive sequence with basal (continental) red beds, beach sands, supratidal to subtidal carbonate flats and subtidal shales, deposited on a passive continental margin. It was first recognized as a formation by Marsh (1983*a*).

Type locality: Mount Wegener; also present at Du Toit Nunataks, Watts Needle and the ridge due east of it, and Nicol Crags.

Metamorphism: The uncemented regolith at the base, the presence of kaolinite, and evidence of only weak pressure solution, show that these rocks were not exposed to high temperatures and pressures. The very low-grade metamorphic sedimentary rocks of the Watts Needle Formation are overlain by low-grade metasedimentary rocks in the Mount Wegener nappe.

Age: Late Precambrian (Riphaean–Vendian).

Introduction

The Watts Needle Formation was described originally as the basal unit of the Mount Wegener Formation (of the former "Turnpike Bluff Group") by Clarkson (1972, 1983) but later it was recognized as a separate formation by Marsh (1983*a*). Nevertheless, most authors regarded the Watts Needle Formation as the base of the "Turnpike Bluff Group". In accordance with Grikurov and Dibner (1979) and Marsh (1983*a*) we can demonstrate that the Watts Needle Formation is an independent formation, separated from the Mount Wegener Formation by its tectonic and palaeogeographical position (see also Buggisch and others, 1990).

The Watts Needle Formation is exposed at five isolated outcrops only: Du Toit Nunataks (Marsh, 1983*a*), Watts Needle, the ridge east of Watts Needle, Nicol Crags and the northern and north-western slopes of Mount Wegener (Figs 5.1 and 5.2). The formation can be divided informally into three members: (1) a basal sandstone member, (2) an overlying carbonate member and (3) an upper shale member.

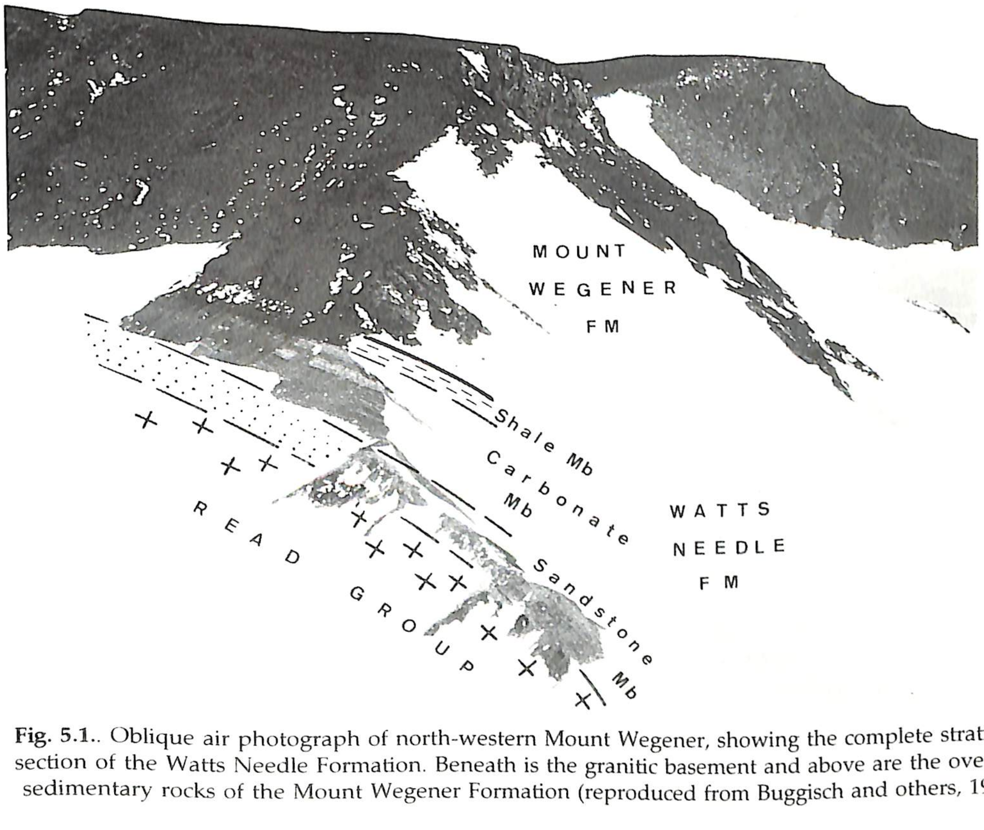

Fig. 5.1.. Oblique air photograph of north-western Mount Wegener, showing the complete stratigraphical section of the Watts Needle Formation. Beneath is the granitic basement and above are the overthrust sedimentary rocks of the Mount Wegener Formation (reproduced from Buggisch and others, 1994*b*).

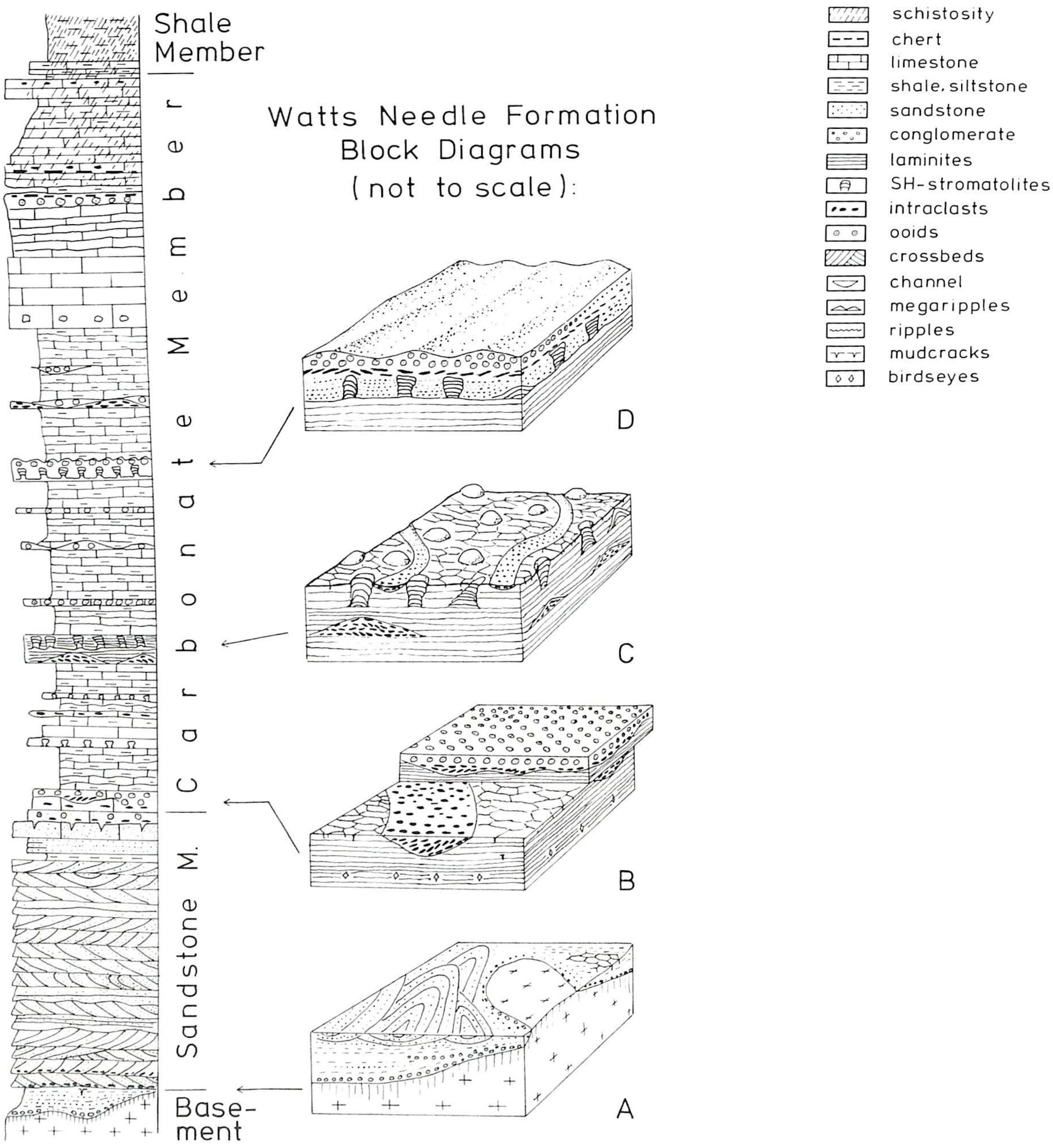

Fig. 5.2. Measured stratigraphical section of the Watts Needle Formation at Mount Wegener (reproduced from Buggisch and others, 1994*a*).

Lithology and sedimentology

Sandstone member: The sandstone member of the Watts Needle Formation rests unconformably on a deeply weathered peneplain cut into the Read Group (Clarkson, 1982*a*; Paech, 1982; Marsh, 1983*a*). The intensive late Precambrian chemical weathering led to the oxidation of biotite, decomposition of feldspar, and new growth of illite, kaolinite and iron oxides along the erosion surface of the crystalline basement rocks, resulting in the formation of regolith and soil. Palaeo-relief of a few metres in the peneplain, exposed at Nicol Crags (Fig. 5.3), is filled with continental red bed deposits: red mudstones and siltstones, and red (and green) sandstones and conglomerates. Pedogenetically broken quartz grains prove a terrestrial environment. The components of the basal sandstones were derived from the underlying weathered crystalline basement. The sandstones were classified in the field as arkoses but quantitative analyses of thin sections has shown that the feldspar is strongly weathered and that it forms <5% of the rock (usually <2%). Because of the low feldspar content and the presence of unstable rock fragments, the basal sandstones are better classified as quartzwackes (Pettijohn and others, 1973).

The basal sandstones (with bed thicknesses varying from centimetres to a few metres in thickness) grade up into 20–25 m thick beds of clean quartz-arenites with a high quartz content (96–100%). The great maturity of the well-sorted quartz-arenite is recorded also by the exclusive presence of stable minerals (green, brown and blue tourmaline and zircon) in the heavy mineral fraction. The well-rounded quartz grains are cemented by homoaxial quartz overgrowth; the boundary between the detrital core and the overgrowth is, in some cases,

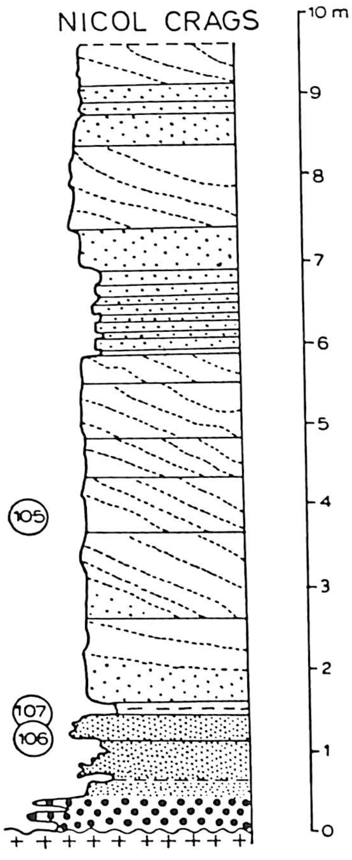

Fig. 5.3. Stratigraphical section of the Watts Needle Formation at Nicol Crags, showing the position of the microfossil-bearing samples. Pecked lines, cross-bedded quartzite; stipple, quartzite; fine stipple, arenaceous rocks (arenites and greywackes); coarse stipple, red conglomerates; crosses, basement; encircled numbers, sample numbers (after Weber, 1991).

marked by a coating of the original detrital grains. Contrary to Paech and others (1991*b*), who "considered [the quartzites] to be of aeolian origin", mean grain-sizes of between 0.5 and 1 mm, and the presence of cross-beds, slumps and water-escape structures, indicate a coastal depositional environment for these rocks. Measurements of cross-bedding directions indicate that northward-directed transport prevailed during the deposition of the quartz-arenities.

Carbonate member: The transitional beds between the sandstone member and the carbonate member consist of calcite-cemented, coarse-grained sandstones and sandy limestones, about 1 m thick. Due to the transport of the hanging Mount Wegener nappe, the carbonate member at Watts Needle and on the ridge due east of it is strongly deformed and partly mylonitized. The only complete exposure of the Watts Needle Formation is at the north-western corner of Mount Wegener, where the laminated marls and well-bedded limestones reach a maximum thickness of about 60 m (Buggisch and others, 1994*a*; see Figs 5.1 and 5.2).

The platy and laminated marls, which are compressed by pressure solution, were probably precipitated by microbial mats. Birds-eye fabric and desiccation cracks prove an intra- to supratidal depositional environment. The LLH- to SH-type stromatolites were formed by microbial activity also. Intra- and oosparites are intercalated between the laminites and stromatolites. Reworked microbial mud-chips and stromatolites are the most prominent components of the intrasparites, which were deposited in tidal channels. Graded oosparites, with erosive bases, have been interpreted as tempestites. Rare ooids and intraclasts that accumulated in ripples or mega-ripples provide evidence of high current velocity. All observed sedimentological features are consistent with the formation of the carbonates in the shallow marine sub-, inter and supratidal environment of a wide tidal flat.

Shale member: The uppermost part of the Watts Needle Formation consists of about 12 m of green shales containing lenses (20 x 2.5 cm) of carbonates with cone-in-cone structures; the shales probably were deposited in a subtidal environment. The shale member is truncated by the basal thrust of the Mount Wegener nappe.

Palaeontology

Sandstone member: The red-coloured basal sandstones, particularly in the upper part of the section beneath the pale-coloured quartz-arenites yielded several samples (especially 106 and 107; Fig. 5.3) containing a moderately preserved microflora. The pale-coloured quartz-arenites (sample 105) yielded only dubious fragmentary microstructures of questionable organic origin.

Normal petrographic thin sections of samples (collected by H.-J.P. in 1976–77) were examined for microfossils using a transmitted light microscope (see photomicrographs in Fig. 5.4). In addition, freshly broken rock surfaces of samples 106 and 107 were examined under the scanning electron microscope (SEM); for details of the methods used see Weber (1991).

The microstructures have a yellowish, brownish or reddish-brown colouration under transmitted light; opaque objects are present also. SEM photomicrographs have proved that many of the objects have a three-dimesional preservation. Although HF-treatment of sediment samples 106 and 107 has so far yielded no structurally preserved material of unquestionable organic remains, SEM and light microscopy showed a very broad spectrum of different morphotypes which can hardly be explained by a presumed inorganic origin alone. These objects are embedded in the siliciclastic matrix between the sedimentary quartz grains.

Five different morphotypes, representing different taxa, occur in the sandstones from Nicol Crags:

(1) solitary, simple spheroidal to ellipsoid cell-like microstructures (vesicles) occurring in some cases apparently in simple, budding cell-groups,
(2) larger grouped or complex spheroids and ellipsoid cell-aggregates or colonies,
(3) octahedral or "triangular" shaped objects,
(4) ellipsoid objects with numerous spiny outgrowths, and
(5) vase-shaped structures.

The predominant group (1) consists of individuals about 20–50 μm in size, group (2) structures are less abundant and examples of groups (3) - (5) are rare to very rare. Considering the predominantly poor preservation of

Table 5.1. Microfossils from the Watts Needle and Stephenson Bastion formations

ALGAE INCERTAE SEDIS
GROUP: ACRITARCHA Evitt, 1963

Morphotypes	*Genus (species)*	*Occurrences* *Nicol Crags*	 *Mount Greenfield*
(1) Solitary spheroids	*Favososphaeridium favosum* Timofeev, 1966		+
	Protosphaeridium Timofeev, 1966	+	
	(?) "*Nucellosphaeridium*" Timofeev, 1963	+	+
	Stictosphaeridium (?) Timofeev, (1962) 1963	+	+
	Trachysphaeridium Timofeev, (1966) 1969 (*T. timofeevi* Vidal, 1976)	+	+
	Kildinosphaera Vidal, 1983 (syn *Kildinella* Timof) (*K.* cf. *chagrinata* Vidal, 1983)	+	+
	Leiosphaeridia (?) Eisenack, 1958 emended Downie et Sarjeant, 1963	(+)	(+)
	Pterospermopsimorpha (?) Timofeev, 1966 (sp.)		(+)
(2) Grouped and complex spheroids	*Bavlinella* Shepeleva, 1962 (*B.* cf. *faveolata* Shepeleva, 1962)	+	
	Satka Jankauskas, 1979 (*S.* cf. *colonialica* Jankauskas, 1979)	+	+
(3) Octahedral or "triangular" shaped objects	(unnamed form A in sample 107)	(+)	
	Octoedryxium truncatum Rudavskaya, (1962) 1973		+
(4) Spiny objects (?Acanthomorphs)	(unnamed form B)	+	
Other microfossils			
(5) Vase-shaped objects (melanocyrillids?)	(unnamed form C)	+	

morphological details in many objects, most of the acritarchs are determined only to genus level; in few cases was it possible to suggest affinities to known Proterozoic acritarch species. Numerous objects remain uncertain as to their taxonomic position. Table 5.1 summarizes the previously identified taxa from Nicol Crags and compares them to data from the Stephenson Bastion Formation (see Chapter 6).

The microfossil assemblage from Nicol Crags is dominated by members of group (1), which are ascribed to (?) "*Nucellosphaeridium*" Timofeev, 1963 and to the genus *Trachysphaeridium* Timofeev, (1966) 1969 (Fig. 5.4). According to Vidal (1976), "*Nucellosphaeridium*" actually seems to represent different stages of preservation of various spheroidal envelopes, and thus it may include several different "taxa" (e.g. *Trachysphaeridium*, *Leiosphaeridia*, *Pterospermopsimorpha*, etc.). The taxa mentioned, as well as others referred to *(?) Stictosphaeridium* Timofeev (1962) 1963, *Kildinosphaera* Vidal, 1983, *Satka* Jankauskas, 1979 and *Leiosphaeridia* Eisenack, 1958 represent typical members of Upper Proterozoic (Riphaean–Vendian) microfossil assemblages. In the samples investigated there is no clear evidence for the presence of typical younger (Phanerozoic) taxa.

The "unnamed forms A, B and C" are isolated examples of uncertain taxonomic position from SEM preparations of sample 107. Form A could be a heavily eroded specimen belonging to the acritarch taxon *Octoedryxium* Rudavskaya which forms typical octahedral-shaped and single-walled vesicles (*c.* 30–80 μm across). They have a stratigraphical range of Vendian (Vidal and Knoll, 1983) to lowermost (?)Cambrian (Vidal, 1976). Form B resembles the vase-shaped microfossils (melanocyrillids) which are striking index fossils of the uppermost Precambrian, hitherto found worldwide but restricted to beds of between 700 and 950 Ma (Hofmann, 1987).

Deposition of the microbiota in sediments within a shallow marine environment seems likely since numerous specimens show differential degradation of their surfaces, caused by sedimentary transport before the embedding process took place. However, degradation could also be due to the redeposition of already fossilized organisms under shallow marine conditions (Weber, 1991). The predominance of the spheroid objects (>85% of the total number of identified individuals) is conspicuous, as is the complete lack of filamentous or thread-shaped microstructures. Filamentous or thread-shaped microbes (e.g. oscillatorian algae) are very typical of many Upper Proterozoic microfossil assemblages. Nevertheless, filamentous or thread-shaped algae could be easily destroyed during transport and redeposition processes, whereas small spheroids would be more resistant to mechanical impacts during their transport. Thus, the present composition of the microfossil assemblage occurring in the Watts Needle Formation may be a secondary effect, and not a true representation of the original composition of the primary microbiota.

Carbonate member: Stromatolites and problematical microfossils occurring in a quartz-chlorite-sericite-

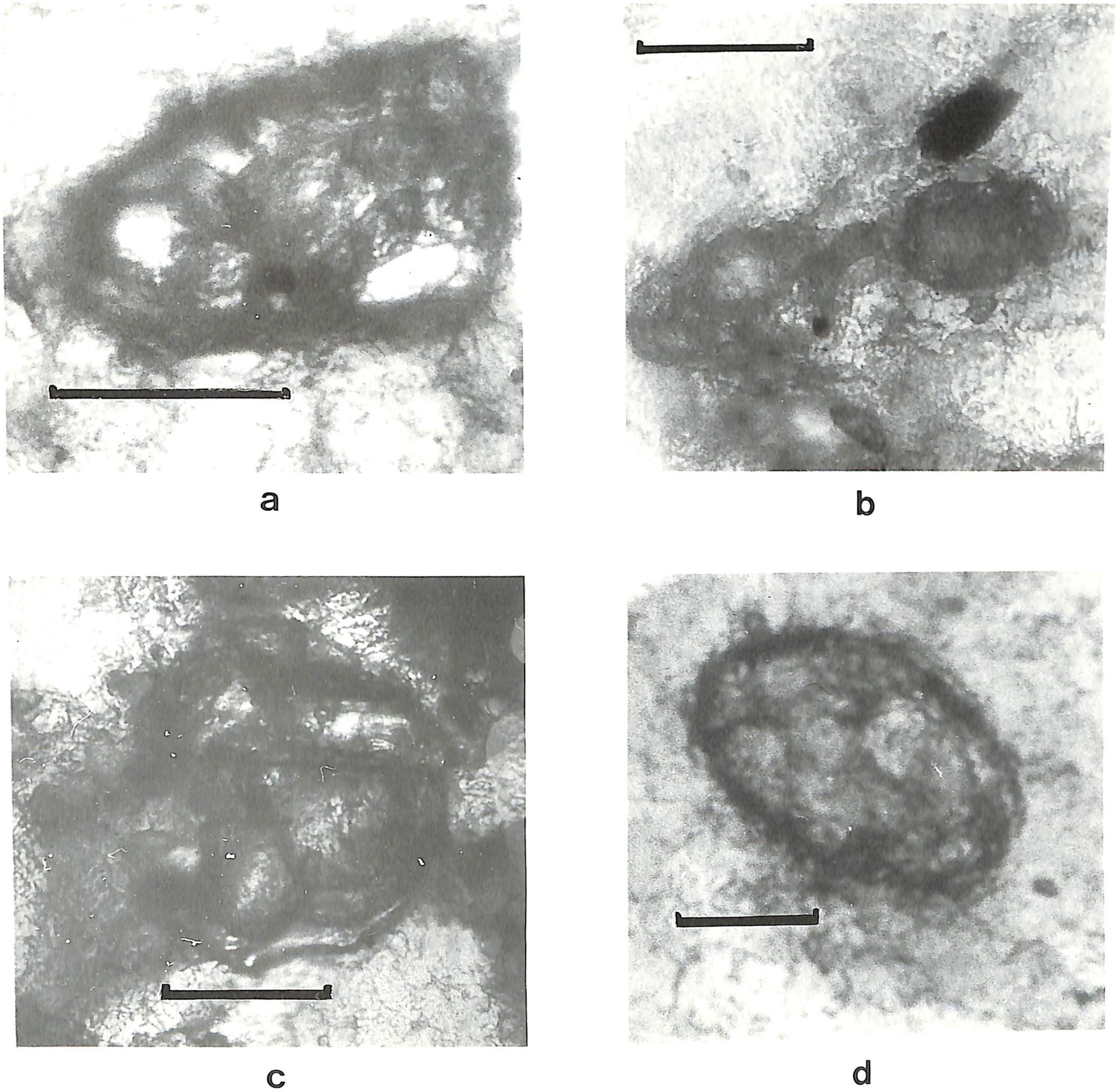

Fig. 5.4. Examples of microfossils from the Watts Needle Formation; scale bar = 10 µm. [Samples prepared (and deposited) at Potsdam.]

a. *Trachysphaeridium* cf. *timofeevi* Vidal, 1976; sample/thin section: 106/6. Thick-walled spherical to ellipsoid single vesicles (length = 25–115 µm, width = 22–77 µm), large dark brown to opaque internal bodies. Stratigraphical range: possibly uppermost Riphaean and Vendian (Vidal, 1976).

b. *(?)Trachysphaeridium* cf. *timofeevi* Vidal, 1976; sample/thin section: 107/2. Two joined specimens forming a "dumb-bell"-shaped cell-aggregate resembling a simple budding stage.

c. *Kildinosphaera* Vidal, 1983 (sp.) (= *Kildinella* Timofeev, 1966 *sensu* Vidal, 1983); sample/thin section: 107/2. Single-walled spheroid vesicles (mostly *c.* 35–64 µm diameter) with granulate or chagrinate surface. Diagenetically deformed individuals show numerous narrow wrinkles on their surfaces. Stratigraphical range: Riphaean to Vendian.

d. *Satka* cf. *colonialica* Jankauskas, 1979; sample/thin section: 107/5. Commonly large, thick-walled, circular to ellipsoidal envelopes containing tightly packed spheroidal "cell-chambers" (8–30 µm diam.). The dimensions of the colonies range up to 150 µm (Vidal and Ford, 1985). Stratigraphical range: possibly Upper Riphaean and Lower Vendian (Vidal and Ford, 1985).

carbonate sequence at Mount Wegener were reported by Golovanov and others (1980). They described two new "forms" within the stromatolite "groups" of *Collumnacollenia* Koroljuk and *Planocollina* Koroljuk: *C. schekltoni* Golovanov and *P. vegeneri* Golovanov. Both forms show several morphological similarities to the Upper Riphaean stromatolite groups *Jurusania* Krylov and *Inseria* Krylov, and the authors discussed the existence of a Gondwanian complex of stromatolite groups occurring in Australia (*Inseria, Jurusania, Minjaria, Boxonia, Linella*) and in eastern Antarctica (*Collumnocollenia* and *Planocollina*). The problematical microfossils from the same sequence were mentioned in name only:

Nubecularites Maslov
Vesicularites lobatus Reitlinger
V. consuetus Yakschin 1972
V. compositus Zhuraleva.

The authors suggested that the stratigraphical age of the assemblage was "Upper Riphaean-Yudomian".

Age

The age of the Watts Needle Formation is late Precambrian (Riphaean–Vendian), based on stromatolites (Golovanov and others, 1980) and acritarchs (Weber, 1990). This age is corroborated by a single Rb-Sr analysis of a purple shale from the ridge on the south-east side of Eskola Cirque, which gave a 720 Ma model age (Pankhurst and others, 1983). Two Rb-Sr errorchrons (Buggisch and others, 1994*a*) yielded a date of 680 ± 57 Ma (IR 0.726 ± 0.008) for the siltstones and quartzwackes from the base of the sandstone member, and 584 ± 41 Ma (IR 0.708 ± 0.006) for pelites from the shale member. K-Ar dates from 2–6 µm sieve-fractions from the Watts Needle Formation range from 520 to 800 Ma.

6 Stephenson Bastion Formation

by W. Buggisch, A. Höhndorf, H.-J. Paech, G. Kleinschmidt, H. Kreuzer and B. Weber

Synopsis

Short description: The Stephenson Bastion Formation forms the central part of the allochthonous units within the Mount Wegener nappe. Conglomerates occur near its base but the formation consists mainly of a sequence of silty shales, siltstones and fine-grained greywackes, deposited in a marine low-energy environment, probably below the wave base.

Metamorphism: The sediments were metamorphosed under very low-grade conditions in late Precambrian times. No Ross ages were obtained from K-Ar and Rb-Sr analyses.

Type locality: A N–S section across the col between Clayton Ramparts and north-eastern Mount Greenfield (Clarkson, 1972).

Age: Late Precambrian.

Introduction

The Stephenson Bastion Formation is part of the allochthonous metasedimentary rocks of the nappe unit described by Clarkson (1972) as the "Turnpike Bluff Group". The group was divided by Clarkson (1972, 1983) into four formations (Mount Wegener, Flett Crags, Stephenson Bastion and Wyeth Heights formations). Three of these formations are geographically separated and they differ in sedimentology, modal composition and age. Therefore, the term "Turnpike Bluff Group" is no longer used and, in this volume, the formations are described separately; the term "Flett Crags Formation" is no longer in current usage (see Appendix 1).

The Stephenson Bastion Formation (Fig. 6.1) is exposed in a syncline at Stephenson Bastion, with an overturned, steeply dipping northern limb at Clayton Ramparts (in the north) and relatively flat-lying, gently folded sandstones and siltstones at Ram Bow Bluff (in the south).

Lithology and sedimentology

The lowest beds exposed at Clayton Ramparts are conglomerates, which consist of strongly recrystallized quartz and polycrystalline quartz pebbles, and feldspar (mostly microcline) embedded in a fine-grained matrix. The conglomerates are interbedded with, and overlain by, fine-grained slates and siltstones which grade up into sandstones. The upper part of the Stephenson Bastion Formation at Ram Bow Bluff is much less deformed. It was described by Clarkson (1983) as a "thick (about 600 m) sequence of sub-horizontal quartzites with some slaty horizons". The fine-grained sandstones are cross-bedded or laminated with a parting lineation. Sediment transportation from the north-west to south-east is indicated by flute-casts and cross-beds. Convolute bedding is very common.

Modal analyses of thin-sections revealed about 10–20% feldspar and 8–22% rock fragments (mostly stable) in the sand fraction. The amount of matrix or cement ranges

Fig. 6.1. Massive quartzites of the Stephenson Bastion Formation exposed in cliffs (80 m high) in the western part of Stephenson Bastion. (Photograph by P.D. Clarkson)

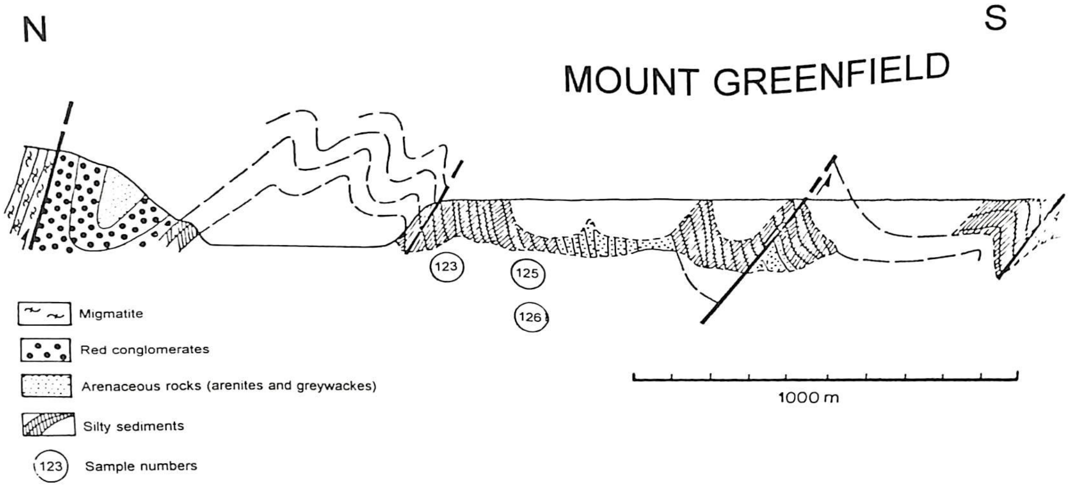

Fig. 6.2. Simplified geological profile of the Stephenson Bastion Formation at Mount Greenfield (from Weber, 1991); encircled numbers, sample numbers

from 30 to 55%. According to their modal compositions, the conglomerates and sandstones are classified as feldspathic- to lithic greywackes. They differ from the conglomerates and sandstones of the Mount Wegener Formation by the low feldspar content and the predominance of microcline.

Palaeontology

Petrographic thin sections of siltstone samples from Mount Greenfield (collected by H.-J.P. in 1976–77) provided the first evidence for the existence of a fossil microflora in these sedimentary rocks. Figure 6.2 shows the location of the fossiliferous samples HJP-123, 125 and 126 on a simplified geological profile of the locality. The same microfossil assemblage has also been confirmed in thin-section investigations of additional material collected from this area by W.B. (thin-section numbers WB ANT 88-225 & 245).

The microfossils are light to dark grey, even opaque under transmitted light. HF treatment of petrographic thick-sections shows the objects to be HF-resistant (i.e. organic-walled). However, a full palynological HF-preparation of samples HJP-123 and 125 has not yet been done because of the lack of sufficient sample material, whereas the HF-demineralization of sample HJP 126 (a related siltstone from the Mount Greenfield locality), using palynological standard methods, yielded relatively well-preserved organic-walled fossils (Fig. 6.3). This microbiota (see Chapter 5, Table 5.1; Figs 6.2 and 6.3) obviously belongs to the same Upper Riphaean–Vendian microfossil assemblage as that of the Watts Needle Formation.

Spheroids belonging to the genera (?) "*Nuclellosphaeridium*", *Trachysphaeridium*, *Leiosphaeridia*, together with *Pterospermopsimorpha*, predominate in the siltstones of the Stephenson Bastion Formation. In addition, the genus *Satka* Jankauskas, 1979 is represented by numerous individuals. Questionable fragments of thread-shaped objects (algae?) also occur in a few examples of the Stephenson Bastion rocks. The microbiota of the Watts Needle and the Stephenson Bastion formations both indicate a late Proterozoic age. Thus, a possible contemporaneous origin of the microbiota from the two formations cannot be excluded. This being the case, it is possible that, whereas the silty sediments of the Stephenson Bastion Formation may represent the undisturbed (primary) sedimentary environment of the microbiota, subsequent reworking of those sediments resulted in the incorporation of a similar microbiota in the somewhat younger Watts Needle Formation (*c.* 700 Ma; Buggisch and others, 1994*a*).

In either case, the available biostratigraphical constraints are not in disagreement with the suggested isotopic age for the deposition of the Stephenson Bastion Formation of about 1250 Ma (Buggisch and others, 1994*a*). However, the occurrence of *Octoedryxium truncatum* (which has a very short stratigraphical range of Lower–Middle Vendian (Varangerian) in the better known sequences of Europe and Greenland (Vidal and Knoll, 1983)) points to a somewhat younger age (about 650–800 Ma) for the Stephenson Bastion Formation. Similar Upper Proterozoic microfossil assemblages have a worldwide distribution. The microbiotas from both the Watts Needle and the Stephenson Bastion formations show similarities in several respects to the microbiotas from the siltstones of the Upper Proterozoic Visingsö-Formation in southern Sweden (Vidal, 1976) as well as to the Upper Proterozoic microfossil assemblage of the d'Atar-Formation in Mauretania (Amard, 1986). Further resemblances were found with the Upper Proterozoic microbiotas described from the Russian platform and from the southern Ural Mountains (Jankauskas, 1979) as well as from the Upper Proterozoic of Arizona and Utah (Vidal and Ford, 1985).

Age

Poorly preserved acritarchs from Mount Greenfield were first described by Weber (1990). However, on the basis of new and better-preserved material from Mount Greenfield, and abundant well-preserved Riphaean acritarchs obtained from the Watts Needle Formation at Nicol Crags and Mount Wegener (see Chapter 5, Table 5.1), we are able here to suggest a correlation between the microbiotas of the Watts Needle and Stephenson Bastion formations.

K-Ar dates obtained from the 2–6 μm fractions of low

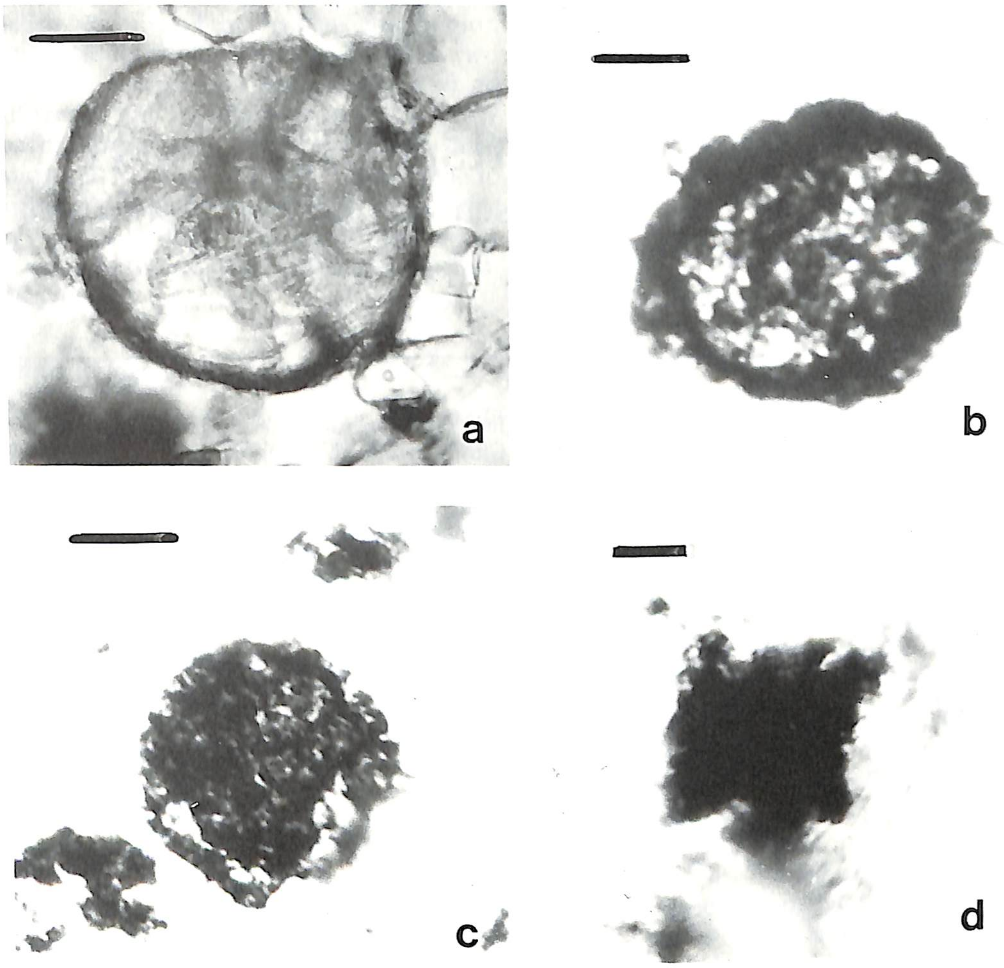

Fig. 6.3. Examples of microfossils from the Stephenson Bastion Formation; scale bar, 10 μm. [Samples were prepared (and are deposited) at Institut fur ,Potsdam.]

a. *Stictosphaeridium* sp. indet. [*Stictosphaeridium* Timofeev (1962) 1963 = *Nucellosphaeridium sensu* Vidal, 1976].
b. *Pterospermopsimorpha* cf. *densicoronata* Timofeev, 1966.
c. *Favososphaeridium favosum* Timofeev, 1966.
d. *Octoedryxium truncatum* Rudavskaya (1962) 1963.

to very low-grade metasiltstones from Clayton Ramparts and Ram Bow Bluff range between 940 and 1050 Ma (Buggisch and others, 1994*b*). These may represent a minimum age for the (diagenesis or) metamorphism of the Stephenson Bastion Formation. Rb-Sr whole-rock age determinations on samples from Ram Bow Bluff define an isochron corresponding to 1251 ± 24 Ma (2 sigma) with IR = 0.7224 ± 0.0032. The samples from Clayton Ramparts apparently follow the correlation line of the Ram Bow Bluff samples but their scatter is too large to permit interpretation as an isochron.

From the isotopic dates Buggisch and others (1994*a*) concluded that the Stephenson Bastion Formation was probably deposited about 1250 Ma ago and was metamorphosed, under very low-grade conditions, in late Precambrian times (>1000 Ma).

7 Wyeth Heights Formation

by W. Buggisch, G. Kleinschmidt and A. Höhndorf

Synopsis

Short description: The metasedimentary rocks of the Wyeth Heights Formation form the westernmost part of the allochthonous Mount Wegener nappe. They consist of dark schists with intercalated quartz-mylonites in the lower part, and thick quartzites in the upper part at Wyeth Heights itself. They are interpreted as a regressive sequence with an increasing maturity of the sediments from bottom to top.

Metamorphism: The Wyeth Heights Formation has been subjected to low-grade metamorphism; the grade increases slightly toward the north, and biotite is present in the northernmost outcrops.

Type locality: South-west face of Turnpike Bluff, southern Otter Highlands (Clarkson, 1972).

Age: (?) Late Precambrian–Palaeozoic.

Introduction

The Wyeth Heights Formation was described by Clarkson (1972, 1983) as a formation within the "Turnpike Bluff Group" (see Appendix 1). Because of the Ross Orogeny metamorphic overprint, correlation with the other formations of the former "Turnpike Bluff Group" is not clear. The Wyeth Heights Formation is exposed in the southern Otter Highlands only. To the north it is bound by the Otter Highlands Thrust (Buggisch and others, 1994*b*) where the medium- to high-grade metamorphic rocks of the Pioneers and Stratton groups are thrust southward along a reverse fault over the low-grade metasedimentary rocks of the Wyeth Heights Formation. All other contacts are covered by snow and ice. Therefore, its relation to the Stephenson Bastion Formation eastward is not known.

Lithology and sedimentology

Close to the Otter Highlands Thrust, the Wyeth Heights Formation (Fig. 7.1) consists of slates, siltstones and minor sandstones. Southward, a sequence of sandstones several metres thick forms the plateau of Wyeth Heights. These sandstones are composed mainly of quartz, with 5-10% feldspar (mostly microcline) and 10% matrix; they have modal compositions of quartz-arenites to subarkoses. Although the relation between the formations of the former "Turnpike Bluff Group", e.g. the Cambrian Mount Wegener Formation, the late Precambrian Stephenson Bastion Formation and the Wyeth Heights Formation is still unclear, the modal composition of the sandstones provide some evidence that the Stephenson Bastion and the Wyeth Heights formations are closly related, whereas both differ from the Mount Wegener Formation. The

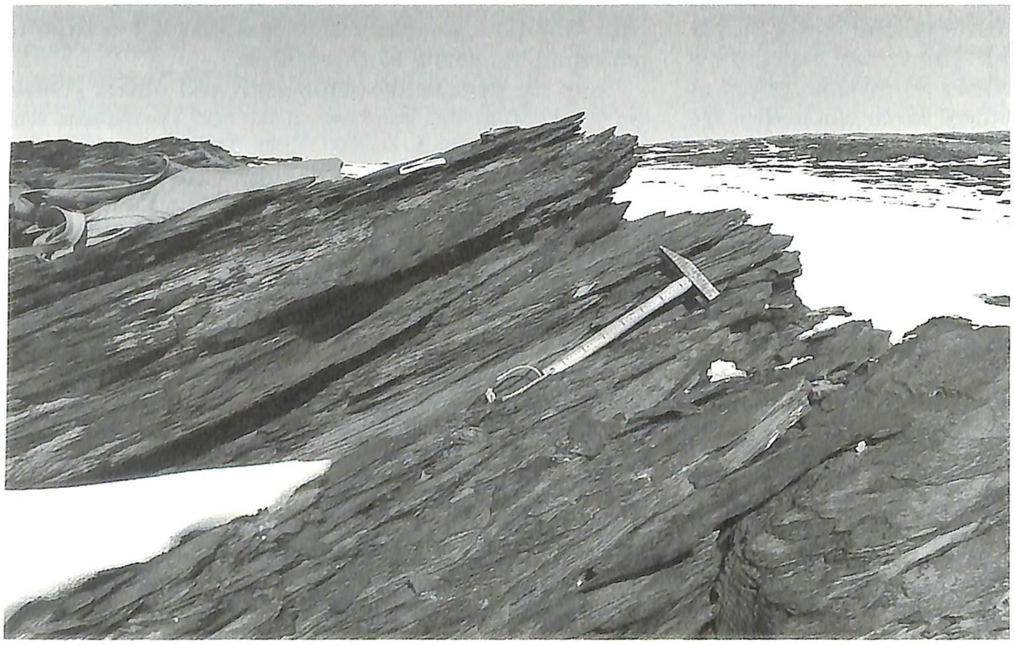

Fig. 7.1. Slates of the Wyeth Heights Formation exposed on a ridge east of Turnpike Bluff. (Photograph by P.D. Clarkson)

latter contains up to 50% feldspar, mostly plagioclase. In contrast, microcline is abundant in the Stephenson Bastion and Wyeth Heights formations. If these two formations are of the same age (see discussion below), an apparent lateral trend with respect to their maturity (lithic to feldspathic arenites occur in the Stephenson Bastion Formation and well-rounded quartzose to feldspathic arenites are present within the Wyeth Heights Formation) may be real. Improved roundness, better sorting and higher maturity indicate a shallower environment toward the west.

Metamorphism and deformation

Close to the Otter Highlands Thrust, the low-grade metasedimentary rocks of the Wyeth Heights Formation are mylonitized. Most of the quartz in the quartzites is dynamically recrystallized and, in the metapelites, white mica, biotite and chlorite have grown parallel to the penetrative cleavage (s_1). Southward, biotite has disappeared and quartz grains are flattened by strong pressure solution and show incipient recrystallization; beards of quartz, sericite and chlorite developed on s_1.

At least three phases of deformation can be recognized. The penetrative schistosity s_1 was formed during D_1 and is usually subparallel to the isoclinally folded bedding plane s_0. A weak crenulation cleavage s_2 was developed during D_2, which refolded s_1. In some samples an older schistosity(s_x), which predates D_1, is still preserved. This older deformation (D_x) may either correspond to the main metamorphic event which affected the Stephenson Bastion Formation (>1 Ga old) or represent an early stage of the Ross Orogeny.

Age

The age of the Wyeth Heights Formation is unknown because of the lack of fossils. However, based on its lithological similarity to the Stephenson Bastion Formation, it is believed to be a stratigraphical equivalent of the latter, despite the metamorphic overprint of the Ross Orogeny (Buggisch and others, 1994*b*). K-Ar analyses on 2-6 μm rock fractions yielded dates of about 500 Ma from phyllites and slates (Buggisch and others, 1994*b*, table 1). The date of 548 Ma of one sample (WB ANT 88-173) seems to be inherited partly from detrital mica and partly from an older diagenetic or metamorphic event. Rb-Sr analyses have yielded scattered data which do not fit an isochron. Two possible, but rather speculative, two-point "isochrons" were reconstructed (Buggisch and others, 1994*a*): one indicates a date of about 1150 Ma (IR = 0.728), the other a date of about 1015 Ma (IR = 0.708); these dates cannot be considered as reliable age information. Moreover, a correlation between the Wyeth Heights Formation and the Lower Cambrian Mount Wegener Formation cannot be totally excluded.

8 Mount Wegener Formation

by W. Buggisch, A. Höhndorf, G. Kleinschmidt and H. Kreuzer

Synopsis:

Short description: The Mount Wegener Formation consists of a metasedimentary sequence of slates, schists, siltstones, sandstones and minor conglomerates. A basinal marine environment for the deposition of the formation is substantiated by the occurrence of distal turbidites and the trace fossil *Oldhamia*. An (intracontinental) back-arc environment for the deposition of the Mount Wegener Formation is indicated by plagioclase compositions and rare volcanic clasts. Southward tectonic transport of the Mount Wegener nappe has moved the formation from its original depositional centre in the Mount Wegener basin, located north of the Watts Needle shelf (Buggisch and others, 1994*a*, fig. 32).

Metamorphism: The metamorphism ranges from very low grade in the south-eastern part of the Read Mountains to low grade (+ biotite) in the northern Read Mountains.

Type locality: The westernmost ridge (from its foot to the summit plateau) of Mount Wegener (Clarkson, 1972). However, no lower or upper boundary is exposed here and the formation is commonly strongly deformed.

Age: Lower Cambrian; Rb-Sr dates correspond to 561 ± 18 Ma and 535 ± 9 Ma (Buggisch and others, 1994*a*).

Introduction

The Mount Wegener Formation and "Flett Crags Formation" were formally recognized by Clarkson (1972, 1983) as two independent formations within the "Turnpike Bluff Group" (see Appendix 1). Based on their sedimentological similarity and because the Mount Wegener Formation and the "Flett Crags Formation" belong to the same tectonic unit (Mount Wegener nappe), the "Flett Crags Formation" is now regarded as the low-grade metamorphic equivalent of the Mount Wegener Formation in the northern part of the Read Mountains. Thus the term "Flett Crags Formation" is considered to be obsolete.

Rocks of the Mount Wegener Formation (Fig. 8.1; see also Chapter 5, Fig. 5.1.) form the eastern part of the Mount Wegener nappe; they crop out to the north and south of older rocks, belonging to the Read Group, that are exposed in the Read window.

Lithology and sedimentology

The Mount Wegener Formation consists mainly of refolded, very low-grade metamorphic slates and low-grade quartz-biotite-schists with intercalated (meta-) conglomerates and sandstones (Buggisch and others, 1994*a*). The metamorphic grade increases continuously from the south-east to the north-west (where the rocks formerly ascribed to the "Flett Crags Formation" are exposed).

In thin section the dark grey and green slates appear as banded dark, fine-grained mudstones and argillaceous siltstones consisting of detrital quartz, white mica, chlorite, biotite and feldspar (Clarkson, 1983). The matrix is largely recrystallized to an illite/sericite-chlorite-quartz cement. Due to the increasing metamorphism northward, the growth of new biotite and quartz constitutes the commonest components of equivalent schists north of the Read window.

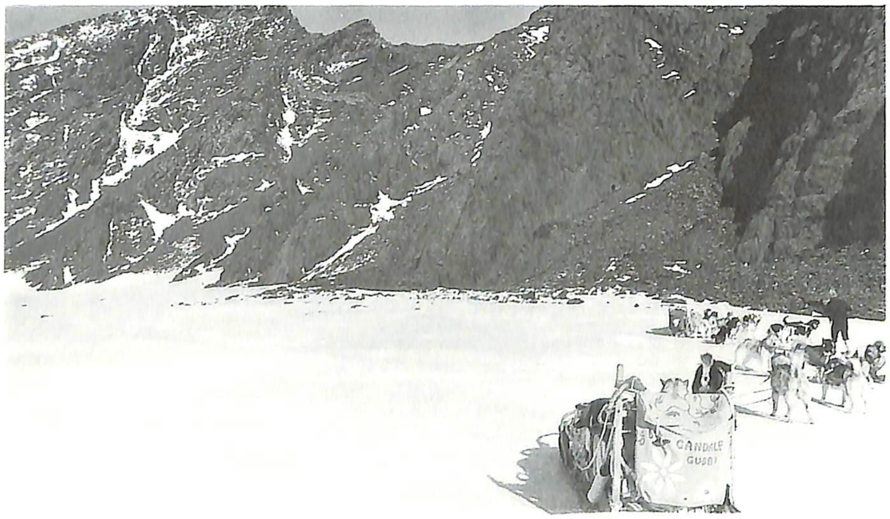

Fig. 8.1. Folded sandstones of the Mount Wegener Formation, west face of Mount Wegener. (Photograph by P.D. Clarkson)

Layers of sandstones (a few centimetres to half a metre in thickness) are interbedded with the shales and siltstones. The base of the sandstone layers is usually sharp; basal erosion and flute-casts are not common but were observed. Thick coarse-grained sandstone and conglomerate beds are commonly graded.

The sandstones consist of detrital quartz, polycrystalline quartz, feldspar (mostly plagioclase, some perthite and microcline), white mica, biotite, and unstable rock fragments within a matrix or cement of illite/sericite, chlorite, biotite (in the low-grade metamorphic rocks), quartz and calcite. Due to the very low-grade to low-grade metamorphism, the feldspars are completely altered to albite. Nevertheless, a large quantity of calcite may result, at least partly, from the anorthite component of the original plagioclase. The accessory minerals include zircon, epidote, sphene, ilmenite and hematite (Clarkson, 1983). Modal compositions are those of feldspathic greywackes.

The conglomerates are composed of clasts (up to 1 cm) of quartz, polycrystalline quartz, feldspar, chert and unstable lithic fragments such as sandstone, limestone and volcaniclastic rocks. The sandy matrix of the conglomerates corresponds compositionally to the sandstones in the formation. Metaconglomerates of the northern Read Mountains contain flattened limestone clasts, recrystallized quartz, and feldspar which has undergone brittle deformation. In contrast, clasts can still be identified in the very low-grade conglomerates exposed the long N–S ridge on the eastern side of Lapworth Cirque, and at Trueman Terraces and Swinnerton Ledge, southern Read Mountains. The limestone clasts are composed of dolosparites, laminites, pelsparites, oosparites, cortoids, ooids, fragments of reworked cement, *Epiphyton* sparites, problematica (fragment of an (?)archaeocyathid) and (?)echinoderms.

The trace fossil *Oldhamia* is usually found in flysch or flysch-like sediments and its presence in the sedimentary rocks of the Mount Wegener Formation indicates that they were probably deposited in a relatively deep basin. Graded-bedding and the presence of rare flute-casts are in accordance with this interpretation. The limestone clasts were derived from a shallow-water environment. The large amount of feldspar (plagioclase) and the occurrence of clasts of volcaniclastic rocks and unstable heavy minerals is consistent with a (? intracontinental) back-arc environment.

Age

The occurrence of *Oldhamia* cf. *antiqua* and *Oldhamia* cf. *radiata* (Fig. 8.2) on the N–S ridge on the eastern side of Lapworth Cirque prove a Lower Cambrian age for the Mount Wegener Formation. This age is corroborated by the presence of *Epiphyton* sp., algae incertae sedis (*Botomaella?* sp.) and (?)echinoderms (Buggisch and others, 1994*a*).

Rb-Sr analysis on six samples of low-grade slates and six samples of low-grade schists from the Mount Wegener Formation yielded two isochrons corresponding to 561 ± 18 Ma (IR = 0.7113 ± 0.0017; MSWD = 2.2) and 535 ± 9 Ma (IR = 0.7139 ± 0.00045; MSWD = 1.8) (Buggisch and others, 1994*a*). The isochron date from the slates corroborates the biostratigraphically determined Lower Cambrian age of the Mount Wegener Formation. As mentioned above, the Mount Wegener Formation was deposited in a basinal environment. Assuming that Sr was isotopically homogenized during deposition, the isochron date of the nearly unmetamorphosed slates could be interpreted as the time of deposition.

The slightly younger isochron date obtained from the metamorphic schists possibly reflects a metamorphic overprint that caused partial loss of radiogenic Sr. It is still an open question whether the isochron gives the age of the metamorphism or if it is only a disturbed isochron contributing no real information on the age of the rocks. K-Ar analyses on artificial 2–6 μm size-fractions of the same samples resulted in consistent dates of about 490 Ma (Buggisch and others, 1994*b*).

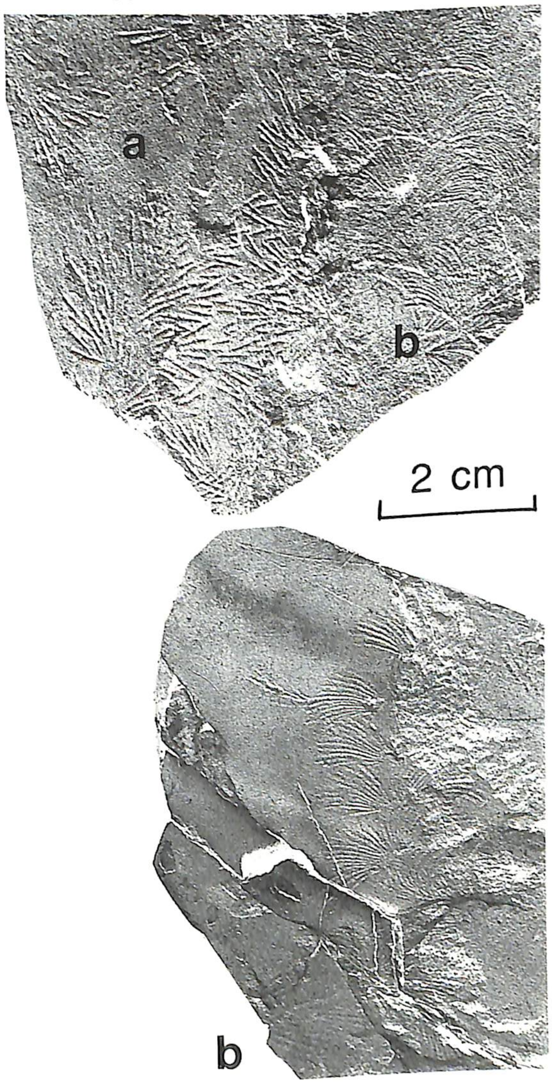

Fig. 8.2. Trace fossils in the Mount Wegener Formation on the N–S ridge on the eastern side of Lapworth Cirque (from Buggisch and others, 1994*a*). a. *Oldhamia* cf. *radiata*; b. *O.* cf. *antiqua*.

9 "Trilobite shales"

by M.R.A. Thomson, I.A. Solov'ev and W. Buggisch

Synopsis

Short description: The "trilobite shales" consist of dark grey silty shales with trilobites and abundant inarticulate brachiopods. They have been found only as clasts in moraines of the Mount Provender area and on the slopes of Mount Provender itself. It is questionable whether the shales are more or less autochthonous or whether they are erratic.

Age: Early Middle Cambrian.

General description

South of Mount Provender, loose blocks of fossiliferous shales and calcareous siltstones in moraine contain Middle Cambrian inarticulate brachiopods, hyolithids and other primitive molluscs, and trilobites (Thomson, 1972; Solov'ev and Grikurov, 1978; Clarkson and others, 1979; Popov and Solov'ev, 1981). In Buggisch and others (1990, 1994*a,b*), these shales and siltstones were named "Haskard Highlands Formation". However, because the shales have not been located *in situ* and might be erratic, it is thought better to drop formal formational nomenclature and to refer to them informally as the "trilobite shales" (see Appendix 1).

Whereas the trilobite shales were interpreted as having been deposited in an open marine, low-energy environment, the brachiopod-bearing siltstones with fragmented shell accumulations point to periodical current action and reworking (Clarkson and others, 1979). Although neither in the field nor in thin sections has a cleavage been observed, the distortion of some fossils (Buggisch and others, 1994*a*, fig. 22) suggests that at least some tectonic deformation has affected these rocks.

The provenance of the blocks of shale and siltstone has aroused considerable controversy. As pointed out by Solov'ev and others (1984), all known Cambrian fossils in the Antarctic come from mountains bordering the Weddell Sea (Ellsworth and Pensacola mountains and Shackleton Range), and the Transantarctic Mountains. Most authors agree that the source of the fossiliferous erratics is very close to the moraine in which they occur: Stephenson (1966) and Clarkson and others (1979) suggested that they may represent beds between the Mount Provender Formation and the Otter Highlands Formation of the Blaiklock Glacier Group (see Chapter 10), whereas Solov'ev and Grikurov (1979) and Paech (1986) supposed that the fossiliferous sediments were deposited (in pockets) above the crystalline basement and below the Mount Provender Formation. However, these interpretations are inconsistent with three important observations:

1. Facies interpretations suggest that the trilobite shales were deposited in an area subject to a low energy environment and far from any coarse-grained clastic input. Such shales would probably have covered a large depositional area.
2. Radiometric data prove Middle to Upper Cambrian or even Ordovician ages for the partly high-grade metamorphic rocks immediately below the trilobite shales (Rex, 1972; Grew and Halpern 1979; Pankhurst and others, 1983; Buggisch and others, 1994*a,b*). Therefore, there would not have been enough time for the observed high-grade metamorphism, and uplift and erosion to a peneplain to have occurred before deposition of the trilobite shales.
3. K-Ar determinations of 2–6 µm fractions from siltstones interbedded with the Middle Cambrian trilobite shales gave Ordovician ages of 455 and 463 Ma, which indicate a later (very low grade) metamorphic overprint; this is consistent with the slight deformation of the trilobites.

We agree that the blocks of the trilobite shales are of local origin. Siltstones and shales occur as reworked clasts in the base of the Mount Provender Formation at Mount Provender and, although no fossils have been found in these clasts, they lithologically resemble the trilobite shales and siltsones. Therefore, we favour a position for the trilobite shales below the Blaiklock Glacier Group. On the other hand, at The Dragons Back, on a nunatak 6.5 km south-east of Mount Provender, and at Mount Gass and Wedge Ridge the Mount Provender Formation rests unconformably on the basement rocks. Consequently, the trilobite shales must have been extensively eroded before the deposition of the Blaiklock Glacier Group. The only alternative explanation for this enigmatic occurrence is that the trilobite shales are relicts of a tectonic slice which is covered by the post-orogenic molasse sediments of the Blaiklock Glacier Group.

Palaeontology

The total fauna (cf. Fig. 9.1) recorded from the trilobite shales is as follows:

Brachiopoda
Notiobolus tenuis Popov, 1981 [Thomson, 1972; Popov and Solov'ev, 1981]

Mollusca (Hyolitha)
Linevitus sp. [Popov and Solov'ev, 1981; see also Clarkson and others, 1979]

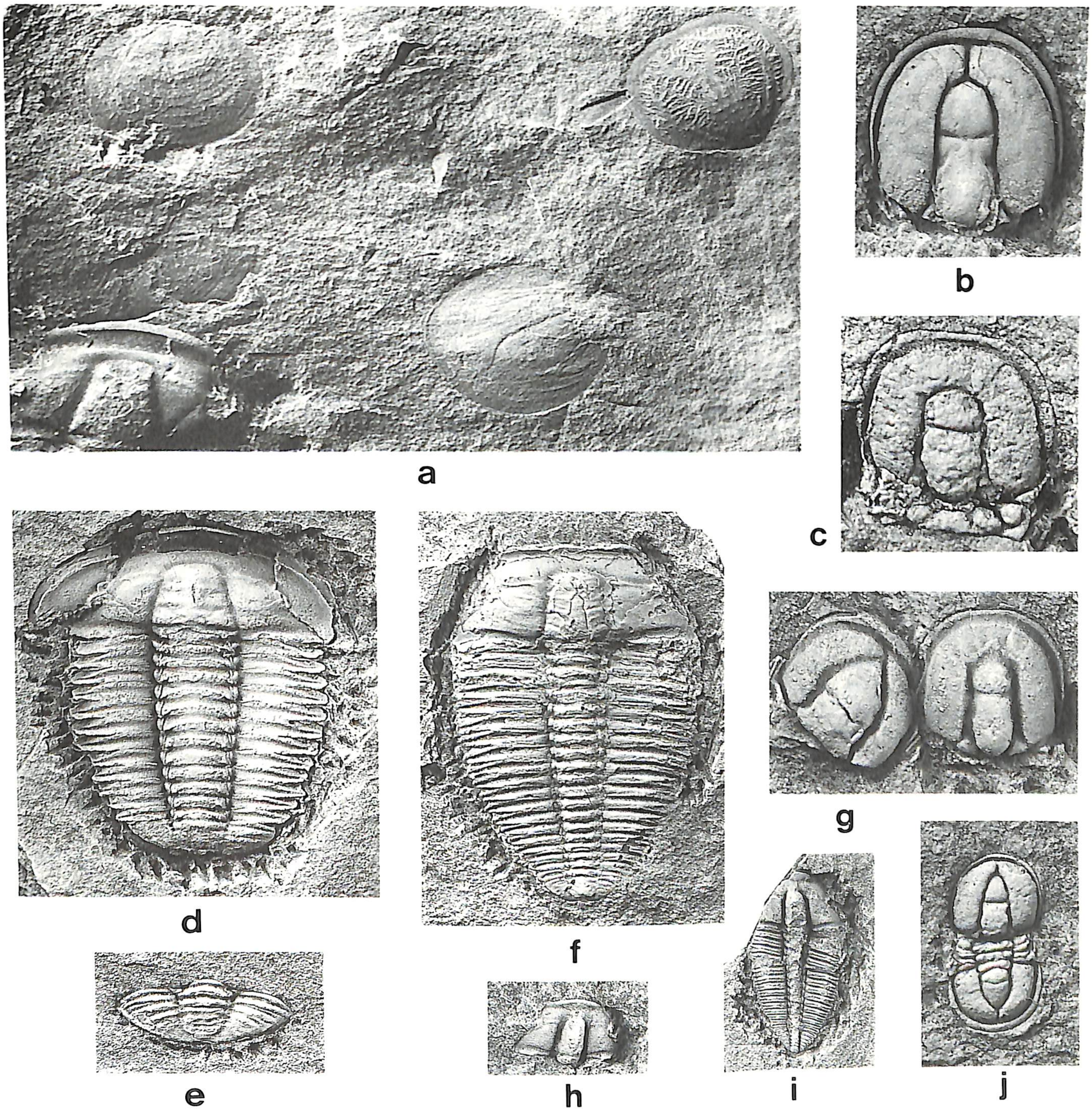

Fig. 9.1. Selected fossils from the "trilobite shales" of the Mount Provender area.

a. Slab showing typical field occurrence of inarticulate brachiopods, *Notiobolus tenuis* Popov, and a part cephalon of the trilobite, *Ehmania shackletonia* Solov'ev and Grikurov; x 3.
b. *Ptychagnostus (Triplagnostus) gibbus* (Linnarsson); x 10.
c. *Peronopsis* cf. *segmenta* (Robison); x 10.
d. *Ehmania shackletonia* Solov'ev and Grikurov; near complete specimen with free cheeks, x 3.
e. *Ehmania shackletonia* Solov'ev and Grikurov; pygidium, x 3.
f. *Lyriaspis antarctica* Solov'ev and Grikurov; x 3.
g. *Peronopsis (Adagnostus) scutalis* (Salter); x 10.
h. *Elrathina parallela longa* Solov'ev and Grikurov; part of cephalon, x 3.
i. *Elrathina parallela longa* Solov'ev and Grikurov; x 3.
j. *Ptychagnostus (Triplagnostus) praecurrens* (Westergård); x 10.

Mollusca (Gastropoda)

Mellopegma or *Helcionella* [Clarkson and others, 1979]

Trilobita

Ptychagnostus (Triplagnostus) praecurrens (Westergård, 1936) [Solov'ev and Grikurov, 1978; = *Triplagnostus ademptus* Porovskaya & Jegorova, 1972 (Solov'ev and Grikurov, 1979, pl. II, figs 4, 6, 7)]

Ptychagnostus (Triplagnostus) gibbus (Linarsson, 1869) [Solov'ev and Grikurov, 1978]

Peronopsis (Peronopsis) quadrata (Tullberg, 1890) [Solov'ev and Grikurov, 1978]

Peronopsis cf. *segmenta* Robison, 1964 [= *Peronopsis* cf. *fallax* (Linarsson) in Solov'ev and Grikurov, 1978, pl. I, figs 6, 7]

Peronopsis (Adagnostus) scutalis (Salter in Hicks, 1872) [Solov'ev and Grikurov, 1978]

Ehmania shackletonia Solov'ev and Grikurov, 1978 [also Solov'ev and Grikurov, 1979]

Ehmania shackletonia stricta Solov'ev and Grikurov, 1978

Elrathina parallela longa Solov'ev and Grikurov, 1978

Lyriaspis antarctica Solov'ev and Grikurov, 1978 [also Solov'ev and Grikurov, 1979]

It is generally agreed that the trilobites from the Mount Provender area (Fig. 9.1) are of early Middle Cambrian age (Solov'ev and Grikurov, 1978; Clarkson and others, 1979; Wolfart, 1994). However, whereas trilobite faunas have been widely reported from isolated localities along the length of the Transantarctic Mountains and the Ellsworth Mountains, there is little in common between many of them. Thus, although Middle Cambrian faunas are known from the Ellsworth, Pensacola and Harold Byrd mountains, and from northern Victoria Land, there is only one species in the Shackleton Range fauna (*Lyriaspis antarctica*) which has even a possible counterpart elsewhere in *Lyriaspis* sp. aff. *L. antarctica,* reported from exotic blocks of limestone on Reilly Ridge, northern Victoria Land (Wolfart, 1994). According to Wolfart (1994, table 1), the Shackleton Range fauna has a stratigraphical age between the fauna from exotic limestone blocks in the Argentina Range, which is slightly older, and the slightly younger fauna from the Nelson Limestone, Neptune Range (Palmer and Gatehouse, 1972). He further suggested that the Shackleton Range fauna was slightly older than the *Eurodeois tessensohni* faunule with *Lyriaspis* at Reilly Ridge, and equated it with the *Dorypyge australis/Centonella glomerata* faunule at the same locality.

Solov'ev and Grikurov (1978) suggested that regional comparisons were with faunas from the Americas, Australia, China and Siberia; Wolfart (1994), however, indicated that similarities with the Americas were less marked.

The non-trilobite elements of the fauna, notably the brachiopods (Fig. 9.1a) and hyolithids are either new or not precisely age-diagnostic.

10 Blaiklock Glacier Group

by W. Buggisch, P.D. Clarkson and G.E. Grikurov

Synopsis

Short description: The Blaiklock Glacier Group is divided into two formations: the Mount Provender Formation and the Otter Highlands Formation (Clarkson, 1972). The red beds of the Blaiklock Glacier Group represent a typical molasses facies of the Ross Orogeny in the Shackleton Range. At the base of the Mount Provender Formation an erosion surface of considerable relief is covered by deposits of gravity slides/fan deposits that grade up into flood-plain deposits with braided river sediments and marine siltstones and sandstones. The more distal and/or younger Otter Highlands Formation consists of fluvial sandstones of a deltaic environment.

Type localities: Mount Provender Formation - the outcrop through the moraine west of Mount Provender (Clarkson and Wyeth, 1983); the upper part of the succession is well exposed at Mount Gass.

Otter Highlands Formation - north-east face of MacQuarrie Edge, northern Otter Highlands (Clarkson and Wyeth, 1983).

Age: Cambro-Ordovician; probably Ordovician.

Introduction

The Blaiklock Glacier Group is exposed only in the north-western part of the Shackleton Range. It was described first by Stephenson (1966) as the "Blaiklock Beds" and subsequently it was formally renamed as the Blaiklock Glacier Group by Clarkson (1972). The group is divided into two formations: the Mount Provender Formation (the lower part of the group) with the Otter Highlands Formation above. A comprehensive description of the group was published by Clarkson and Wyeth (1983).

Lithology and sedimentology

Mount Provender Formation

As originally described by Clarkson and Wyeth (1983), the Mount Provender Formation is exposed on the western margin of the Haskard Highlands, and at a small nunatak in Stratton Glacier (6 km west of Lister Heights); here we include two extra localities, north-western Wedge Ridge and The Dragons Back. The definition of the Mount Provender Formation should be amended accordingly.

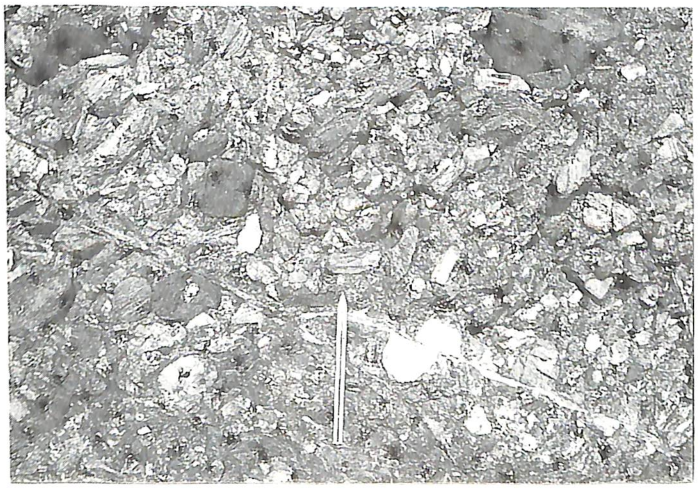

Fig. 10.1. Fanglomerate of the Mount Provender Formation, north-east of Wedge Ridge (reproduced from Buggisch and others, 1994*a*).

The Mount Provender Formation rests unconformably on the Pioneers and Stratton groups, and perhaps on the trilobite shales. The contact is complicated by minor faults at most outcrops but the transgressive nature of this formation is evident.

A relief of at least several tens of metres exhibits a great diversification of rock types in the basal units over short lateral distances. Typical fanglomerates are exposed on the nunatak at the north-western end of Wedge Ridge. The boulder beds (Fig. 10.1) and coarse-grained, poorly sorted breccias and conglomerates of local origin represent a typical sequence from gravity slides into fan conglomerates - probably of flash flood origin.

These basal units pass downslope into alluvial braided channel sediments which are exposed at a nunatak 6.5 km south-east of Mount Provender (Fig. 10.2). Coarse-grained conglomerates interbedded with pebbly sandstones are restricted to the first tens of metres in the other outcrops. A typical succession of the upper part of the Mount Provender Formation is exposed in the Mount Gass section. Strongly bioturbated siltstones and mudstones with mudcracks alternate with cross-bedded, medium- to fine-grained sandstones in which convolute bedding is common. Trace fossils (Fig. 10.3) are abundant in the upper part. The sandstones, consisting of 30–50% quartz, 10–20% feldspar, and 30–60% rock fragments are classified as lithic-arenites. Quartz, with or without low undulating extinction, is more common than stressed quartz. Furthermore, volcanic quartz, with typical resorption, is present and untwinned feldspar is more abundant than twinned acid plagioclase; biotite is strongly altered to chlorite and hematite. Up to 30% of the rock fragment component is actually represented by detrital mica, the rest is made up of quartzites, mica-schists, heavy minerals and gneisses. The uppermost beds of the Mount Gass section, which forms the

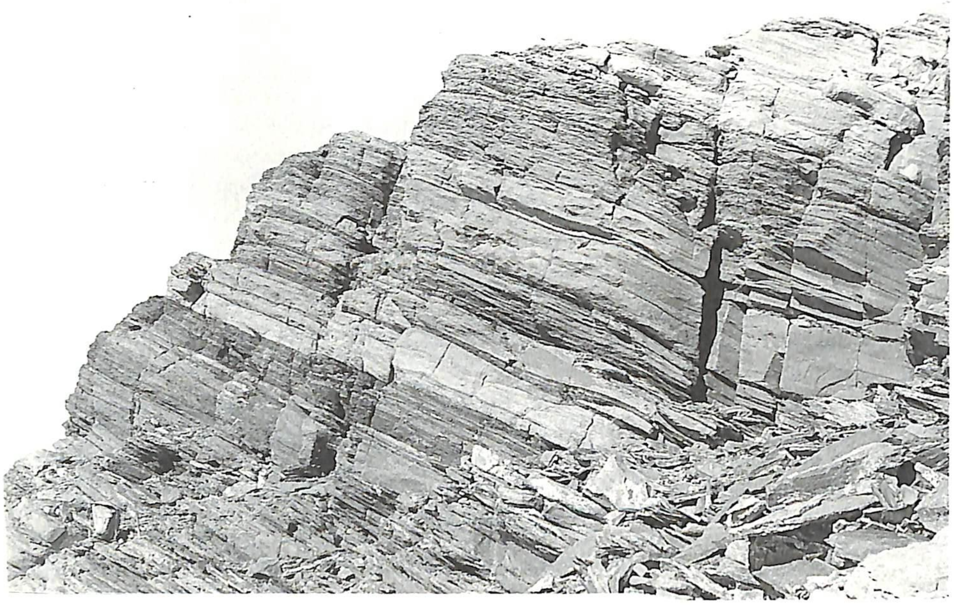

Fig. 10.2. Sandstones of the Mount Provender Formation, nunatak 6.5 km south-east of Mount Provender. (Photograph by R.B. Wyeth)

transition to the Otter Highlands Formation, exhibit modal compositions with up to 40% feldspar.

Otter Highlands Formation

The Otter Highlands Formation is exclusively exposed in the northern Otter Highlands (Fig. 10.4). Whether it represents the more distal sequence of the Mount Provender Formation or the upper part of the Blaiklock Glacier Group is unclear due to the lack of continuous sections. The type section at MacQuarrie Edge was described by Clarkson and Wyeth (1983). The sandstones are composed of quartz (24%), feldspar (25%) and rock fragments (51%) and are classified as lithic-arenites. Feldspar is enriched compared with the rocks of the Mount Provender Formation and the amount of matrix is low; open pores are cemented by calcite. Detrital mica is common, and unstable heavy minerals such as garnet form up to 30% of the rock in placers. The coarse grain-size and the presence of trough cross-bedding in these sandstones are suggestive of fluvial deposits from a deltaic environment.

Although the direction of sediment transport varied greatly in the Mount Provender Formation, a NE–SW-directed transport was determined by cross-bed measurements in the Otter Highlands Formation.

Palaeontology

Trace fossils were found at Mount Gass, The Dragons Back and at the small nunatak west of Lister Heights. At least some (Fig. 10.3) are identifiable as trilobite tracks and trails which substantiate a marine environment for the upper Mount Provender Formation.

Age

The relatively large size of the trilobite trace fossils place the age of the Mount Provender Formation between Cambrian and Devonian. Thus, the Permian age assumed by Grikurov and Dibner (1979) and Paech (1986) can now be discarded. The sedimentological similarity between the Mount Provender Formation in Antarctica and the basal units of the Table Mountains Group in South Africa (personal observations of WB) suggests a possible correlation and hence an Ordovician age for the Mount Provender Formation. This is supported by palaeomagnetic data (Buggisch and others, 1994*a*). The samples studied were originally collected for geological purposes rather than palaeomagnetic analyses and only the inclination of the remanent magnetization relative to the bedding plane could be determined. In view of this incomplete dataset, the results discussed below should be considered as preliminary.

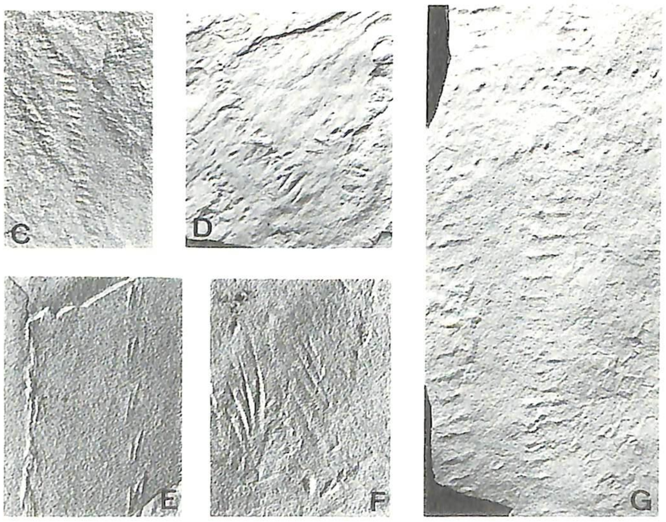

Fig. 10.3. Trilobite tracks in the sandstones of the Mount Provender Formation, Mount Gass; x 0.65 (from Buggisch and others, 1994*a*).

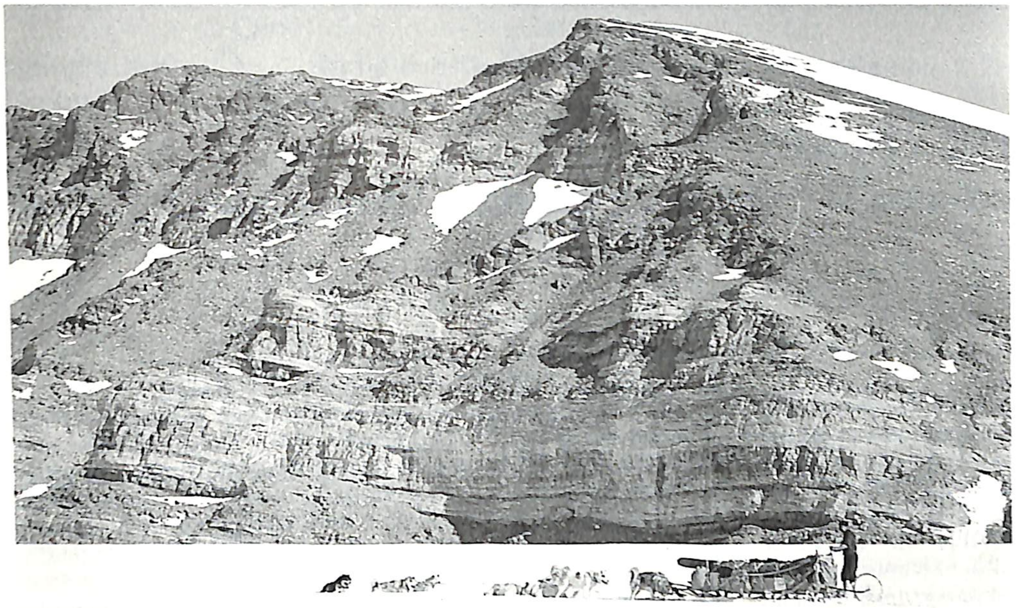

Fig. 10.4. The lowest exposed part of the Otter Highlands Formation, north-east face of MacQuarrie Edge. (Photograph by R.B. Wyeth)

Nine samples from different sites yielding 36 subspecimens were investigated. The majority of the samples revealed a natural remanent magnetization with an inclination of 0°–30°. A predominantly shallow inclination of the characteristic remanent magnetization is to be expected if the magnetization was acquired in Ordovician times. According to palaeocontinental reconstructions (e.g. Smith and others, 1981; Ziegler, 1981) and the palaeomagnetic pole database (Piper, 1987), a low-latitude position for Antarctica can be expected during the Ordovician, leading to shallow inclinations of remanent magnetizations in rocks of this age.

11 Mafic dykes

by K.S. Techmer, M. Peters, G. Spaeth, K. Weber and P.T. Leat

Synopsis

Short description: Mafic dykes in the Shackleton Range were first observed by Stephenson (1966). Subsequent field, petrographic and geochemical descriptions and isotopic determinations were carried out by Rex (1972), Clarkson (1972, 1981), Hofmann and others (1980, 1981), Peters and Spaeth (1988) and Hotten (1993). The dykes strike discordantly to the metamorphic foliation of the country rock. There is a range of alteration/metamorphism of the dykes from essentially unaltered to greenschist-facies metamorphism. The dykes are compositionally diverse, and can be classified into several distinct chemical groups. All of the dykes are thought to represent episodes of continental intraplate magmatism, ranging from tholeiitic to mildly alkaline. Mafic dykes in the Read Mountains are poorly dated, but probably of Late Proterozoic age. They range from tholeiitic to alkaline, are similar to ocean island basalts (OIB), and probably were emplaced during one or more continental rifting events. Two groups of dykes occurring in the Haskard Highlands have similar intra-trace element ratios, indicating a common mantle source; one group, of Silurian K-Ar age, is similar to continental tholeiites, whereas the other, undated one, is more alkali-rich. Dykes from the Herbert Mountains and Pioneers Escarpment form a distinctive group of alkali-rich, slightly potassic, locally lamprophyric compositions, and one dyke from La Grange Nunataks is similar. The source of these magmas is thought to be in the subcontinental lithospheric mantle. Existing K-Ar ages for this group range from Ordovician to Carboniferous. The rest of the dykes from La Grange Nunataks are tholeiites belonging to the Jurassic Ferrar Magmatic Province (Ford and Kistler, 1980).

Geographical distribution: Haskard Highlands, La Grange Nunataks, Herbert Mountains, Read Mountains, Pioneers Escarpment, The Dragons Back.

Age relations: K-Ar data indicate that most of the dykes are Palaeozoic in age. Metamorphosed dolerites in the Read Mountains are probably Late Proterozoic in age. A few dykes are Jurassic in age.

Introduction

Several groups of mafic dykes occur in the Shackleton Range. They are compositionally diverse, and record several episodes of ?Late Proterozoic, Palaeozoic and Jurassic intrusion. The dykes crop out in most parts of the Shackleton Range. They are abundant as single dykes, striking discordantly to the metamorphic foliation of the country rocks, and there are a few occurrences of small dyke swarms. Macroscopically, the mafic dykes have chilled margins, and a dark, homogeneous matrix with different amounts of olivine and feldspar phenocrysts. Some dykes have been heavily altered during greenschist-facies metamorphism. This chapter summarizes important features of the mafic dykes and presents new chemical data, including the first published INAA trace element data.

Previous work

During the Trans-Antarctic Expedition of 1955–58, one mafic dyke was observed in the Shackleton Range (Stephenson, 1966). A larger number of dykes was collected during a British geological survey of 1970–71 (Clarkson, 1971), and these were described briefly by Clarkson (1972); Rex (1972) published K-Ar ages for two of the dolerites. These yielded Palaeozoic ages which strongly suggested that the Shackleton Range mafic dykes were emplaced earlier than the Jurassic Ferrar Magmatic Group, which is widespread in the Transantarctic Mountains region. Hofmann and others (1980) presented three further K-Ar ages for the dolerites, two of which yielded Palaeozoic ages, similar to those obtained by Rex (1972). Their third age, on a sample from La Grange Nunataks, was Jurassic. Petrographic and major and trace element data were presented for about 12 dykes by Clarkson (1981). This work demonstrated that the dykes were varied in composition, and chemically cluster as several groups related to geographical location. Clarkson suggested, on geo-chemical grounds, that a dolerite from La Grange Nunataks was a local representative of Jurassic mafic magmatism in the Transantarctic Mountains and Dronning Maud Land. Peters and Spaeth (1988) recollected and described the field characteristics of the dolerites. Their collection of dykes was used by Hotten (1983), and is further described in this chapter. The total number of mafic dykes cropping out in the Shackleton Range is not known. Some dykes evidently were sampled by both Clarkson (1981) and by Peters and Spaeth (1988). Hotten (1993) described the petrography and alteration features of the dykes in detail, and presented comprehensive major and trace element analyses and a few K-Ar ages and Sm-Nd isotopic ratios. He used petrographic features to divide the dykes into five groups, which generally correspond well to geochemical characteristics. Group I dykes in his scheme comprise relatively fresh Jurassic tholeiites, Groups II and III more altered, probably Palaeozoic, mafic rocks of variable chemical composition, and Groups IV and V, meta-morphosed dolerites, of possible Proterozoic age.

Field relationships

The 14 mafic dykes observed in the Read Mountains (Peters and Spaeth, 1988) intrude rocks of the Read

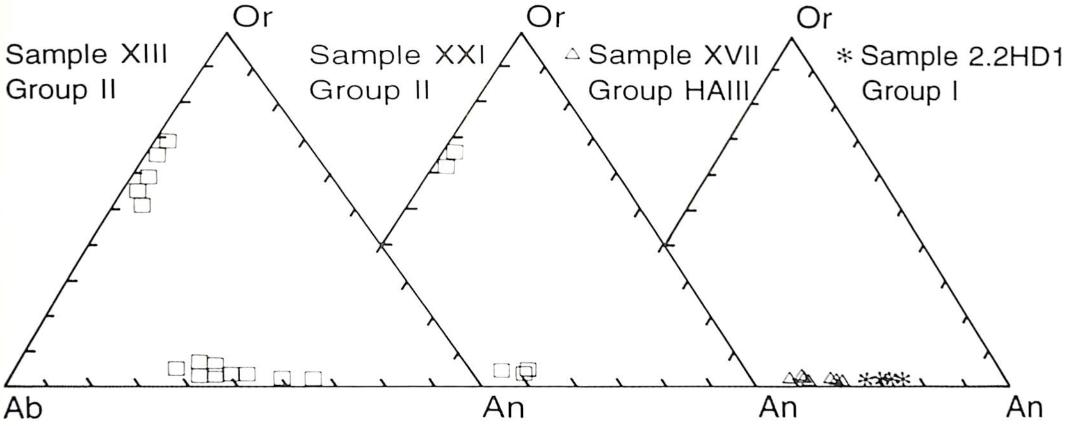

Fig. 11.1. EDX analyses of feldspars in the mafic dykes.

Group, but not the Mount Wegener and Stephenson Bastion formations. These dykes increase in frequency from west to east and trend mostly N–S; two trend NE–SW. Their width varies from 2 to 25 m and their contacts with the crystalline basement rocks are generally sharp. They are apparently cut by mylonitic shear zones.

In the northern part of the Shackleton Range (Haskard Highlands, La Grange Nunataks and Herbert Mountains), a total of 15 dolerite dykes were investigated by Peters and Spaeth (1988), following the studies by Clarkson (1972, 1981) and Hofmann and others (1980). Most of the dykes intrude the basement rocks of the Pioneers and Stratton groups but two (samples XIII.1 and 2.2.HD1) cut the Blaiklock Glacier Group. The contact between the mafic dykes and the country rock is usually sharp but the trend of the dykes varies and they range from 0.3 to 12 m in width.

Petrography

The petrography of the dykes has been described by Clarkson (1981) and Hotten (1993).

Most of the dykes in the Read Mountains have a fine-grained basaltic matrix with phenocrysts of feldspar and less common pyroxene. In thin section, some samples show alteration, especially of feldspar phenocrysts, the plagioclase being partially sericitized and saussuritized. Some of the dykes show a hydrothermal overprinting; Hotten (1993) suggested that they had experienced low-grade metamorphism.

In the dykes of the Haskard Highlands, La Grange Nunataks, Herbert Mountains and Pioneers Escarpment, phenocrysts of plagioclase, olivine, pyroxene, biotite, amphibole and Fe-Ti oxides are present in a fine-grained matrix. The dykes are altered to different extents: in some samples, feldspar is fresh, pyroxene is unaltered, and some olivine remains; in others, feldspar is strongly altered and olivine crystals are altered to talc and serpentine along grain boundaries and cracks. The different intensity of alteration is particularly obvious in the large, interspersed feldspar crystals. In some basalt dykes in the Haskard Highlands, sericitization is minimal and affects plagioclase crystals in the groundmass, and at grain boundaries and along cracks. However, in others, plagioclase crystals are totally altered. Alteration minerals like epidote, calcite, chlorite and sericite are commonly present. Plagioclase compositions have been studied by energy dispersive X-ray (EDX) analysis (Fig. 11.1). They range from medium to high anorthite contents (andesine to bytownite). Fine-grained K-feldspar is present in two Group II dykes from the Herbert Mountains and La Grange Nunataks.

Samples from the Haskard Highlands contain plagioclase and olivine ± pyroxene phenocrysts. By contrast, samples from the Herbert Mountains contain phenocrysts of plagioclase, pyroxene ± biotite ± amphibole. Sample Z.628.1 from Pioneers Escarpment (Clarkson, 1981) is a kersantite (calc-alkaline lamprophyre), being dominated by plagioclase and biotite.

Geochemistry

New geochemical analyses (given in Appendix 4) were prepared by the Geochemisches Institut, Göttingen. The samples were collected from the following localities: Read Mountains, western Haskard Highlands, La Grange Nunataks and Herbert Mountains. The analytical methods used are listed in Table 11.1 and the analyses and CIPW norms for the samples, all of which are mafic, are given in the appendix (see Tables A3.1–3). The data are summarized in normative triangular plots in Fig. 11.2 and in selected Harker diagrams in Fig. 11.3.

Table 11.1. Analytical methods used to determine chemical compositions of mafic dykes from the Shackleton Range

Elements	*Method*
Si, Ti, Al, ΣFe, Mn, Mg, Ca, K, P	RFA[1] (XRF)
FeO, ΣH_2O, CO_2, S	titration[2]
Na, K, Rb, Li	AES[2]
Ba, Sr, Y, Zr, Nb	ICP-AES[4]
La, Ce, Sm, Eu, Tb, Yb, Cr, Lu, Sc, Co, Hf, Ta, Th	INAA[3]

[1] Schulz-Dobrick (1975); [2] Hermann (1975); [3] Gibson and Jagan (1980); [4] Heinrichs and Hermann (1990).

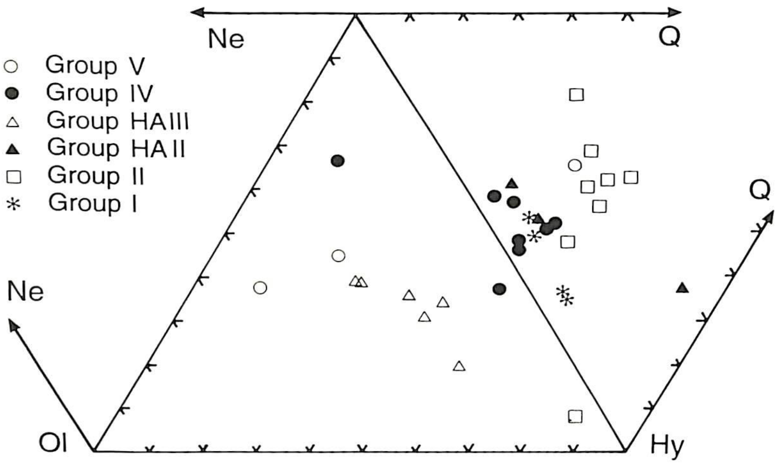

Fig. 11.2. Normative compositions plotted on Q-Di-Hy-Ol-Ne triangular diagrams.

Read Mountains

The dykes are chemically different from those of the rest of the Shackleton Range. SiO_2 varies inversely with TiO_2, Zr and Nb within the group (Fig. 11.3). According to Hotten's (1993) classification, the high TiO_2 dykes belong to Group V, and the low TiO_2 dykes to Group IV. Hotten interpreted these groups to represent tholeiitic flood basalts and alkaline within-plate magmas respectively, an interpretation consistent with REE data (Fig. 11.4). The Read Mountains dykes have low La/Ta ratios (12.8–25.2) which are comparable to those of mid-ocean basalt (MORB) and ocean island basalt (OIB) (Figs 11.5 and 11.6). The lower TiO_2 samples have La/Yb ratios of 3.3–4.8 and Zr/Y ratios of 4.5–6.4, comparable to enriched MORB and tholeiitic OIB. Higher TiO_2 samples have La/Yb (8.5–10.4) ratios and Zr/Y ratios (7.1–8.3), comparable to alkaline OIB. The likely explanation is that the suite represents variable degrees of partial melting of OIB- or MORB-source mantle. The samples form an overall negative correlation between Th/Ta and La/Yb, plausibly because the lower-La/Yb magmas were the more contaminated by crust during uprise. The dykes are probably Proterozoic in age in that they are not seen to intrude the Mount Wegener and Stephenson Bastion formations (interpreted to have experienced diagenesis/metamorphism at approximately 530 Ma and 1250 Ma respectively, see Chapter 12), and in that they have yielded one K-Ar whole rock age of 800.5 ± 15.8 Ma (Hotten, 1993). The Read Mountains dykes probably record one or more episodes of intracontinental magmatism, possibly related to rifting.

Haskard Highlands

The dykes of the Haskard Highlands belong to Groups II and III according to Hotten's (1993) classification. However, Hotten also classified geochemically different samples from La Grange Nunataks and Herbert Mountains in these groups. To avoid ambiguity, we refer to Groups II and III samples in the Haskard Highlands as Groups HAII and HAIII respectively. These groups are different in that HAII samples are the more alkali- and silica-rich, having higher incompatible trace element abundances (Nb = 36–42 ppm, Ba = 1425–2000 ppm) than HAIII samples (Nb = <8–11 ppm, Ba = 520–580) (Figs 11.4 and 11.5). Both Groups HAII and HAIII are geochemically distinct from other mafic dykes from the Shackleton Range (Hotten, 1993).

Group HAIII samples form a homogeneous group (see Appendix 3, Table A3.2; Clarkson, 1981, table 1, columns 19–23), having olivine-tholeiite normative compositions and relatively low SiO_2 (46.5–47.8 wt.%) and high TiO_2 (2.53–2.76 wt.%) contents. Their narrow range of La/Yb (5.6–6.7) is appropriate for continental tholeiites. They have moderate Ta- and Nb-depletion relative to LREE (La/Ta = 38–44), but no depletion of Ti relative to HREE (e.g. Ti/Y = 360–393). These features are consistent with an origin as intracontinental tholeiites.

Group HAII samples are Q-normative (Fig. 11.2; Clarkson, 1981, table 1, columns 13–23). They have relatively high alkali contents, but K_2O abundances are variable (0.85–2.19), possibly a result of K-loss. The group is similar to the shoshonitic series, although TiO_2 abundances (2.35–2.79) are rather too high. The one sample analysed for REE (3.2HD1 in Table A3.2) has a La/Yb ratio of 25.3, much higher than those of Group HAIII. It nevertheless has a La/Ta ratio (40.5) which falls within the relatively narrow range of Group HAIII (Fig. 11.6), and the same absence of Ti-depletion (Ti/Y = 427). None of the dykes has relative enrichment of Ba, Rb, Th or K with respect to La (Fig. 11.5), indicating that they are not typical magmatic arc magmas. These similarities between Groups HAII and HAIII indicated that they may have been derived from the same, or similar mantle sources, but that Group HAII represents smaller degree partial melts than Group HAIII. The most likely tectonic setting of emplacement is an intraplate one, with Ta- and Nb-depletion being a result of tapping subcontinental lithospheric mantle previously modified by subduction.

There are two whole rock K-Ar age determinations on Group HAIII dykes: 406 ± 17 Ma (Hotten, 1993) and 418 ± 11 Ma (P. Leat, unpublished data, 1994). These suggest a Late Silurian age of emplacement. No age determinations are available for Group HAII, but they might have been emplaced during the same event.

Herbert Mountains

All dykes from the Herbert Mountains belong to a distinctive group. Similar rocks occur at La Grange Nunataks (sample XIII.1 in Table A3.2; probably

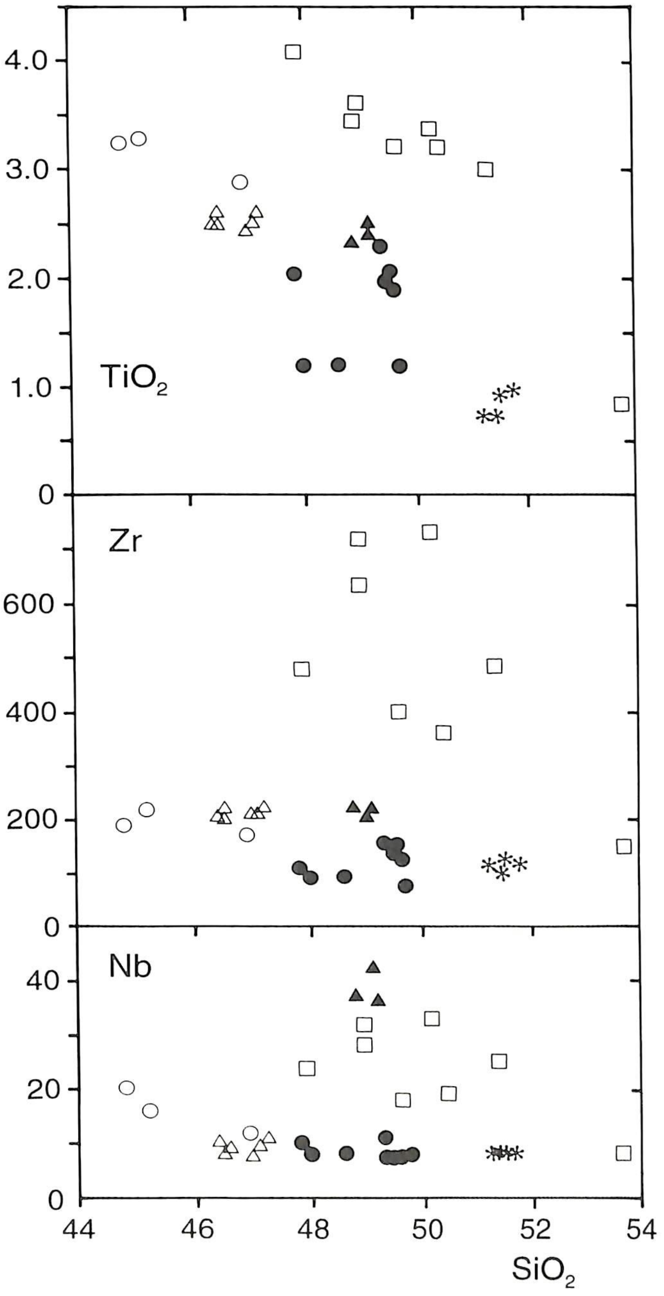

Fig. 11.3. Selected Harker diagrams; symbols as in Fig. 11.2.

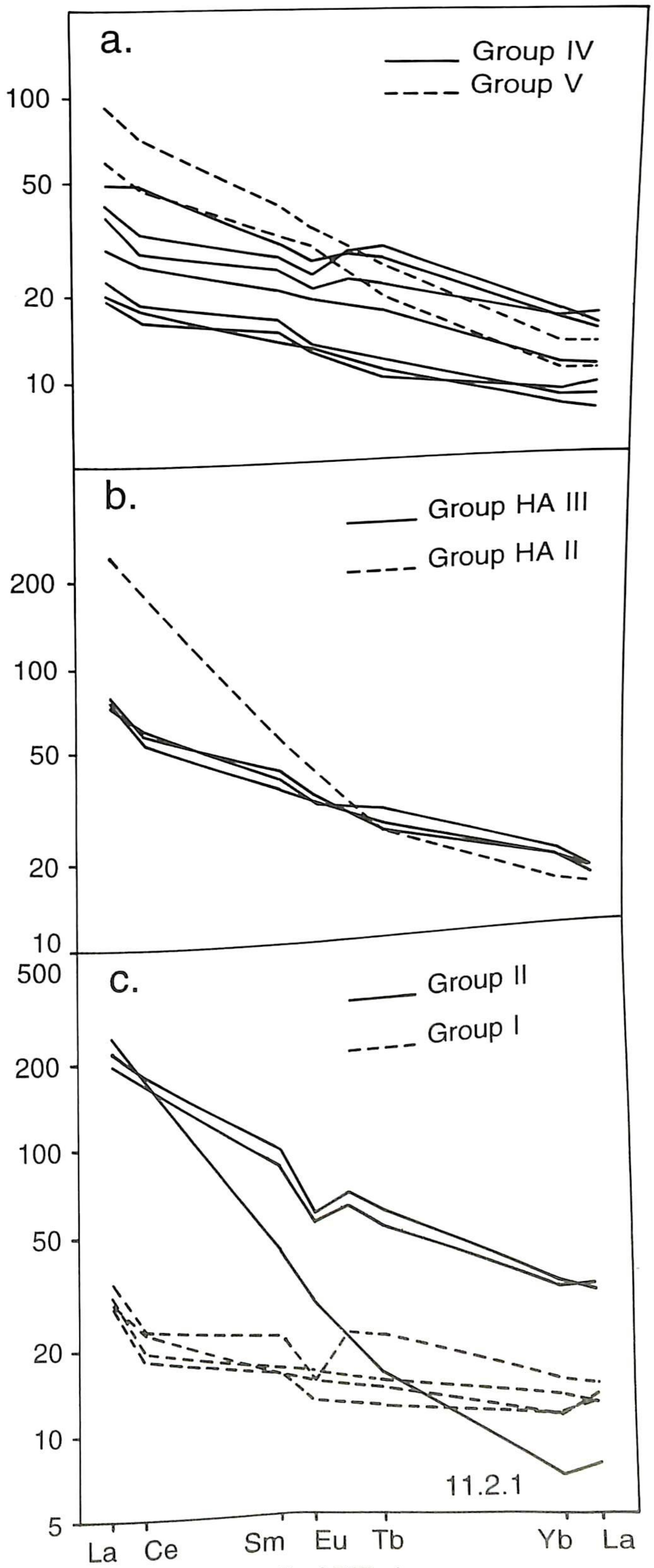

Fig. 11.4. Chondrite-normalized REE plots.

equivalent to sample Z.736.4 of Clarkson, 1981), and at Pioneers Escarpment (sample Z.628.1 of Clarkson, 1981). Hotten placed most of these dykes in his Group II, despite there being clear geochemical differences between these and the Groups II and III dykes of the Haskard Highlands. The dykes are labelled as Group II in Appendix 3. The samples have high TiO_2 (3.1–4.3 wt.%), Na_2O (1.9–2.6 wt.%), K_2O (2.0–2.7 wt.%), and Th (4.2–9.1 ppm) abundances, and are enriched in all LIL elements relative to LREE (Fig. 11.5). Most of the samples are slightly potassic ($K_2O > Na_2O$ wt.%). Low MgO abundances (4.4–6.6 wt.%) and high HREE (e.g. Y = 71–97 ppm) indicate that the magmas experienced significant fractional crystallization from mantle-derived melts, despite relatively low SiO_2 abundances. The samples have significantly higher P_2O_5 and Zr, and lower Al_2O_3 and Y abundances than other dykes in the Shackleton Range (Hotten, 1993), and La/Yb ratios of the group (10.2–17.5) are among the highest there (Fig. 11.6). These features indicate that the samples form an alkali -rich, mildly potassic suite, consistent with the lamprophyric petrography of at least one of the samples. Nevertheless, they are Q-normative. La/Ta ratios are high (45.2–63.9), among the highest from the Shackleton Range, indicating that the mantle source was modified by

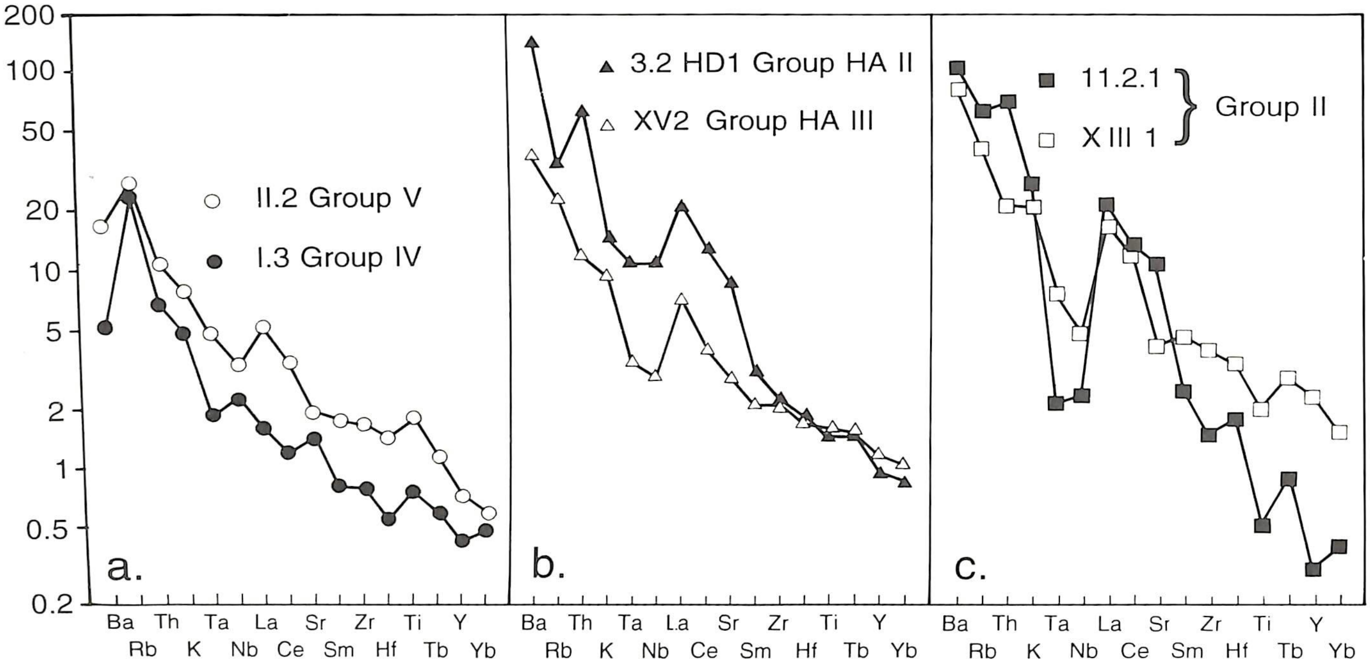

Fig. 11.5. Selected N-MORB-normalized multi-element enrichment diagrams; the MORB values are those of Hofmann (1988).

subduction. The most likely origin of the magmas was by partial melting of subcontinental lithospheric mantle, as widely proposed for intraplate lamprophyres (e.g. Thompson and others, 1990). Six samples from this group have been dated by K-Ar methods: Rex (1972) obtained an age of 466 ± 18 Ma (recalculated) on a dyke from Pioneers Escarpment, Hofmann and others (1980) obtained ages of 391 ± 31 Ma and 417 ± 33 Ma on two dykes that probably belong to this group, and Hotten (1993) obtained an age of 425 ± 9 Ma for a Herbert Mountains sample, and 369 ± 4 Ma on a representative of the group from La Grange Nunataks (XIII.1, pyroxene separate). Two whole rock ages of 304 ± 12 and 319 ± 8 Ma were obtained respectively by Rex (1972, recalculated age) and (P. Leat, unpublished data, 1994) on sample Z.736.4, which probably is the same dyke as sample XIII.1. It is not known whether this range of ages, from Ordovician to Carboniferous, records real emplacement ages or not: because they probably were derived from subcontinental lithospheric mantle, the same mantle source would have been available for partial melting at different times.

Sample 11.2.1 (Table A3.3) is distinct, being Ol-normative, with higher alkali and lower TiO_2 abundances, and the highest La/Yb and La/Ta ratios of any dyke in the Shackleton Range (Fig. 11.6). Like the rest of the group, it may be classified as calc-alkaline lamprophyric; it is undated.

La Grange Nunataks

Apart from the alkali-rich dykes included with the Herbert Mountains group, samples from La Grange Nunataks form a distinctive group of low-Zr, low-Ti tholeiites. These tholeiites form Hotten's (1993) Group I, the least altered group, which has been found only at La Grange Nunataks. Whole rock, plagioclase and pyroxene K-Ar ages for four of the dykes are all Jurassic (176.6 ± 5– 195 ± 20: Hofmann and others, 1980; Hotten, 1993), confirming the suggestion by Clarkson (1981) that they are related to the Ferrar Group magmatism (Ford and Kistler, 1980). Generation of Ferrar magmas was related to intracontinental rifting processes associated with Jurassic break-up of the Gondwana supercontinent (Dalziel and others, 1987; Brewer and others, 1992). The samples belong to the low-Ti group of Gondwana break-up basalts according to a range of chemical criteria (Peate and others, 1992). Within Antarctica, the rocks are similar to the Ferrar Magmatic Province, rather than the Dronning Maud Land Province (Brewer and others, 1992).

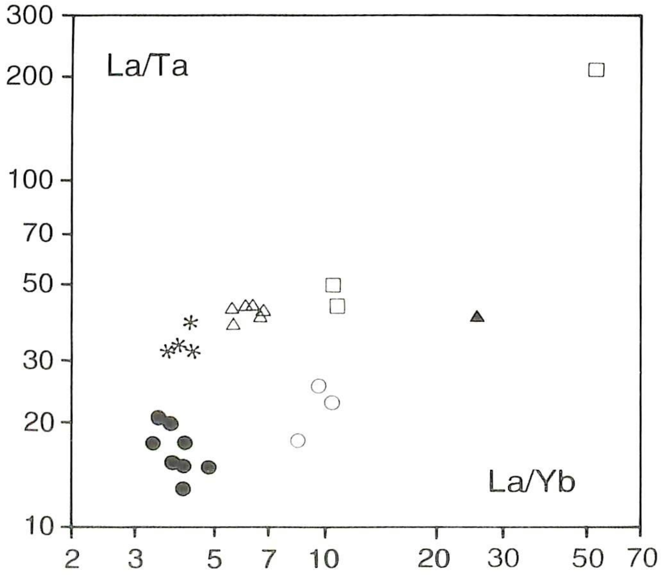

Fig. 11.6. Plot of La/Yb versus La/Ta for the Shackleton Range mafic dykes; symbols as in Fig. 11.2.

12 Geochronology

by R.J. Pankhurst, H. Kreuzer, A. Höhndorf and B. Belyatsky

A large amount of geochronological data has been acquired on the rocks of the Shackleton Range since the earliest field investigations by Stephenson (1966) and Clarkson (1972). The most significant of these are summarized in Tables 12.1 and 12.2; a few imprecise determinations have been omitted from the tables as they do not affect the overall interpretation. Attempts have been made to ensure that all the results listed in the tables are produced and treated in accordance with modern practices regarding decay constants, errors, etc. The distribution of the rock groups discussed below are shown schematically in Fig. 12.1.

Read Group

The predominantly granitic orthogneisses and massive granitoids of the Read Mountains, southern Shackleton Range, consistently record middle Proterozoic ages. The maximum possible age for emplacement of the parent magmas is given by the Sm-Nd depleted-mantle model ages of *c*. 2200 Ma (Belyatsky, unpublished data 1992). The Rb-Sr whole-rock isochron of 1763 ± 32 Ma (Pankhurst and others, 1983) and the Sm-Nd mineral isochron of 1787 ± 210 Ma (Belyatsky, unpublished data 1992) appear to record a discrete event. This event might refer to the climax of metamorphic recrystallization but in polymetamorphosed orthogneisses, such isochrons would commonly be interpreted as dating igneous crystallization.

It is possible that emplacement and deformation were essentially synchronous at this time and that the magmas were derived from (or that they partly incorporated) pre-existing crustal material, although the primitive initial isotopic compositions of Sr and Nd require that this was a relatively minor effect. The concentration of Rb-Sr and K-Ar mineral ages in the interval 1550–1650 Ma may be seen to be related to lower-temperature resetting, either during extended Proterozoic metamorphism or post-metamorphic cooling. The single U-Pb zircon age of 1240 ± 80 Ma (Belyatsky, unpublished data 1992, discordia forced through zero) is among the youngest of the ages recorded for the Read Group.

There are no obvious effects of resetting in the rocks of the Read Group during Cambro-Ordovician orogenic events, although such events have been recorded in the metamorphic rocks of northern Shackleton Range.

Stratton Group

The high-grade (mostly amphibolite facies) metamorphic rocks of the western and northern Shackleton Range also have Proterozoic protolith ages, although the intense

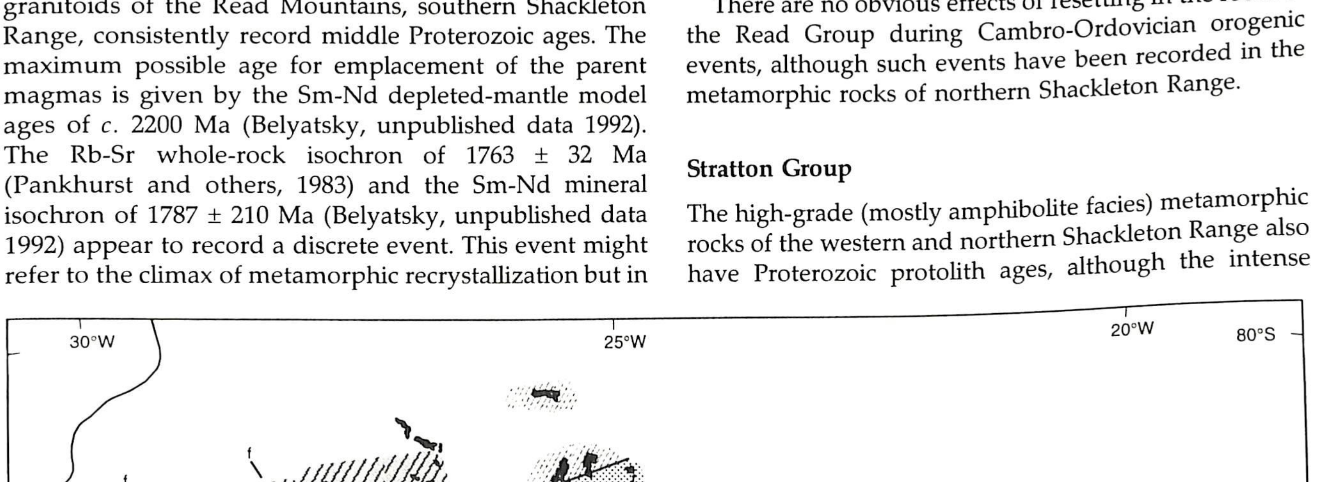

Fig. 12.1. Schematic geological map of the Shackleton Range (see Fig. 1.1 for principal place-names referred to in the text). MWT, Mount Wegener Thrust; OHT, Otter Highlands Thrust.

Table 12.1. Synopsis of K-Ar and U-Pb geochronological data, Shackleton Range

Locality	*Rock type*	*K-Ar age in Ma*	*U-Pb age in Ma*	*Ref.*
Read Group				
Du Toit Nunataks	granite		zircon 1240 ± 80	1
Read Mountains	amphibolite	amph 1395 ± 49; amph/bi 652 ± 32		2
Read Mountains	migmatite	bi 619 ± 28		2
Strachey Stump	amphibolite	bi 1420 ± 9, 1338 ± 7		3
W Mount Wegener	monzonite	hb+bi 1584 ± 23, 1659 ± 23; bi 1617 ± 11, 1619 ± 11		3
Beche Blade	diorite	hb 1603 ± 16, 1672 ± 16; bi 1546 ± 11, 1544 ± 11; WR 1407 ± 70		3,4
Peak "1246" SE of The Ark	qz monzodiorite	hb+bi 1548 ± 22, 1661 ± 23; bi 1645 ± 12, 1630 ± 12		3
and E of Watts Needle	monzodiorite	hb+bi 1528 ± 22, 1588 ± 22; bi 1608 ± 25, 1590 ± 22		3
S Read Mountains	gd dykes	WR 1454 ± 60; mafic mins 830 ± 68		5,2
Stratton Group (northern Shackleton Range basement)				
Pratts Peak	gneiss		zircon 740 ± 90, 990 ± 70, 500 ± 100, 430 ± 10	1
Pioneers Group				
Herbert Mountains	amphibolite	WR 442 ± 35; 407 ± 32		4
	amph-gt gneiss	amph/bi 714±35		2
Mount Skidmore	amph. gneiss	amph/bi 1312 ± 46		2
Mount Etchells	migmatite	mica 468 ± 21, feldspar 397± 20		2
Nostoc Lake	gr-gneiss; augen gneiss		zircon *c.* 550; *c.* 500	6
	gneiss	hb 531 ± 13		7
Williams Ridge	mica schist	WRF (d) 492 ± 4, (e) 478 ± 6, (f) 418 ± 6		8
Stephenson Bastion Formation				
Clayton Ramparts	low-grade	WRF (d) 1020 ± 9, (e) 904 ± 8, (g) 486 ± 5		8
	shales, siltst	WRF (d) 997 ± 8, (e) 855 ± 7		8
		WRF (d) 1028 ± 9, (e) 882 ± 8, (g) 452 ± 5 (Ar-Ar for (d) suggests >1230)		8
Ram Bow Bluff	siltstone	WRF (d) 939 ± 7, (e) 1036 ± 7		8
		WRF (d) 1046 ± 8, (e) 1045 ± 9		8
Watts Needle Formation	slate	WRF (d) 802 ± 7, (e) 714 ± 7, (f) 389 ± 4		8
	quartzwacke	WRF (d) 594 ± 6, (e) 601 ± 6, (f) 529 ± 5		8
	slate	WRF (d) 680 ± 6, (e) 612 ± 6, (f) 521 ± 5		8
	quartzwacke	WRF (d) 530 ± 5, (e) 511 ± 5, (f) 481 ± 5		8
	quartzwacke	WRF (d) 523 ± 5, (e) 512 ± 5, (f) 480 ± 5		8
	siltstone	WRF (d) 546 ± 5, (e) 556 ± 5, (f) 485 ± 5		8
Wyeth Heights Formation				
Otter Highlands		WRF (d) 512 ± 5, (e) 498 ± 5		8
		WRF (d) 505 ± 11, (e) 492 ± 7, (g) 267 ± 3		8
		WRF (d) 548 ± 5, (e) 515 ± 5, (f) 484 ± 5, (g) 304 ± 3		
Mount Wegener Formation				
N Read Mountains	bi-schist	WRF (d) 493 ± 5, (e) 475 ± 4		8
		WRF (a) 500 ± 5, (c) 498 ± 5, (d) 497 ± 3, (e) 479 ± 7, (f) 410 ± 4, (g) 244 ± 3		8
		WRF (d) 486 ± 5, (e) 467 ± 5: (d) 483 ± 5, (e) 470 ± 5		8
		WRF (d) 492 ± 5, (e) 477 ± 5: (d) 486 ± 5, (e) 468 ± 5		8
		WRF (d) 494 ± 5, (e) 475 ± 5: (d) 495 ± 5, (e) 483 ± 5		8
S Read Mountains	shale, siltst	WRF (d) 509 ± 5, (e) 495 ± 5: (d) 511 ± 5, (e) 500 ± 5		8
		WRF (a) 514 ± 5, (b) 517 ± 5, (c) 517 ± 5, (d) 508 ± 4, (e) 501 ± 5, (g) 333 ± 3		8
		WRF (d) 542 ± 4, (e) 515 ± 5, (g) 339 ± 3		8
		WRF (d) 533 ± 3, (e) 511 ± 4, (g) 426 ± 4		8
	lowest grade	WRF (d) 530 ± 5, (e) 476 ± 5: (d) 513 ± 5, (e) 497 ± 5		8
		WRF (d) 526 ± 5, (e) 480 ± 5: (d) 547 ± 5, (e) 497 ± 5: (d) 528 ± 5, (e) 483 ± 5		8
Blaiklock Glacier Group		No data		
trilobite shales	shale	WRF (d) 455 ± 5, (e) 451 ± 5, (f) 422 ± 4		8
		WRF (d) 462 ± 5, (e) 448 ± 5, (f) 424 ± 4		8
mafic dykes				
E Shackleton Range	dolerite	WR 467 ± 18		5
Herbert Mountains	dolerite	WR 399 ± 31, 425 ± 33		4
La Grange Nunataks	dolerite	WR 202 ± 20; 303 ± 12		4,5
Various	dolerite	I: WR & mins 179 ± 5 to 182 ± 11 (7 results)		9
		II: WR 352 ± 8, pl 281 ± 7, py 370 ± 4; WR 406 ± 17; 425 ± 9		9

amph, amphibole; bi, biotite; gd, granodiorite; gr, granite; gt, garnet; hb, hornblende; mins, mixed minerals; pl, plagioclase feldspar; py, pyroxene; qz, quartz; siltst, siltstone; WR, whole-rock; WRF, whole-rock size fractions: (a)=630–200, (b)=200–63, (c)=20–6, (d)=6–2, (e)=2–0.6, (f)=<0.6, (g)=<0.2 (all microns).

1, Belyatsky (unpublished data 1992); 2, Pilot, Schmidt, Hofmann and Paech (unpublished data 1990); 3, Kreuzer, Müller and Roland, quoted in (8, table 2); 4, Hofmann and others (1980); 5, Rex (1972); 6, Grew and Manton (1980); 7, Pankhurst and others (1983); 8, Buggisch and others (1994*b*); 9, Hotten (1993). Multiple references cited in a single line apply sequentially.

Table 12.2. Synopsis of Rb-Sr and Sm-Nd geochronological data, Shackleton Range

Locality	*Rock type*	*Rb-Sr age in Ma (and I.R.)*	*Sm-Nd age in Ma (and ΣNd_t)*	*Ref.*
Read Group				
The Ark	gr-gneiss	WR <1820 ± 160 (0.705 ± 3)		1
Hatch Plain	gr-gneiss	WR 1763 ± 32 (0.704 ± 1)		1
Du Toit Nunataks	gr-gneiss	WR 1599 ± 38 (0.714 ± 1)		1
	granite		mins 1787 ± 210 (+1.9), T_{dm} ~2200	2
Strachey Stump	amphibolite	bi 1487 ± 30 (0.7027 ± 6)		3
W Mount Wegener	monzonite	bi 1602 ± 33 (0.7055 ± 5)		3
Beche Blade	diorite	bi 1531 ± 31 (0.7063 ± 5)		3
Peak "1246" SE of The Ark	qz monzodiorite	bi 1555 ± 31 (0.7059 ± 5)		3
and E of Watts Needle	monzodiorite	bi 1580 ± 32 (0.7058 ± 4)		3
S Read Mountains	gd dykes	WR >1300		1
Stratton Group (northern Shackleton Range basement)				
Wedge Ridge	orthogneiss	WR 2700 ± 100 (0.700 ± 4)		1
		mu 1700 ± 50		1
		mins 504 ± 6 (0.8820 ± 3)		1
Pratts Peak	pyroxenite		mins 509 ± 16 (-4.3), T_{dm} 1300	4
La Grange Nunataks	gt-gr-gneiss	WR 2310 ± 130 (0.722 ± 4)		1
Lewis Chain	ky-mi-schist	WR 505 ± 18 (0.714 ± 2)		1
Herbert Mountains			T_{dm} 1830–2720	2
Mount Weston	gt-ky-si-schists	WR model *c.* 1550 (0.707)		1
Mount Gass	gt-mica-schist	WR model 1500–900 (0.703), >700		1
Pioneers Group				
Nostoc Lake	gr-gneiss	WR 656 ± 66 (0.708 ± 6)		5
	augen-gneiss	WR 583 ± 48 (0.708 ± 2)		5
	gneiss	WR 537 ± 36 (0.7086 ± 3); 580 ± 10 (0.7077 ± 2)		1
		bi 514 ± 15		5
		mins 500 ± 5 (0.7085 ± 1)		1
	pegmatite	510 ± 5 (0.7082 ± 1)		1
	gneiss		T_{dm} 1500–1840	2
			min 517± 16 (-4.5), T_{dm} ~2500	2
Williams Ridge	mica-schist	WR 520 ± 24 (0.7134 ± 6)		1
Mount Skidmore area	gt-mica-schist	WR 1384 ± 180 (0.719 ± 4)/460 ± 35 (0.728 ± 1)		6
Stephenson Bastion Formation				
Ram Bow Bluff	low-grade shales siltst	WR 1251 ± 24 (0.7224 ± 32)		7
Watts Needle Formation		WR model 720 (0.715)		1
		WR 680 ± 57 (0.726 ± 8)		7
		WR 584 ± 41 (0.708 ± 6)		7
Wyeth Heights Formation				
Otter Highlands		WR *c.* 1000–1200 (0.708–0.728)		7
Mount Wegener Formation				
S Read Mountains	shale, siltst	WR 526 ± 6 (0.7152 ± 5)		1
		WR 535 ± 9 (0.7139 ± 5)		7
	lowest grade	WR 561 ± 18 (0.7113 ± 17)		7
Blaiklock Glacier Group				
Mount Provender Fm	shale	WR 475 ± 40 (0.716), 482 ± 11		1
trilobite shales		No data		
mafic dykes		No data		

bi, biotite; Fm, Formation; gd, granodiorite; gr, granite; gt, garnet; ky, kyanite; mi, mica; mins, mixed mineral isochron; mu, muscovite; qz, quartz; si, sillimanite; siltst, siltstone; WR, whole-rock; I.R., initial $^{87}Sr/^{86}Sr$; T_{dm}, depleted-mantle Nd model age.

1, Pankhurst and others (1983); 2, Belyatsky (unpublished data 1992); 3, Höhndorf, Müller and Roland, quoted in (8); 4, Millar and Pankhurst (unpublished data 1986); 5, Grew and Halpern (1979); 6, Hofmann and others (1981); 7, Buggisch and others (1994*a*); 8, Buggisch and others (1994*b*).

effects of overprinting by Ross orogenic events at about 500 Ma are consistently recorded by all mineral, and some whole-rock, ages. On the other hand, it is possible that these more varied rocks could have an older provenance than the Read Group. The 1700 ± 50 Ma pegmatitic muscovite from Wedge Ridge, in the Haskard Highlands, gives a minimum age for metamorphism, but the orthogneisses may be as old as 2700 Ma (Pankhurst and others, 1983). In the La Grange Nunataks, the whole-rock isochron of 2310 ± 130 Ma for the garnetiferous orthogneisses has a high initial $^{87}Sr/^{86}Sr$ ratio that indicates an even older protolith. The two younger U-Pb zircon ages, which clearly indicate crystal growth during the Ross event, have upper intercept ages of 2700–3200 Ma, and biotite-schists from the Herbert Mountains have Sm-Nd model ages as old as 2700 Ma (Belyatsky, unpublished data 1992).

Pioneers Group

These data are more difficult to interpret, in part due to the very extensive recrystallization of the rocks and apparent overprinting at about 500–520 Ma, especially evident in the mineral isochrons and pegmatite ages. Grew and Halpern (1979) considered that their Rb-Sr isochron ages of 583 ± 38 and 656 ± 66 Ma indicated a pre-Ross metamorphic event. A further problem is that the majority of these rocks are metasedimentary, the Pioneers Group being a cover sequence to, and perhaps in part derived from, the metamorphic basement. Thus the moderately high initial $^{87}Sr/^{86}Sr$ ratios of 0.707–0.710 at 500 Ma, as well as the U-Pb zircon indications of 700–1000 Ma and the Sm-Nd model ages of 1500–1800 Ma, could all relate to the provenance area of the sedimentary rocks rather than to early metamorphism. Nevertheless, the relatively high metamorphic grade of these rocks compared to the Eocambrian cover sequences of the southern Shackleton Range certainly suggests earlier Proterozoic metamorphism and/or that it constitutes a separate terrane. These arguments apply equally to the rocks referred to the former "Williams Ridge Formation" and also to the Wyeth Heights Formation (see below).

Low-grade metasedimentary sequences

Some of the low-grade metasedimentary rocks exposed in the southern part of the Shackleton Range are clearly Proterozoic in age. This is especially true of the Stephenson Bastion Formation, for which Rb-Sr whole-rock isochron and Ar-Ar ages demonstrate isotopic homogenization (either during diagenesis or an early metamorphism) at ~1250 Ma. The relatively high initial $^{87}Sr/^{86}Sr$ ratios of 0.72–0.73 would allow derivation from the Read Group. Even the coarser-size fractions of these rocks retain most of their radiogenic argon, giving K-Ar ages of *c.* 1000 Ma; only in the very finest fractions (<0.2 mm) is there any evidence for resetting during the Ross event.

A rather younger depositional age of at least 700 Ma might be inferred from the Rb-Sr and K-Ar data for the *Wyeth Heights Formation* and the *Watts Needle Formation*, but the effect of Ar loss from whole rocks during the Ross orogeny is much more prevalent in all size fractions.

The *Mount Wegener Formation* is the most affected by overprinting, and only the initial $^{87}Sr/^{86}Sr$ ratios of *c.* 0.713–0.715 give a hint of a Precambrian history or provenance. It is noticeable that the coarsest fractions from the lowest grade material give significantly older K-Ar ages than the remainder, averaging ~530 Ma. This could be interpreted either as the age of diagenesis (suggesting sedimentation some 30 Ma before the climax of the Ross orogeny), or as a mixed age resulting from partial overprinting of detrital material. Early Cambrian fossil remains found on the ridge south-east of Lapworth Cirque (Buggisch and others, 1990) support the former interpretation.

Blaiklock Glacier Group

The ages derived from the Blaiklock Glacier Group are consistent with it being a post-orogenic sedimentary sequence. Although the Rb-Sr whole-rock age is too imprecise as a stratigraphical constraint, the mean K-Ar age of 454 ± 5 Ma for the coarser size fractions corresponds to mid-to-late Ordovician.

Mafic dykes

Hotten (1993) presented petrographical, geochemical and K-Ar geochronological data from which he defined five dyke groups (I-III from the northern Shackleton Range, IV and V from the Read Mountains). For Group I (La Grange Nunataks), very concordant whole-rock, pyroxene and plagioclase ages clearly represent mid-Jurassic flood basalt magmatism equivalent to the Ferrar dolerites of the Transantarctic Mountains, as does the age of a dyke from La Grange Nunataks determined by Hofmann and others (1980). The discordant whole-rock and mineral results from one of the Group II samples do not justify detailed interpretation, but the results of two other whole-rock determinations by Hotten (1993) agree with two ages obtained from dykes in the Herbert Mountains (Hofmann and others, 1980) and, together, they make a reasonable case for an Early Devonian event. However, similar K-Ar ages are shown for amphibolite migmatites in the Herbert Mountains and, alternatively, it is possible that all the 400–470 Ma ages reflect Ar loss after a Ross metamorphic event. Other data of Hotten (1993) not listed in Table 12.1, for a Group V dyke (WR= 801 ± 16 Ma and biotite 1250–1350 Ma based on an *estimated* K content), are uninterpretable although $^{143}Nd/^{144}Nd$ compositions presented for the Read Mountains dykes (Hotten, 1993) are compatible with Proterozoic mantle separation.

13 Geological history and regional implications

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Introduction

The Shackleton Range can be divided very roughly into a northern and a southern belt (Fig. 13.1). The northern belt comprises the northern Otter Highlands, Haskard Highlands, La Grange Nunataks, Herbert Mountains and Pioneers Escarpment. It consists of medium- to high-grade metamorphic rocks, partly regarded as "basement" and partly as "supracrustals", which are intensely interleaved. To the north-west the metamorphic rocks are overlain by undeformed, horizontal sedimentary rocks of the Ordovician Blaiklock Glacier Group. The southern belt extends from the southern Otter Highlands via Stephenson Bastion to the Read Mountains in the east. This belt is made up of crystalline basement rocks (Read Group), upon which rest small remnants of an internally undeformed and unmetamorphosed Eocambrian platform cover (Watts Needle Formation: Golovanov and others, 1980; Weber, 1990). On top of this basement and its cover are low-grade metasedimentary rocks; these are of Lower to Middle Cambrian age to the east (Mount Wegener Formation: Buggisch and others, 1990), and of Proterozoic age to the west (Stephenson and Wyeth Heights formations: Weber, 1990).

The medium- to high-grade metamorphic rocks of both the northern and southern belts differ in their metamorphic histories and tectonic positions. The northern belt was strongly affected and rejuvenated during the Ross Orogeny (Grew and Halpern, 1979; Grew and Manton, 1980; Hofmann and Peters, 1980; Hofmann and others, 1981; Pankhurst and others, 1983). By contrast the southern basement may preserve a Precambrian K-Ar signal (Rex, 1972; Hofmann and others, 1980; Pankhurst and others, 1983).

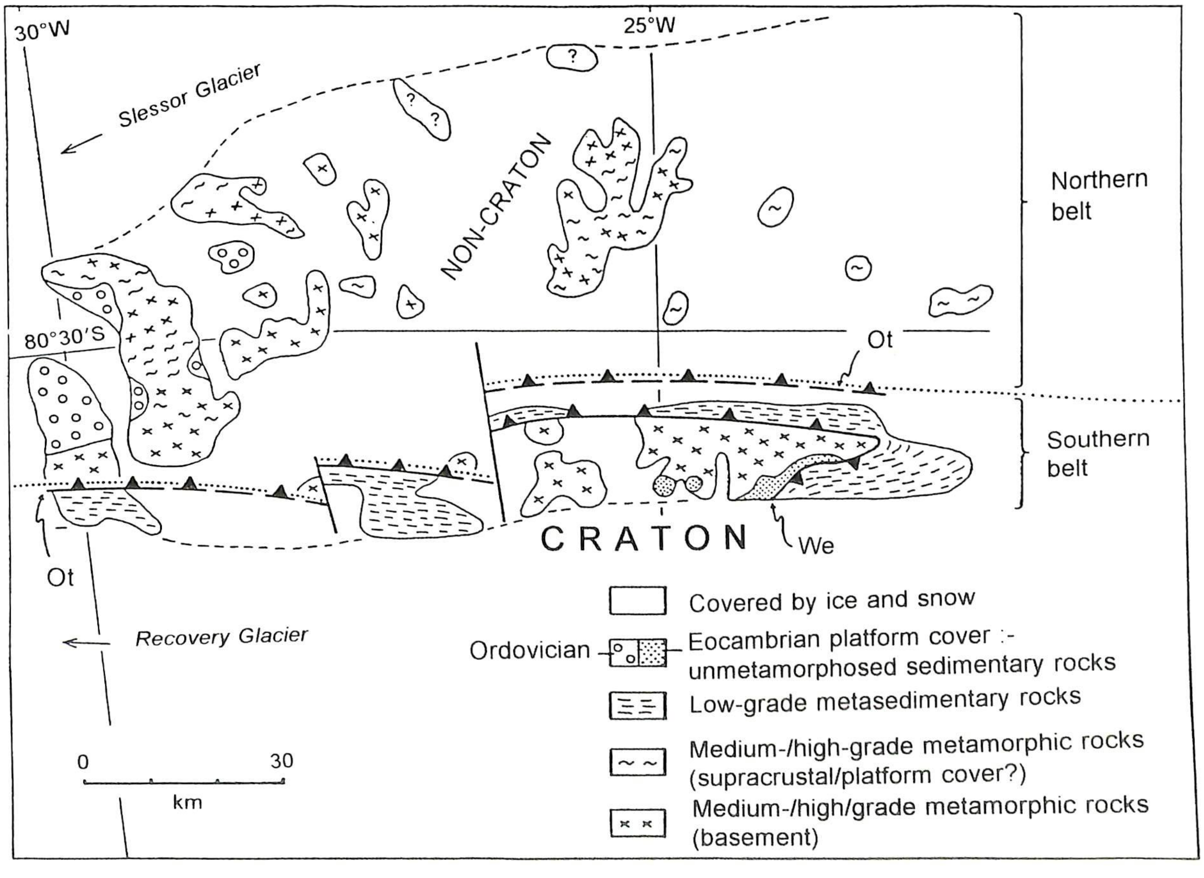

Fig. 13.1. Simplified tectonic scheme for the Shackleton Range (after Kleinschmidt and others, 1992). Ot, Otter Highlands Thrust; We, Mount Wegener Thrust.

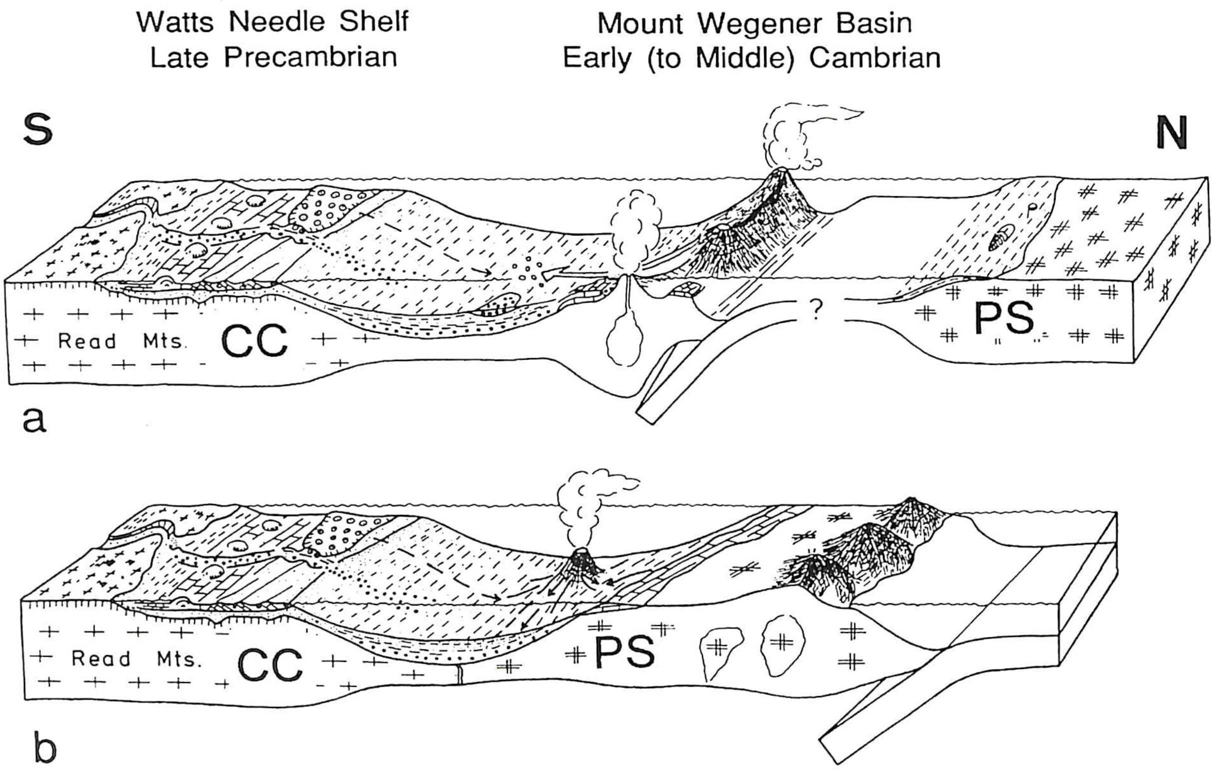

Fig. 13.2. Alternative hypotheses (a and b) to explain diachronous sedimentation, and the plate tectonic situation in the Shackleton Range during the late Precambrian–Middle Cambrian; see text for explanation. CC, continental crust of the East Antarctic craton (Read Group); PS, basement rocks of the northern Shackleton Range (Pioneers and Stratton groups) (after Kleinschmidt and Buggisch, 1994).

Thrust and nappe tectonics

The Precambrian Read Group is overlain and surrounded by the low-grade Early to Middle Cambrian Mount Wegener Formation in the north, east and south. In the south (at Mount Wegener) the unmetamorphosed Eocambrian Watts Needle Formation is interposed. This kind of inversion of metamorphic grade (Paech, 1982) is conclusive evidence for an allochthonous position of the hanging wall. From there the boundary of the two main units is traceable via Strachey Stump/Lapworth Cirque along the northern margin of the Read Mountains (Flett Crags to Spath Crest). There, the tectonic boundary was interpreted formerly as a normal fault (Clarkson, 1983). But all shear sense indicators, i.e. the geometry of folds, phacoids of allochthonous basement slivers, phacoidal imbrication of quartz veins, σ- and δ-clasts, and shear bands prove southward-directed transport (180-200°). Therefore the boundary between the two main units in the Read Mountains forms a thrust (Mount Wegener Thrust), the Mount Wegener Formation a nappe (Mount Wegener nappe), and the central Read Mountains a window within which the top of Watts Needle represents a klippe. The tectonic transport of the nappe (the first one described from Antarctica so far) has a movement of at least 20 km (Roland and others, 1988; Buggisch and others, 1994*b*).

The northern boundary of the Mount Wegener nappe, towards the crystalline rocks of the northern belt of the Shackleton Range (Pioneers and Stratton groups), is exposed at a small Y-shaped nunatak in the southern Otter Highlands, where medium- to high-grade metamorphic rocks of the northern belt are thrust southwards over the low-grade metasedimentary rocks of the Wyeth Heights Formation (Otter Highlands Thrust). This boundary was regarded formerly as a normal fault (Clarkson, 1972, 1982*a*) but Marsh (1983*a*) assumed thrusting because of the sequence of rocks. Both units, the low-grade metasedimentary rocks and the basement rocks, are mylonitized close to the thrust system. The mylonites of the Wyeth Heights Formation are characterized by top-to-south directed shear bands. Vergence of minor B_2-folds, and transposition and imbrication of early quartz veins indicate the same kinetics; B-axes of minor first folds are rotated imperfectly into the tectonic transport direction. Structures in the mylonites of the basement rocks are consistent: top-to-south movement is indicated by book-shelf structures of sheared feldspars and by asymmetric feldspar augen (σ-clasts), cross-cutting pegmatitic veins have been sheared off southwards, and metre-sized slivers of quartzites and schists of the Wyeth Heights Formation are incorporated into the basal parts of the hanging wall.

A similar situation to that at the Y-shaped nunatak may occur north of Stephenson Bastion, indicated by the inversion of the low-grade rocks at Clayton Ramparts.

Age of thrusting

These thrust and nappe tectonics are the best dated event in the Shackleton Range. The rocks of the Mount Wegener Nappe contain calcareous algae, like *Epiphyton* sp., echinoderms, trace fossils (*Oldhamia*

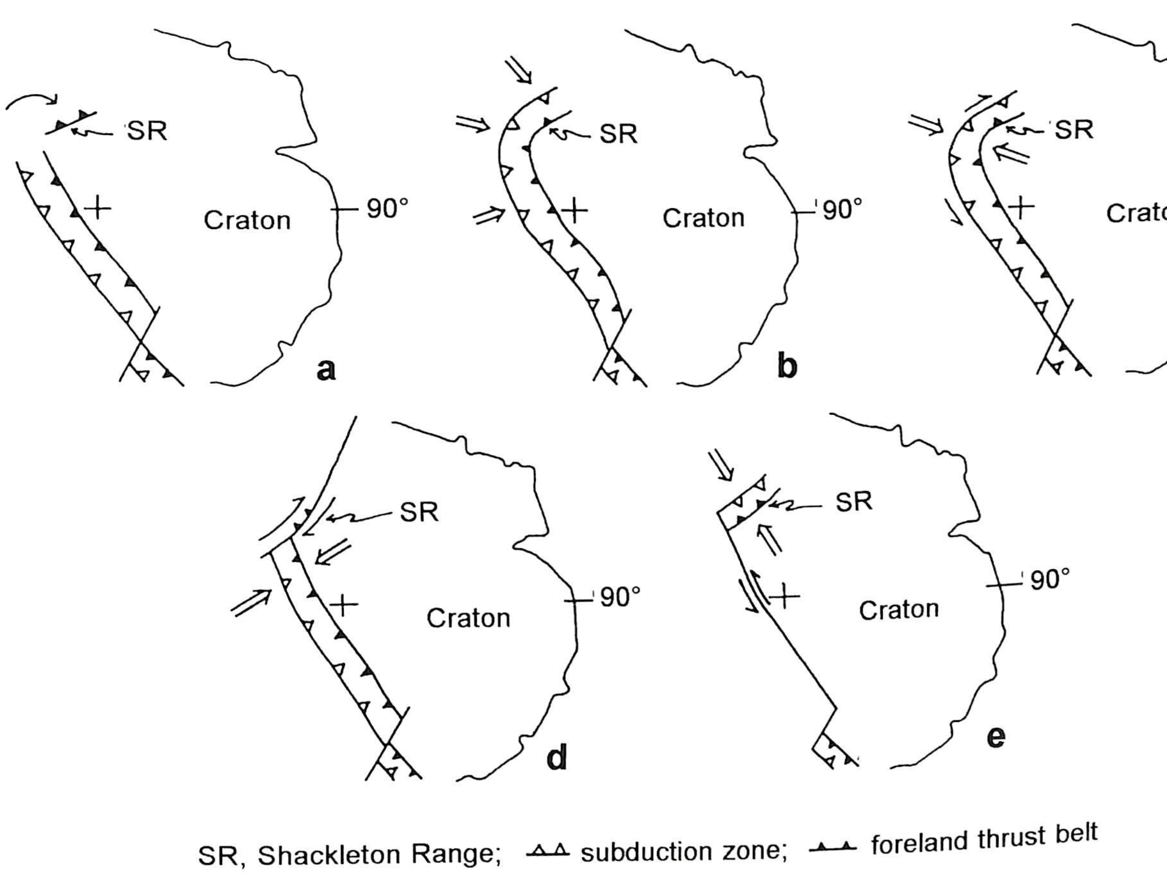

Fig. 13.3. Possible plate tectonic interpretations (a-e) for the Ross Orogen (after Kleinschmidt and Buggisch, 1994).

radiata and *O. antiqua*), and microfossils (Buggisch and others, 1990; Buggisch and others, 1994*a*). Therefore, an Early (to Middle) Cambrian age for the sedimentation of the Mount Wegener Formation is most probable. K-Ar data between 485 and 515 Ma (Buggisch and others, 1994*b*) are related to the low-grade metamorphism which accompanies or outlasts the main thrust tectonics. Finally, the Blaiklock Glacier Group, which is probably of Ordovician age (Buggisch and others, 1994*a*), is not affected by any metamorphic or compressional tectonic event at all. Therefore, the main thrust event has to be of about 500 Ma, i.e. Ross age.

Moreover, Ross ages (480–520 Ma) as well as "Beardmore" ages (580–660 Ma) are common in the northern belt, around the Mount Provender region (Grew and Halpern, 1979; Grew and Manton, 1980; Pankhurst and others, 1983). The Ross ages *sensu stricto* seem to be related to the formation of mylonites, whereas regional metamorphism of the supracrustal rocks may account for K-Ar ages of 490 Ma in the central Haskard Highlands (Williams Ridge; Buggisch and others, 1990).

Earlier events

There are indications of tectono-metamorphic events preceding the Ross Orogeny in the Shackleton Range. In the Read Group, quartz veins and pegmatites are commonly tightly to isoclinally folded and refolded. Veins running obliquely to this foliation form asymmetrical multiple folds, and veins paralleling the schistosity led to intrafolial folds with sheared limbs. The axes of these early folds scatter widely around a mean E–W trend. K-Ar data between 1.82 and 1.4 Ga (concentrated around 1.6 Ga) may indicate the main regional metamorphic event of the Read Group (Rex, 1972; Hofmann and others, 1980; Pankhurst and others, 1983).

K-Ar ages of 1.55 Ga from the Mount Weston gneiss (Haskard Highlands) may correspond to the Read Group's main event (Pankhurst and others, 1983). However, structural analyses of the northern belt (Hofmann, 1982; Braun, 1995) have so far provided no clear picture of events.

Nearly all rocks of the Wyeth Heights Formation were deformed at least twice. Whilst the flat-lying and E–W-trending F_2-folds are related to the Ross-age thrusting, F_1 was affected by this process passively. Nevertheless, available K-Ar data do not show any fingerprint of this pre-Ross event in the southern Otter Highlands, whereas at Stephenson Bastion all K-Ar data plot around 1 Ga (Buggisch and others, 1994*b*). Similar ages have been obtained from rocks previously referred to the "Mount Gass Formation" in the northern Haskard Highlands, with Rb-Sr model ages from individual samples between 900 and 1500 Ma (Pankhurst and others, 1983).

Later events

The Mount Wegener Thrust plane is bent around an E–W-trending anticlinal axis. This seems to be an additional, later deformational event responsible for the Read window anticline. But thrusting occurred mainly on the s_2-planes, which are north-dipping, even on the southern limb of the Read window anticline, where the main thrust dips south. "Ironing out" the Read window anticline would make these "s_2-thrusts" ineffective. Therefore, thrusting, and uplifting of the Read window anticline have to be more or less coeval, although thrusting outlasted the formation of the anticline, at least in the southern part of the window.

Thus the only clearly later (post-Ross) tectonic event was normal faulting parallel to the Slessor and Recovery glaciers, which formed the Shackleton Range as a horst structure.

Local implications

Because the Eocambrian platform cover of the Watts Needle Formation rests unconformably on top of the Precambrian basement of the Read Group, the basement within the Read window is, by definition, part of the East Antarctic craton. As the unmetamorphosed platform cover may be at least partly the equivalent of the lithologically very similar, but metamorphosed supracrustal rocks of the northern belt (Marsh, 1983*a*, table 1; Kleinschmidt, 1989), the ancient craton margin apparently ran more or less along the centre of the Shackleton Range, dividing the range into a cratonic southern and a non-cratonic northern part (Fig. 13.1). Whereas the Read Group represents the autochthonous continental crust with an epicontinental sedimentary cover (Watts Needle Formation), the lithofacies of the allochthonous Mount Wegener Formation is interpreted as a back-arc filling (Buggisch and others, 1994*a*). The main thrusting in the southern Shackleton Range, directed southward on to the East Antarctic craton, has therefore to be interpreted as foreland thrusting.

Because of the back-arc basin facies of the Mount Wegener Formation, the existence of a hypothetical magmatic arc is required farther to the north. For this magmatic arc two positions can be assumed (Fig. 13.2):

(1) It was situated south of the present northern basement of the Shackleton Range. In this case the northern basement (Stratton Group) would be (part of) a more northern, separate continent, microcontinent or terrane (Fig. 13.2a).

(2) The northern basement was mixed with, and constituted part of, the magmatic arc. In this case, the Stratton and Pioneers groups would represent parts of the East Antarctic craton that were reworked by magmatic activity, and separated from the main craton by a thinned (continental) crust below the Mount Wegener basin (Fig. 13.2b).

Both models require the presence of a subduction zone directed southward, with corresponding structural and lithological fingerprints within the northern basement or north of it, e.g. N-directed thrusting. Indications of the required N-directed thrusting may be represented by the Ross-aged mylonite zones in the northern Haskard Highlands (Braun, 1995).

Regional implications

The presence of the Ross Orogeny in the Shackleton Range is now evident from dated compressional deformation, i.e. thrust and nappe tectonics, directed toward the craton and orthogonally to the craton's margin, and by dating of related metamorphism. Metamorphism, orthogonal compression leading to thrust tectonics and formation of nappes, and lack of indications of important strike-slip movements (i.e. transpression) are also characteristic features of the Ross Orogeny in Victoria Land. But in Victoria Land, there are also indications of paired metamorphic belts, paired belts of S- and I-type granitoids, a main suture marked by relics of ultramafic rocks, and of a conjugate system of thrusting (toward and away from the craton) (Kleinschmidt and others, 1992). The results from the Shackleton Range confirm that the Cambro-Ordovician Ross Orogeny (Gunn and Warren, 1962), which formed the first main post-Precambrian orogenic belt along the Pacific margin of the East Antarctic craton (Craddock, 1972), can be recognized from Victoria Land, through the central Transantarctic Mountains to the Shackleton Range. It is characterized mainly by orthogonal, conjugate thrusting and nappe formation. Today, the Ross Orogen forms a smooth curve from northern Victoria Land to the Pensacola Mountains, but from there to the Shackleton Range is seems to be bent sharply in an E–W orientation. In spite of this strong oroclinal bend, the Ross Orogeny and parts of it cannot be interpreted as a strike-slip orogeny (Fig. 13.3d,e), but rather as a "normal" orthogonal subductional or collisional orogeny (Fig. 13.3b,c). Palaeomagnetic data by Hotten (1993) preclude any secondary rotation of the Shackleton Range (Fig. 13.3a).

In addition to the alternatives shown in Fig. 13.3a-e, two further hypotheses have been put forward by other authors. Kamenev and Semonov (1980) suggested an aulacogen hypothesis, and Dalla Salda and others (1992) suggested that the Shackleton Range might represent the "southern" termination of the southern Iapetus Ocean.

ACKNOWLEDGEMENTS

The geological sheet map and this accompanying booklet summarize the work of many geologists, from different nations, who have participated in field investigations of the Shackleton Range over the years. Whilst acknowledging the valuable work of the Trans-Antarctic Expedition in discovering the different lithological groups and describing them for the first time, it was the reconnaissance surveys between 1968 and 1977, undertaken by members of the British Antarctic Survey (BAS), that led to the creation of a stratigraphical framework for the Shackleton Range. Thanks are due to BAS field personnel who participated in these early surveys, and to the US Navy for providing air support for much of the BAS work in the range.

Further significant discoveries were made during the Soviet Antarctic Expeditions (between 1975 and 1978), which included participants from the German Democratic Republic, and by the "Geologische Expedition in die Shackleton Range" (GEISHA), of the Federal Republic of Germany, in 1987–88. Fieldwork for the GEISHA programme was supported by the Deutsche Forschungsgemeinschaft (DFG) through personal grants to several members of the expedition. Logistic support for GEISHA was provided by the Alfred-Wegener-Institut für Polar- und Meeresforschung, Bremerhaven (AWI) and by the Bundesanstalt für Geowissenschaften und Rohstoffe, Hannover (BGR).

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REFERENCES

The references listed below include those cited in this volume and on the accompanying map as well as additional papers of related interest published before 1990. The list does not, however, represent a bibliography of all papers published about the geology of the Shackleton Range.

AMARD, B. 1986. Microfossiles (Acritarches) du Proterozoique superieur dans les shales de la formation d'Atar (Mauretanie). *Precambrian Research*, **31**, 69–95.

ANONYMOUS. 1964. Outstanding flights. *Bulletin of the US Antarctic Projects Officer*, **5** (10), 18–23.

ANONYMOUS. 1968*a*. Support activities: October 27–December 15, 1967. *Antarctic Journal of the United States*, **3**(1), 6–10.

ANONYMOUS. 1968*b*. Evacuation flight to Halley Bay. *Antarctic Journal of the United States*, **3**(1), 14–15.

ANONYMOUS. 1968*c*. Notes: VX-6 commended for evacuation flight. *Antarctic Journal of the United States*, **3**(2), 51.

ARANOVICH, L.Y. *and* PODLESSKII, K.K. 1983. The cordierite-garnet-sillimanite-quartz equilibrium: experiments and applications. (*In* SAXENA, S.K., *ed*. *Advances in physical geochemistry. 3. Kinetics and equilibrium in mineral reactions*. Berlin, Springer Verlag, 173–98.)

BARDIN, V.I. 1981. Glacio-geomorfologicheskie nablyudeniya v gorakh Sekelton. [Glaciomorphological observations in the Shackleton Range.] *Antarktika*, **20**, 73–81.

BIRD, G.W. *and* FAWCETT, J.J. 1973. Stability relations of Mg-chlorite-muscovite and quartz between 5 and 10 kb water pressure. *Journal of Petrology*, **14**, 415–28.

BLAIKLOCK, K.V., STRATTON, D.G. *and* MILLER, J.H. 1966. Survey. *Trans-Antarctic Expedition Scientific Reports*, No. 15, 27 pp. and 15 sheet maps.

BRAUN, H.-M. 1995. Structural investigations in Proterozoic to Lower Palaeozoic rocks in the Read Mountains and Haskard Highlands of the Shackleton Range, Antarctica. *Polarforschung*, **63**, 63–99.

BRAUN, H.-M., KLEINSCHMIDT, G. *and* SPAETH, G. 1988. Geologische Expedition in die Shackleton Range (GEISHA): 3.7.4. Strukturgeologie der Shackleton Range. *Berichte zur Polarforschung*, **58**, 208–18.

BREWER, T.S., HERGT, J.M., HAWKESWORTH, C.J., REX, D. *and* STOREY, B.C. 1992. Coats Land dolerites and the generation of Antarctic continental flood basalts. (*In* STOREY, B.C., ALABASTER, T. *and* PANKHURST, R.J. *eds. Magmatism and the causes of continental break-up*. Geological Society of London Special Publications, No. 68, 185–208.)

BRITISH ANTARCTIC SURVEY. 1978*a*. *British Antarctic Survey annual report, 1977–78*. Cambridge, British Antarctic Survey, 72 pp.

BRITISH ANTARCTIC SURVEY. 1978*b*. *Shackleton Range, British Antarctic Territory/Dronning Maud Land*, Sheet SU 26-30/1 (extended). 1:250 000 scale map, BAS 250P Series.

BUGGISCH, W. 1988. Stratigraphie und Fazies der sedimentären Serien in der Shackleton Range. *Berichte für Polarforschung*, **58**, 218–22.

BUGGISCH, W., KLEINSCHMIDT, G., HÖHNDORF, A. *and* POHL, J. 1994*a*. Stratigraphy and facies of sediments and low-grade metasediments in the Shackleton Range, Antarctica. *Polarforschung*, **63**, 9–32.

BUGGISCH, W., KLEINSCHMIDT, G., KREUZER, H. *and* KRUMM, S. 1990. Stratigraphy, metamorphism and nappe-tectonics in the Shackleton Range (Antarctica). *Geodätische und geophysikalische Veröffentlichungen*, Reihe I, **15**, 64–86.

BUGGISCH, W., KLEINSCHMIDT, G., KREUZER, H. *and* KRUMM, S. 1994*b*. Metamorphic and structural evolution of the southern Shackleton Range during the Ross Orogeny. *Polarforschung*, **63**, 33–56.

CHATTERJEE, N.D. *and* JOHANNES, W. 1974. Thermal stability and standard thermodynamic properties of synthetic 2M1-muscovite, $KAl_2AlSi_3O_{10}(OH)_2$. *Contributions to Mineralogy and Petrology*, **48**, 89–114.

CLARKSON, P.D. 1971. Shackleton Range geological survey 1970–1971. *Antarctic Journal of the United States*, **6**(4), 121–22.

CLARKSON, P.D. 1972. Geology of the Shackleton Range: a preliminary report. *British Antarctic Survey Bulletin*, No. 31, 1–15.

CLARKSON, P.D. 1981. Geology of the Shackleton Range: IV. The dolerite dykes. *British Antarctic Survey Bulletin*, No. 53, 201–12.

CLARKSON, P.D. 1982*a*. Geology of the Shackleton Range: I. The Shackleton Range Metamorphic Complex. *British Antarctic Survey Bulletin*, No. 51, 257–83.

CLARKSON, P.D. 1982*b*. Tectonic significance of the Shackleton Range. (*In* CRADDOCK, C. *ed*. *Antarctic geoscience*. Madison, University of Wisconsin Press, 835–39.)

CLARKSON, P.D. 1983. Geology of the Shackleton Range. II. The Turnpike Bluff Group. *British Antarctic Survey Bulletin*, No. 52, 109–24.

CLARKSON, P.D. *and* WYETH, R.B. 1983. Geology of the Shackleton Range: III. The Blaiklock Glacier Group. *British Antarctic Survey Bulletin*, No. 52, 233–44.

CLARKSON, P.D., HUGHES, C.P. *and* THOMSON, M.R.A. 1979. Geological significance of a Middle Cambrian fauna from Antarctica. *Nature*, **279**, 791–92.

CONDIE, K.C. 1989. *Plate tectonics and crustal evolution.* 3rd ed. Oxford, Pergamon Press, 476 pp.

CRADDOCK, C. 1972. Antarctic tectonics. (*In* ADIE, R.J. *ed. Antarctic geology and geophysics.* Oslo, Universitetsforlaget, 449–55.)

DALLA SALDA, L.H., DALZIEL, I.W.D., CINGOLANI, C.A. *and* VARELA, R. 1992. Did the Tacomic Appalachians continue into southern South America? *Geology*, **20**, 1059–62.

DALZIEL, I.W.D. 1991. Pacific margins of Laurentia and East Antarctica–Australia as a conjugate rift pair: evidence and implications for an Eocambrian supercontinent. *Geology*, **19**, 598–601.

DALZIEL, I.W.D. 1992. On the organization of American plates in the neoproterozoic and the breakout of Laurentia. *GSA Today*, **2**, 237–41.

DALZIEL, I.W.D., STOREY, B.C., GARRETT, S.W., GRUNOW, A.M., HERROD, L.D.B. *and* PANKHURST, R.J. 1987. Extensional tectonics and the fragmentation of Gondwanaland. (*In* COWARD, M.P., DEWEY, J.F. *and* HANCOCK, P.L. *eds. Continental extensional tectonics.* Geological Society of London Special Publications, No. 28, 433–41.)

DANYUSHEVSKAYA, A.J., BELYAEV, K.R., BENEVOLENSKI, S.E. *and* GRIKUROV, G.E. 1983. Geokhimiya organicheskogo veshchestva porod khrebta shekletona i gor pensakola (zapadnaya Antarktida). [Geochemistry of the organic matter of rocks from the Shackleton Range and the Pensacola Mountains.] *Izvestiya Akademii Nauk SSR, Seriya geologicheskaya*, **1**, 125–32.

FERRY, J.M. *and* SPEAR, F.S. 1978. Experimental calibration of the partitioning of Fe and Mg between garnet and biotite. *Contributions to Mineralogy and Petrology*, **66**, 113–17.

FORD, A.B. 1977. Geological comparison of the Shackleton Range and the Pensacola Mountains during the 22nd Soviet Antarctic Expedition. *Antarctic Journal of the United States*, **12**(4), 88–90.

FORD, A.B. *and* KISTLER, R.W. 1980. K-Ar age, composition, and origin of Mesozoic mafic rocks related to Ferrar Group, Pensacola Mountains, Antarctica. *New Zealand Journal of Geology and Geophysics*, **23**, 371–90.

FUCHS, V.E. 1969. Shackleton Range traverse. *Antarctic Journal of the United States*, **4**(4), 139–40.

FUCHS, V.E. 1970. Shackleton Range traverse, 1969–1970. *Antarctic Journal of the United States*, **5**(4), 107–08.

FUCHS, V.E. 1982. *Of ice and men.* Oswestry, Anthony Nelson, 383 pp.

FUCHS, V.E. *and* E. HILLARY. 1959. *The crossing of Antarctica. The Commonwealth Trans-Antarctic Expedition, 1955–58.* London, Cassell and Company Limited, 338 pp.

GHENT, E.D., ROBBINS, D.B. *and* STOUT, M.Z. 1979. Geothermometry, geobarometry, and fluid compositions of metamorphosed calcsilicates and pelites, Mica Creek, British Columbia. *American Mineralogist*, **64**, 874–85.

GIBSON, J.L. *and* JAGAN, P. 1980. Instrumental neutron activation analysis of rocks and minerals. (*In* MUECKE, G. *ed. Short course in neutron activation analysis*, 109–32.)

GLEBOVITSKI, V.A., DRUGOVA, G.M., *and* EKIMOV, S.P. 1977. *Thermo- i barometria metamorphicheskich porod.* [Thermo-barometry of metamorphic rocks.] Leningrad, Nauka.

GOLOVANOV, N.P., MICHAJLOV, V.M. *and* SHULJATIN, O.G. 1980. Pervie diagnostiruemie stromatoliti Antarktidi i ich biostratigraficheskoe znachenie. [First diagnostic stromatolites from Antarctica and their biostratigraphical significance.] *Antarktika*, **19**, 152–59.

GOODGE, J.W., HANSEN, V.L. *and* PEACOCK, S.M. 1992. Multiple petrotectonic events in high-grade metamorphic rocks of the Nimrod Group, central Transantarctic Mountains, Antarctica. (*In* YOSHIDA, Y., KAMINUMA, K. *and* SHIRAISHI, K. *eds. Recent progress in Antarctic earth science.* Tokyo, Terra Scientific Publishing Co., 203–09.)

GREEN, N.L. *and* USDANSKY, S.J. 1986. Ternary-feldspar mixing relations and thermobarometry. *American Mineralogist*, **71**, 1100–08

GREW, E.S. 1977. With the Soviets in Antarctica, austral summer 1976–1977. *Antarctic Journal of the United States*, **12**(4), 86–88.

GREW, E.S. *and* HALPERN, M. 1979. Rubidium-strontium dates from the Shackleton Range Metamorphic Complex in the Mount Provender area, Shackleton Range, Antarctica. *Journal of Geology*, **87**(3), 325–32.

GREW, E.S. *and* MANTON, W.I. 1980. Uranium-lead ages of zircons from Mount Provender, Shackleton Range, Transantarctic Mountains. *Antarctic Journal of the United States*, **15**(5), 45–46.

GRIKUROV, G.E. *and* DIBNER, A.F. 1979. Vozrast i strukturnoe polozenie tolsc zapadnoj casti chrebta Shekleton (Antarktida). [Age and structural position of sedimentary rocks in the western part of the Shackleton Range (Antarctica)]. *Antarktika*, **18**, 20–31.

GUNN, B.M. *and* WARREN, G. 1962. Geology of Victoria Land between the Mawson and Mulock glaciers, Antarctica. *New Zealand Geological Survey Bulletin*, **71**, 1–157.

HEINRICHS, H. *and* HERRMANN, A.G. 1990. *Praktikum der anlytischen Geochemie.* Berlin, Springer Verlag, 669 pp.

HERRMANN, A.G. 1975. *Praktikum der Gesteinsanalyse.* Berlin, Springer Verlag, 204 pp.

HOFMANN, H.J. 1987. Precambrian biostratigraphy. *Geoscience Canada*, **14**(3), 135–54.

HOFMANN, J. 1982. Tektonische Untersuchungen in den Herbert Mountains (Shackleton Range, Antarctica). *Freiberger Forschungshefte*, **C 371**, 9-40.

HOFMANN, J. *and* PAECH, H.-J. 1980. Zum strukturgeologischen Bau am Westrand der Ostantarktischen Tafel. *Zeitschrift für geologische Wissenschaften*, **8**(4), 425–35.

HOFMANN, J. *and* PAECH, H.-J. 1983. Tectonics and relationships between structural stages in the Precambrian of the Shackleton Range, western margin of the East Antarctic Craton. (*In* OLIVER, R.L., JAMES, P.R. *and* JAGO, J.B. *eds. Antarctic earth science.* Canberra, Australian Academy of Science and

Cambridge, Cambridge University Press, 183–89.)

HOFMANN, J., PILOT, J. *and* SCHLICHTING, M. 1981. Das Rb/Sr-Alter von Metamorphiten der Herbert Mountains, Shackleton Range, Antarktika. *Zeitschrift Geologische Wissenschaften*, **9**, 835–42.

HOFMANN, J., WEBER, W. *and* SAMAON, V.V. 1982. Beiträge zur Geologie der Shackleton Range und der Pensacola Mountains (Antarktika). *Freiberger Forschungshefte*, **C 371**, 12–19.

HOFMANN, J., KAISER, G., KLEMM, W. *and* PAECH, H.-J. 1980. K/Ar- Alter von Doleriten und Metamorphiten der Shackleton Range und der Whichaway-Nunataks, Ost- und Südostumrandung des Filchner-Eisschelfs (Antarktis). *Zeitschrift für geologische Wissenschaften*, **8**, 1227–32.

HOLDAWAY, M. J. 1971. Stability of andalusite and the aluminium silicate phase diagram. *American Journal of Science*, **271**, 97–131.

HOTTEN, R. 1993. Die mafischen Gange der Shackleton Range/Antarktika: Petrographie, Geochemie, Isotopengeochemie und Paläomagnetik. (The mafic dykes of the Shackleton Range/Antarctica: petrography, geochemistry, isotope geochemistry and palaeomagnetism.) *Berichte zur Polarforschung*, **118**, 225 pp.

HOTTEN, R. 1995. Palaeomagnetic studies on mafic dykes of the Shackleton Range, Antarctica, and their geotectonic relevance. *Polarforschung*, **63**(2/3), 123–51.

HÖFLE, H.-C. 1988. Vereisungsgeschichte der Shackleton Range (GEISHA). *Berichte für Polarforschung*, **58**, 229–34.

HÖFLE, H.-C. *and* BUGGISCH, W. 1995. Glacial geology and petrography of erratics in the Shackleton Range, Antarctica. *Polarforschung*, **63**(2/3), 183–201.

IVANOV, V.L. *and* KAMENEV, E.N. 1990. Osnovnye cherty tektonicheskoy strukturoy i potencialnaya mudonosnosst khrebta Sekltona i rayona lednika denmana. [Main features of the tectonic structure and potential ore-bearing of the Shackleton Range and the region of Denman Glacier.] (*In* IVANOV, V.L. *and* KAMENEV, E.N. *eds*. *Geologiya i mineralnie ressurci Antarctidy*. Nedra, Ministersvo Geologii SSSR, Institute VNIIOkeangeologiya Moskva, 148–50.)

JANKAUSKAS, T.V. 1979. Sredniyerifeiskaya mikrobiota Juschovo Urala. [Middle Riphean microbiota from the Southern Urals.] *Doklady Akademiya Nauk SSSR*, (Geological Sciences Section), **248**, 190–93.

JOHANNES, W. 1984. Beginning of melting in the granite system Qz-Or-Ab-An-H_2O. *Contributions to Mineralogy and Petrology*. **87**, 264–73.

KAMENEV, E.N. *and* SEMENOV, V.S. 1980. Regional metamorphism in Antarctica. (*In* CRESSWELL, M.M. *and* VELLA, P. *eds*. *Gondwana Five*. Rotterdam, A.A. Balkema, 209–15.)

KERRICK, D.M. 1972. Experimental determination of muscovite + quartz stability with $P_{H_2O} < P_{total}$. *American Journal of Science*, **272**, 946–58.

KLEINSCHMIDT, G. 1989. Die Shackleton Range im Innern der Antarktis. *Die Geowissenschaften*, **7**(1), 10–14.

KLEINSCHMIDT, G. *and* BUGGISCH, W. 1994. The tectonic implications of the structure of the Shackleton Range, Antarctica. *Polarforschung*, **63**(1), 57–62.

KLEINSCHMIDT, G. *and* ROLAND, N.W. 1988. Geologische Expedition in die Shackleton Range (GEISHA): 3.7.1 Einführung in die Geologie der Shackleton Range und Zeilsetzung von GEISHA. *Berichte zur Polarforschung*, **58**, 196–99.

KLEINSCHMIDT, G., BRAUN, H.-M. *and* BUGGISCH, W. 1991. Gondwana's Pacific margin during the early Paleozoic: The Ross Orogen and its structure in the Shackleton Range and north Victoria Land (Antarctica). (*In* ULBRICH, H. *and* ROCHA CAMPOS, A.C. *eds*. *Gondwana Seven Proceedings*. São Paulo, Universidad de São Paulo, 19–32.)

KLEINSCHMIDT, G., BUGGISCH, W. *and* FLOETTMANN, T. 1992. Compressional causes for the early Paleozoic Ross Orogen–evidence from Victoria Land and the Shackleton Range. (*In* YOSHIDA, Y., KAMINUMA, K. *and* SHIRAISHI, K. *eds*. *Recent progress in Antarctic earth science*. Tokyo, Terra Scientific Publishing Company, 227–33.)

KOTHE, J., ROLAND, N.W. *and* BÄSSLER, K.-H. 1994. Logistics of the GEISHA Expedition. *Polarforschung*, **63**(1), 5–8.

LAPPIN, A.R. *and* HOLLISTER, L.S. 1980. Partial melting in the Central Gneiss Complex near Prince Rupert, British Columbia. *American Journal of Science*, **280**, 518–45.

MARSH, P.D. 1983*a*. The Late Precambrian and Early Palaeozoic history of the Shackleton Range, Coats Land. (*In* OLIVER, R.L., JAMES, P.R. *and* JAGO, J.B. *eds*. *Antarctic earth science*. Canberra, Australian Academy of Science and Cambridge, Cambridge University Press, 190–93.)

MARSH, P.D. 1983*b*. The stratigraphy and structure of the metamorphic rocks of the Haskard Highlands and Otter Highlands of the Shackleton Range. *British Antarctic Survey Bulletin*, No. 60, 23–43.

MARSH, P.D. 1984. The stratigraphy and structure of the Lagrange Nunataks, northern Fuchs Dome and Herbert Mountains of the Shackleton Range. *British Antarctic Survey Bulletin*, No. 63, 19–40.

MARSH, P.D. 1985. Ice surface and bedrock topography in Coats Land and part of Dronning Maud Land, Antarctica, from satellite imagery. *British Antarctic Survey Bulletin*, No. 68, 16–36.

MOORES, E.M. 1991. Southwest U.S.–East Antarctic (SWEAT) connection: a hypothesis. *Geology*, **19**, 425–28.

NOBLE, P. 1968. The Shackleton route reconnaissance (middle section), Summer 1968. British Antarctic Survey travel report, BAS Archives No. AD6/2Z/1968/K1, 32 pp. [Unpublished]

OLESCH, M. 1991. Metamorphism of basement rocks from the southern Shackleton Range. *Abstracts-Sixth International Symposium on Antarctic Earth Sciences*, Saitama, p. 456.

OLESCH, M. *and* SCHUBERT, W. 1988. Petrologie des kristallinen Grundgebirges der südlichen und norwestlichen Shackleton Range. *Berichte für Polarforschung*, **58**, 205–08.

PAECH, H.-J. 1977. Teilnahme an der 22 Sowjetischen Antarktis-expedition in Bereich der sowjetischen Station Družnaja. *Record, Zentralinstituts für Physik der Erde Akademie Wissenschaften DDR*, 25 pp. [Unpublished]

PAECH, H.-J. 1982. Als Geologie in den Read Mountains. (*In* LANGE, G. *ed. Bewährung in Antarktika. Antarktisforschung der DDR*. Leipzig, Brockhaus Verlag, 159–64.)

PAECH, H.-J. 1985. Tectonic structures of the crystalline basement in the Shackleton Range, Antarctica. *Zeitschrift für geologische Wissenschaften*, **13**(3), 309–19.

PAECH, H.-J. 1986. Vergleich der geologischen Entwicklung des südlichen Afrika mit der des antarktischen Kontinents. *Veröffentlichungen des Zentralinstituts für Physik der Erde*, Nr. 87, 100–02.

PAECH, H.-J. 1990. Comments on "Stratigraphy and nappe-tectonics in the Shackleton Range (Antarctica)" by BUGGISCH *et al. Geodätisch-geophysikalische Veröffentlichungen*, Reihe I, **15**, 87–91.

PAECH, H.-J., HAHNE, K. *and* VOGLER, P. 1986. Sedimentological characterization of the Turnpike Group, Shackleton Range, Antarctica. *Geodätisch-geophysikalische Veröffentlichungen*, Reihe I, **13**, 35–39.

PAECH, H.-J., HAHNE, K. *and* MAASS, I. 1991*a*. Sedimentological and tectonical results on sedimentary rocks outcropping at the southern flank of the Shackleton Range, Antarctica. *Zeitschrift für geologische Wissenschaften*, **19**, 159–67.

PAECH, H.-J., HAHNE, K. *and* VOGLER, P. 1991*b*. Sedimentary palaeoenvironments of the Riphaean Turnpike Bluff Group, Shackleton Range. (*In* THOMSON, M.R.A., CRAME, J.A. *and* THOMSON, J.W. *eds. Geological evolution of Antarctica*. Cambridge, Cambridge University Press, 123–28.)

PAECH, H.-J., HOFMANN, J. *and* FRISCHBUTTER, A. 1980. Zur Geologie der Gebirge in der Umrandung des Filchner-Eisschelfs. *Geodätisch-geophysikalische Veröffentlichungen*, Reihe I, **7**, 54–63.

PALMER, A.R. *and* GATEHOUSE, C.G. 1972. Early and Middle Cambrian trilobites from Antarctica. *Professional Paper of the US Geological Survey*, No. 456, 37 pp.

PANKHURST, R.J., MARSH, P.D. *and* CLARKSON, P.D. 1983. A geochronological investigation of the Shackleton Range. (*In* OLIVER, R.L., JAMES, P.R. *and* JAGO, J.B. *eds. Antarctic earth sciences*. Canberra, Australian Academy of Science and Cambridge, Cambridge University Press, 176–82).

PEATE, D.W., HAWKESWORTH, C.J. *and* MANTOVANI, S.M. 1992. Chemical stratigraphy of the Paraná lavas (South America): classification of magma types and their spatial distribution. *Bulletin of Volcanology*, **55**, 119–39.

PERCHUK, L.L. 1977. Thermodynamic control of metamorphic processes. (*In* SAXENA, S.K. *and* BHATTACHARJI, S. *eds. Energetics of geological processes*. Berlin, Springer Verlag, 286–352.)

PERCHUK, L.L., ARANOVICH, L.Y., PODLESSKII, K.K., LAVRENT'EVA, I.V., GERASIMOV, V.Y., FED'KIN, V.V., KITSUL, V.I., KARKASOV, L.P. *and* BERDNIKOV, N.V. 1985. Precambrian granulites of the Aldan shield, eastern Siberia, USSR. *Journal of Metamorphic Geology*, **3**, 265–310.

PETERS, M. *and* SPAETH, G. 1988. Basische Gänge in der Shackleton Range. *Berichte zur Polarforschung*, **58**, 222–27.

PIPER, J.D.A. 1987. *Palaeomagnetism and the continental crust*. Milton Keynes, Open University Press, 434 pp.

POPOV, L.E. *and* SOLOV'EV, I.A. 1981. Srednekembriyskie bezzamkovye brachiopody chancellorii, konikonchii i trilobity zapadnoy Antarktidy (chrebty Sheklton i Ardzhentina). [Middle Cambrian inarticulate brachiopoda, conches and trilobites of western Antarctica (Shackleton and Argentina ranges).] *Antarktika*, **20**, 64–72.

PUJATO, H. 1977. Los vuelos precursores del General Pujato. *Antártida*, No. 8, 32–39.

REX, D.C. 1972. K-Ar age determinations on volcanic and associated rocks from the Antarctic Peninsula and Dronning Maud Land. (*In* ADIE, R.J. *ed. Antarctic geology and geophysics*. Oslo, Universitetsforlaget, 133–36).

ROLAND, N.W. 1994. Planning and scientific program of the GEISHA Expedition. *Polarforschung*, **63**(1), 1–3.

ROLAND, N.W., KLEINSCHMIDT, G. *and* BUGGISCH, W. 1988. Geological Expedition to the Shackleton Range-GEISHA 1987/1988–nappe structures and a meteorite find. *Bundesanstalt für Geowissenschaften und Rohstoffe Circular*, No. 7, 3–20.

ROLAND, N.W., OLESCH, M. *and* SCHUBERT, W. 1995. Petrogenesis of the metasediments from the Pioneers Escarpment, Shackleton Range, Antarctica. *Polarforschung*, **63**(2/3), 165–82.

SCHUBERT, W. *and* OLESCH, M. 1995. Cordierite in the Shackleton Range, Antarctica: first recorded occurrence. *Polarforschung*, **63**(2/3), 153–64.

SCHUBERT, W. *and* WILL, T. 1994. Granulite-facies rocks of the Shackleton Range, Antarctica. Conditions of formation and preliminary petrogenetic implications. *Chemie der Erde*, **54**, 355–71.

SCHULZ-DOBRICK, B. 1975. *Chemischer Stoffbestand varistischer Geosynklinalablagerungen im Rhenoherzynikum*. Ph.D. thesis Georg-August Universität Göttingen. [Unpublished]

SCHULZE, P. *and* OLESCH, M. 1990. Granulitfazielle Relikte im Pioneers Escarpment, Shackleton Range, Antarktis. *European Journal of Mineralogy*, **2**, 234.

SEMENOV, V.S. 1985. Usloviya formirovaniya kianit-ortoklassoderzhaschikh paragenezisov v rayone gory Provender i Pika Pratt (khr. Shekltona, Antarktida). [Condition of the formation of kyanite-orthoclase-bearing paragenesis in the region of Mount Provender and Pratts Peak (Shackleton Range, Antarctica).] *Doklady Akademiya Nauk SSSR*, **281**(5), 1188–91.

SEMENOV, V.S. *and* SOLOV'EV, I.A. 1986. Pozdenarkheysko–ranneproterozoyskie metamorficheskie poyasa khrebta Shekltona i gor Princ Charles (Antarktika). [Late Archean – Early Proterozoic metamorphic belts of the Shackleton Range and the Prince Charles Mountains, Antarctica.] *Geotektonika*, **5**, 35–52.

SEMENOV, V.S. *and* VAPNIK, E.A. 1991. Conditions of metamorphism and fluid characteristics of the high-pressure complex of the Shackleton Range, Antarctica. *International geology review*, **33**, 385–96.

SHACKLETON, E. 1919. *South: the story of Shackleton's last expedition, 1914–1917*. London, William Heinemann, 376 pp.

SKIDMORE, M.J. *and* CLARKSON, P.D. 1972. Physiography and glacial geomorphology of the Shackleton Range. *British Antarctic Survey Bulletin*, No. 30, 69–80.

SMITH, A.G., HURLEY, A.M. *and* BRIDEN, J.C. 1981. *Phanerozoic paleocontinental world maps*. Cambridge, Cambridge University Press, 102 pp.

SOLOV'EV, I.A. *and* GRIKUROV, G.E. 1978. Prevye nakhodki srednekembriskikh trilobitov v khrebte Sheklton (Antarktida). [First reports of Middle Cambrian trilobites in the Shackleton Range (Antarctica).] *Antarktika*, **17**, 187–203.

SOLOV'EV, I.A. *and* GRIKUROV, G.E. 1979. Novye dannye o rasprostranenii kembriskikh trilobitov khrebtakh Ardzhetina i Sheklton. [New data about the distribution of Cambrian trilobites in the Argentina and Shackleton Ranges.] *Antarktika*, **18**, 554–73.

SOLOV'EV, I.A., POPOV, L.E. *and* SAMSONOV, V.V. 1984. Novye dannye o verkhnekembriskikh faune gor Elsnert i Pensakola (Zapadnaia Antarktida). [New data on Upper Cambrian fauna of Ellsworth and Pensacola Mountains, Antarctica.] *Antarktika*, **23**, 46–71.

SOVIET COMMITTEE ON ANTARCTIC RESEARCH. 1976. *USSR National Report No 18 to SCAR*. Moscow, Academy of Sciences of the USSR, 62 pp.

SOVIET COMMITTEE ON ANTARCTIC RESEARCH. 1977. *USSR National Report No 19 to SCAR*. Moscow, Academy of Sciences of the USSR, 66 pp.

SOVIET COMMITTEE ON ANTARCTIC RESEARCH. 1978. *USSR National Report No 20 to SCAR*. Moscow, Academy of Sciences of the USSR, 64 pp.

SOVIET COMMITTEE ON ANTARCTIC RESEARCH. 1979.*USSR National Report No 21 to SCAR*. Moscow, Academy of Sciences of the USSR, 72 pp.

SOVIET COMMITTEE ON ANTARCTIC RESEARCH. 1982. *USSR National Report No 24 to SCAR*. Moscow, Academy of Sciences of the USSR, 68 pp.

SOVIET COMMITTEE ON ANTARCTIC RESEARCH. 1983. *USSR National Report No 25 to SCAR*. Moscow, Academy of Sciences of the USSR, 72 pp.

SPAETH, G. *and* FIELITZ, W. 1991. Structural evolution of western Neuschwabenland and the Shackleton Range – a comparison. (*In* ULBRICH, H. *and* ROCHA CAMPOS, A.C. *eds. Gondwana Seven Proceedings*. São Paulo, Universidad de São Paulo, 3–18.)

SPAETH, G., HOTTEN, R., PETERS, M. *and* TECHMER, K. 1995. Mafic dykes in the Shackleton Range, Antarctica. *Polarforschung*, **63**(2/3), 101–21.

SPEAR, F.S. *and* CHENEY, J.T. 1989. A petrogenetic grid for pelitic schists in the system SiO_2-Al_2O_3-FeO-MgO-K_2O-H_2O. *Contributions to Mineralogy and Petrology*, **101**, 149–64.

STEIGER, R.H. *and* JÄGER, E. 1977. Subcommission on Geochronology: Convention on the use of decay constants in geo- and cosmochronology. *Earth and Planetary Science Letters*, **36**(3), 359–62.

STEPHENSON, P.J. 1966. Geology. 1. Theron Mountains, Shackleton Range and Whichaway Nunataks (with a section on palaeomagnetism of the dolerite intrusions by D.J. BLUNDELL). *Trans-Antarctic Expedition Scientific Reports*, No. 8, 79 pp.

TESSENSOHN, F. *and* THOMSON, M.R.A. 1990. European geological initiative for the Shackleton Range. *Antarctic Science*, **2**(3), 265–66.

THOMPSON, A.B. *and* ALGOR, J.R. 1977. Model system for anatexis of pelitic rocks. I. Theory of melting reactions in the system $KAlO_2$-$NaAlO_2.SiO_2.H_2O$. *Contributions to Mineralogy and Petrology*, **63**, 247–69.

THOMPSON, R.N., LEAT, P.T., DICKIN, A.P., MORRISON, M.A., HENDRY, G.L. *and* GIBSON, S.A. 1990. Strongly potassic mafic magmas from lithospheric mantle sources during continental extension and heating: evidence from Miocene minettes of northwest Colorado, USA. *Earth and Planetary Science Letters*, **98**, 139–53.

THOMSON, M.R.A. 1972. Inarticulate Brachiopoda from the Shackleton Range and their stratigraphical significance. *British Antarctic Survey Bulletin*, No. 31, 17–20.

TINGEY, R.J. 1992. The regional geology of Archaean and Proterozoic rocks in Antarctica: 1.2.2. Shackleton Range - Coats Land. (*In* TINGEY, R.J. *The geology of Antarctica*. Oxford, Oxford University Press, 4–10.)

UNITED STATES GEOLOGICAL SURVEY. 1983. *Shackleton Range*, Sheet SU26–30/1* (20°W–31°W). Antarctica 1:250 000 Reconnaissance Series. Washington DC, US Department of the Interior.

VIDAL, G. 1976. Late Precambrian microfossils from the Visingsö Beds in southern Sweden. *Fossils and Strata*, No. 9, 1–57.

VIDAL, G. *and* FORD, T.R. 1985. Microbiotas from the Late Proterozoic Chuar Group (Northern Arizona) and Unita Mountain Group (Utah) and their chronostratigraphic implications. *Precambrian Research*, **28**, 349–89.

VIDAL, G. *and* KNOLL, A.H. 1983. Proterozoic plankton. *Geological Society of America Bulletin*, **161**, 265–77.

WALKER, K.R., JOPLIN, G.A., LOVERING, J.F. *and* GREEN, R. 1960. Metamorphic and metasomatic convergence of basic igneous rocks and lime-magnesia sediments of the Precambrian of NW Queensland. *Journal of the Geological Society of Australia*, **6**, 149–78.

WEBER, B. 1990. Late Proterozoic microbiota from the Turnpike Bluff Group, Shackleton Range. *Geodätische und geophysikalische Veröffentlichungen*, Reihe I, **15**, 118.

WEBER, B. 1991. Microfossils in Proterozoic sediments from the southern Shackleton Range, Antarctica: a preliminary report. *Zeitschrift für Geologische Wissenschaften*, **19** (2), 185–97.

WILSON, J.L. 1975. *Carbonate facies in geologic history*. Berlin, Heidelberg, New York, Springer Verlag, 471 pp.

WOLFART, R. 1994. Middle Cambrian faunas (Brachiopoda, Mollusca, Trilobita) from exotic limestone blocks, Reilly Ridge, north Victoria Land, Antarctica: their biostratigraphic and palaeobiogeographic significance. *Geologische Jahrbuch*, Reihe B, **84**, 161 pp.

ZIEGLER, A.M. 1981. Paleozoic paleogeography. (*In* McELHINNY, M.W. *and* VALENCIO, D.A. *eds. Paleoreconstruction of the continents*. Geodynamics Series, **2**. Washington DC, American Geophysical Union, 31–37.)

Appendix 1 Summary of old and new stratigraphical terms, Shackleton Range

by J.W. Thomson

Since the original geological survey of the Shackleton Range during the Trans-Antarctic Expedition of 1957–58 (Stephenson, 1966), many separate studies of parts of the range have been undertaken by British, German and Russian scientists. The simple stratigraphical terminology adopted by Stephenson (1966) has been adapted and extended by subsequent workers (e.g. Clarkson, 1972; Grew and Halpern, 1979; Marsh, 1983*a*,*b*, 1984; Hofmann and Paech, 1983; Buggisch and others, 1990, 1994*a*) and different names have been assigned to the same rocks by scientists working independently of each other.

In 1990 an European workshop was convened to synethize the results from the different geological research programmes carried out in the Shackleton Range since 1967, and to minimize the existing duplication of stratigraphical names by formulating an agreed terminology for future use. The terminology arising from this workshop (Tessensohn and Thomson, 1990, table 1) has been adopted throughout this volume and on the accompanying geological map. It is summarized in Table A1.1.

High-grade metamorphic rocks belonging to the Stratton Group, probably the oldest rocks in the Shackleton Range, are widespread in the western and northern parts of the range, whereas the granitic orthogneisses and massive granitoids of the Read Group (possibly contemporaneous in part with the Stratton Group) are restricted to the Read Mountains in the south. The most extensive outcrops of the younger rocks, the Blaiklock Glacier Group, are in the western part of the Shackleton Range, particularly in the Otter Highlands.

Table A1.2 links the stratigraphical terms in current usage to those that had been assigned to the same or similar litholgical units in the past. Because many of the

Table A1.1. Current stratigraphical terminology for rock units in the Shackleton Range

Current name	*Age*
Blaiklock Glacier Group[1]	
Otter Highlands Formation[1,2] }	Between Cambrian and Devonian, possibly Ordovician
Mount Provender Formation[1,2] }	
[trilobite shales[1,3,4]]†	Early Middle Cambrian
Mount Wegener Formation[1]	Lower Cambrian
Wyeth Heights Formation[1]	(?) late Precambrian–Palaeozoic (Lower Cambrian)
Stephenson Bastion Formation[1]	Late Precambrian
Watts Needle Formation[5]	Late Precambrian (Riphaean–Vendian)
Pioneers Group*	Middle–late Precambrian (middle–late Proterozoic)
Read Group*	Middle Precambrian (early–middle Proterozoic)
Stratton Group*‡	Early Precambrian (Archaean–middle Proterozoic)
Mount Weston gneiss[6]	
Wedge Ridge gneiss[6]	
Fuchs Dome gneiss[7]	
Mathys gneiss[7]	
Wiggans blastomylonites[7]	
Charpentier gneiss[7]	
Stratton gneiss[6]	
Pratts Peak intrusion[6]	

Sources cited give the first substantive description(s) of these stratigraphical terms/rock groups: [1], Clarkson (1972); [2], Clarkson and Wyeth (1983); [3], Thomson (1972); [4], Solov'ev and Grikurov (1978); [5], Marsh (1983*a*); [6], Marsh (1983*b*); [7], Marsh (1984).

† Not a formally defined unit; erratic blocks which are probably of local origin.

* Term (after Tessensohn and Thomson (1990)) and rock unit described for the first time in this volume.

‡ Name changed from Haskard Group (Tessensohn and Thomson, 1990) to Stratton Group (this volume) when it was discovered that the term Haskard Group had been applied by Marsh (1984) to rocks that are now referred to the Pioneers Group.

outcrops in the Shackleton Range are isolated and the stratigraphical units have been disrupted by a complex of northward-dipping nappes (Marsh 1983*a*; Roland and others, 1988; Kleinschmidt and others, 1992), the correlation of rock units between outcrops has been difficult. Several of the formation names were given to rocks that were geographically restricted and these terms have no significance in the wider context of the range. Thus it has been decided that the variety of formation names applied to the supracrustal rocks so widespread in the northern part of the Shackleton Range (now all referred to the Pioneers Group) should be held in abeyance for the present.

Table A1.3 (modified from Marsh (1984, table 1) shows

Table A1.2. Linkage between current (bold type) and former stratigraphical terminology, Shackleton Range

Current name	*Former name(s)*
Blaiklock Glacier Group [1]	Blaiklock Beds[3]; Blaiklock Group [4]
Otter Highlands Formation[1,2]	upper group[3]
Mount Provender Formation[1,2]	lower group[3]
[trilobite shales[1,5]]*	black shales[6]; Haskard Highlands Formation[7]
	Turnpike Bluff Group[1,8]; Turnpike Metamorphics[3]
Wyeth Heights Formation[1,8]	Wyeth Heights Formation[1,8]
Stephenson Bastion Formation[1,8]	Stephenson Bastion Formation[1,8]
Mount Wegener Formation[1,8]	Mount Wegener Formation[1,8]
	Flett Craggs Formation[1,8]
Watts Needle Formation[9]	
Pioneers Group[10]	Shackleton Metamorphics[3]; Shackleton Range Metamorphic Complex [1,11]
	Skidmore Complex[12]; Skidmore Group/Skidmore-gruppe[13,14,15,16]
	Herbert Series[15,17]; Herbert Group/Herbert-gruppe[16]
	Venetz Peak sequence[17]
	Bonney Bowl sequence[17]
	Sumgin Buttress sequence[17]
	Jamieson Ridge sequence[17]
	Shaler Cliffs sequence[17]
	Haskard Group[18]
	Williams Ridge Formation[18,19]
	Hollingworth metasediments[18]
	Butterfly Formation[18]
	Schimper Group[18]
	Nostoc Lake Formation[18,19] = units (b) and (c)[20]
	Mount Gass Formation[18,19]
	Maclaren [Monolith] Formation[18]
	Bonney Formation[18]
Stratton Group†	Older gneisses of Shackleton Range Metamorphic Complex[1]
	Provender Complex[21]; Provende-Gruppe[22]
	Charpentier Series[15,21]
	Read Complex[18]; Haskard Group[10]
	Wedge Ridge schist[19]
Mount Weston gneiss[19]	Mount Weston gneiss[19]
Wedge Ridge gneiss[19]	Wedge Ridge gneiss[19]
Fuchs Dome gneiss[18]	Fuchs Dome gneiss[18]
Mathys gneiss[18]	Mathys gneiss[18]
Wiggans blastomylonites[18]	Wiggans blastomylonites[18]
Charpentier gneiss[18]	Charpentier gneiss[18]
Pratts Peak intrusion[19]	Pratts Peak intrusion[19]
Stratton gneiss[19]	Stratton gneiss[19]
	Unit (a)[20]
Read Group[10]	Shackleton Metamorphics[3]; Shackleton Range Metamorphic Complex[1] (SRMC); Older gneisses of SRMC[11]; Shackleton Crystalline Complex[13]; Basement Complex[9]; Read Gruppe[22]; Read Mountains Basement Complex[7]

Primary sources for terminology: [1], Clarkson (1972); [2], Clarkson and Wyeth (1983); [3], Stephenson (1966); [4], Grikurov and Dibner (1979); [5], Thomson (1972); [6], Solov'ev and Grikurov (1978); [7], Buggisch and others (1990); [8], Clarkson (1983); [9], Marsh (1983*a*); [10], Tessensohn and Thomson (1990); [11], Clarkson (1982*a*); [12], Kamenev and Semenov (1980); [13], Paech (1977); [14], Paech (1985); [15], Hofmann and Paech (1983); [16], Hofmann and Paech (1980); [17], Hofmann (1982); [18], Marsh (1984); [19], Marsh (1983*b*); [20], Grew and Halpern (1979); [21], Hofmann and others (1981); [22], Paech (1986).

* Not a formally defined unit; occurs only as erratic blocks.

† This volume.

the possible correlation between lithologically similar units exposed at different geographical localities in the western and central parts of northern Shackleton Range. Former names for the units (see Table A1.2) are included to show how they could be linked to the stratigraphical terms in current usage.

Table A1.3. Correlation between former stratigraphical terms and the Stratton and Pioneers groups (after Marsh, 1984); names in bold type are in current usage

Group name	*Geographical location*			
	Haskard Highlands	*Fuchs Dome*	*La Grange Nunataks*	*Herbert Mountains*
Pioneers Group				Skidmore Complex
				Herbert Series
	Haskard Group			Herbert Group
	Williams Ridge Formation		Butterfly Formation	Hollingworth metasediments
	Schimper Group			
	Nostoc Lake Formation		Present but units not defined	Maclaren Formation
	Mount Gass Formation			Bonney Formation
Stratton Group	Read Complex			
	Mount Weston gneiss	**Fuchs Dome gneiss**	**Mathys gneiss**	**Charpentier gneiss**
	Wedge Ridge gneiss		**?Wiggans blastomylonites**	
	Stratton gneiss			
	Provender Complex			Charpentier Series

Appendix 2 Geochemical analyses of selected rocks of the Pioneers Group

by N.W. Roland

Many samples of the lithological variations within the Pioneers Group have been collected over a wide geographical area (see Chapter 4). The geochemical analyses of a selection of samples are given in Tables A2.1–3 but these analyses should not be regarded necessarily as being representative of a given lithology at a particular locality.

Table A2.1. Chemical analyses of selected gneisses and schists, Pioneers Group

Sample	1	2	3	4	5	6	7	8	9	10	11	12	13	14
SiO_2	63.62	70.72	56.84	73.16	64.58	52.22	56.05	56.93	73.77	73.49	66.29	71.02	74.29	70.84
TiO_2	0.96	0.37	0.85	0.14	0.49	1.09	0.81	1.11	0.43	0.04	0.64	0.61	0.02	0.69
Al_2O_3	17.61	15.63	15.22	15.28	15.50	26.63	19.06	23.27	12.71	13.89	16.31	12.73	14.49	13.48
Fe_2O_3	7.16	2.36	7.57	2.07	3.70	10.75	7.26	5.63	2.92	0.36	4.39	5.46	0.30	4.34
MnO	0.09	0.05	0.13	0.03	0.09	0.16	0.12	0.02	0.05	0.02	0.07	0.05	0.02	0.06
MgO	2.76	0.88	4.82	0.35	2.54	0.95	4.27	1.24	0.95	0.18	1.83	2.29	<0.10	1.98
CaO	0.44	1.48	5.68	0.82	3.10	0.76	3.09	0.22	1.05	0.58	2.12	0.77	0.38	1.47
Na_2O	0.67	5.16	2.94	2.93	4.96	3.36	2.25	1.02	3.71	2.79	3.44	2.09	3.02	2.52
K_2O	4.54	1.92	3.88	3.18	2.33	1.79	4.39	7.27	2.25	7.47	3.08	2.95	6.14	2.86
P_2O_5	0.06	0.06	0.28	0.11	0.18	0.11	0.13	0.05	0.17	0.02	0.04	0.04	0.08	0.20
(SO_3)	<0.05	<0.05	0.21	<0.05	<0.05	<0.05	0.16	<0.05	0.06	<0.05	<0.05	<0.05	0.08	<0.05
LOI	1.77	1.11	1.16	1.73	2.19	1.85	2.14	2.95	1.68	0.91	1.45	1.70	0.92	1.29
Ba	696	504	1513	340	955	187	617	396	626	750	882	531	1042	291
Bi	<10	<10	<10	<10	10	<10	13	<10	<10	<10	<10	13	<10	<10
Ce	126	59	72	<35	99	149	108	100	49	<35	129	97	<35	113
Co	15	<7	24	<7	<7	12	17	14	<7	<7	18	21	<7	15
Cr	98	<7	196	<7	85	80	82	95	24	<7	45	60	<7	54
Cu	11	<10	90	<10	<10	<10	22	<10	<10	<10	10	25	<10	113
Ga	26	20	18	13	23	29	27	32	16	16	27	15	11	20
Nb	18	6	10	10	13	19	18	24	10	<5	21	13	<5	15
Ni	40	<7	54	12	50	29	49	35	20	<7	27	43	<7	29
Pb	16	18	11	24	16	151	24	<10	<10	41	24	<10	26	17
Rb	239	74	178	111	79	69	184	264	136	198	114	142	170	128
Sr	88	420	424	77	445	422	129	47	180	73	317	108	173	131
Th	32	<10	12	<10	<10	26	21	20	23	<10	32	14	<10	15
U	11	<5	11	<5	<5	<5	7	12	<5	<5	<5	8	6	<5
V	121	21	167	<10	68	104	110	139	38	<10	66	74	10	72
Y	47	<5	17	13	10	38	41	64	18	5	11	24	15	35
Zn	124	44	91	<7	63	139	127	<7	49	<7	68	30	<7	66
Zr	352	185	209	14	153	410	156	323	176	47	105	241	53	323

Gneisses and schists: 1 (HR 012) Nobleknausane; 2 (HR 015) Gallsworthyryggen; 3 (HR 017) Carterknattane; 4 (HR 018) north-west of Lindqvist Nunatak; 5 (HR 021) Freshfield Nunatak; 6 (HR 026) Lord Nunatak; 7 (HR 027) Baines Nunatak; 8 (HR 030) Jackson Tooth; 9 (HR 036) Skiltvakta; 10 (HR 038) Rileyryggen; 11 (HR 043) Lundström Knoll; 12 (HR 045) Chevreul Cliffs; 13 (HR 050) Mount Dewar; 14 (HR 053) Mummery Cliff.

Table A2.2. Chemical analyses of selected gneisses, schists and quartzites, Pioneers Group

Sample	15	16	17	18	19	20	21	22	23	24	25	26	27	28
SiO_2	55.13	42.51	59.93	51.80	57.33	60.44	65.33	75.85	96.41	89.84	82.91	78.94	97.99	94.26
TiO_2	0.73	1.22	1.43	0.94	1.00	1.23	0.78	0.10	0.09	0.21	0.27	0.16	0.03	0.07
Al_2O_3	19.20	24.68	12.99	20.16	18.94	17.39	16.44	13.14	1.44	3.46	6.04	11.15	1.02	3.50
Fe_2O_3	8.61	11.49	11.97	9.74	9.24	12.37	7.15	0.62	0.60	2.61	6.62	1.15	0.08	0.12
MnO	0.14	0.30	0.12	0.15	0.11	0.07	0.12	0.03	0.01	0.07	0.02	0.02	0.01	0.01
MgO	5.30	6.62	4.41	5.55	3.61	2.34	2.48	‹0.10	‹0.10	0.83	0.52	0.56	‹0.10	‹0.10
CaO	1.11	1.48	1.21	1.04	2.61	1.10	0.89	2.14	0.05	0.10	0.07	1.65	0.05	0.08
Na_2O	1.09	1.11	1.48	1.89	2.80	0.11	1.26	3.14	‹0.10	0.47	‹0.10	3.20	‹0.10	‹0.10
K_2O	6.07	7.59	4.75	5.51	2.51	2.46	3.32	3.58	0.51	0.56	1.82	1.96	0.15	0.96
P_2O_5	0.12	0.10	0.13	0.13	0.02	0.79	0.07	‹0.01	‹0.01	0.03	0.03	0.01	‹0.01	‹0.01
(SO_3)	0.06	0.05	‹0.05	0.15	‹0.05	‹0.05	‹0.05	‹0.05	‹0.05	‹0.05	‹0.05	‹0.05	‹0.05	‹0.05
LOI	2.16	2.46	1.16	2.64	1.51	1.37	1.86	1.09	0.63	1.63	1.47	0.98	0.58	0.79
Ba	590	991	1094	649	534	329	677	245	71	79	135	342	<50	<50
Bi	<10	<10	21	15	<10	<10	<10	<10	11	<10	<10	<10	<10	<10
Ce	91	153	213	109	105	162	114	<35	44	<35	<35	<35	44	<35
Co	42	42	34	32	30	27	24	<7	<7	<7	11	<7	<7	<7
Cr	83	132	8	97	170	114	129	<7	8	12	11	<7	33	52
Cu	<10	<10	<10	<10	41	37	18	<10	218	<10	<10	<10	<10	<10
Ga	30	45	22	33	33	25	23	24	<5	6	11	12	<5	<5
Nb	16	21	25	11	12	25	17	15	7	7	<5	10	<5	<5
Ni	49	75	29	46	80	59	50	<7	10	<7	18	<7	<7	<7
Pb	31	14	<10	24	29	<10	24	61	<10	<10	<10	23	<10	<10
Rb	263	360	245	262	121	203	197	222	19	29	81	72	10	27
Sr	128	103	42	135	104	44	98	489	6	21	10	84	7	<5
Th	18	25	38	18	14	27	20	151	<10	<10	12	14	<10	<10
U	<5	<5	<5	<5	<5	<5	8	20	<5	<5	5	<5	<5	17
V	140	177	302	164	179	192	137	<10	<10	24	50	15	<10	19
Y	24	29	67	28	39	68	33	11	5	11	16	6	10	<5
Zn	135	189	227	144	202	105	96	9	<7	11	<7	14	<7	<7
Zr	130	203	309	168	207	379	174	114	100	181	153	164	28	48

Gneisses and schists: 15 (HR 062) east of Blanchard Hill; 16 (HR 064) Blanchard Hill; 17 (HR 068b) Meade Nunatak (south); 18 (HR 072) M'Clintock Bastion; 19 (HR 076b) Meade Nunatak; 20 (HR 205) Jamieson Ridge; 21 (HR 221) Lewis Chain.

Quartzites: 22 (HR 010) Lindqvist Nunatak; 23 (HR 019) Bergan Castle; 24 (HR 022) north-east of Freshfield Nunatak; 25 (HR 031) Jackson Tooth; 26 (HR 037) Rileyryggen; 27 (HR 041) Sauria Buttress; 28 (HR 048) Mount Dewar.

Table A2.3. Chemical analyses of selected acid volcanic gneisses, amphibolites and metacarbonate rocks, Pioneers Group

Sample	29	30	31	32	33	34	35	36	37	38	39	40	41	42
SiO_2	73.00	70.94	70.91	49.35	45.41	47.35	48.59	48.86	50.81	6.53	21.25	46.80	1.63	39.39
TiO_2	0.43	0.46	0.51	0.81	1.59	1.68	0.37	1.59	0.76	0.01	0.01	0.04	0.02	0.06
Al_2O_3	12.16	12.08	11.68	14.31	11.28	13.75	15.44	13.54	13.86	0.04	0.07	0.67	0.25	1.24
Fe_2O_3	4.06	5.05	5.72	9.99	12.37	15.68	10.03	14.59	10.60	0.23	0.18	0.27	0.13	1.05
MnO	0.08	0.09	0.09	0.16	0.16	0.22	0.18	0.22	0.16	0.03	0.02	0.01	0.01	0.03
MgO	1.11	0.44	0.56	9.92	15.35	7.22	9.99	6.78	7.54	20.81	22.97	15.75	21.59	11.32
CaO	2.58	1.86	1.92	9.94	9.95	10.67	10.08	8.79	10.65	30.43	25.69	21.55	30.22	26.36
Na_2O	2.66	3.17	2.94	1.67	2.27	1.46	2.07	1.77	3.52	<0.10	<0.10	<0.10	<0.10	<0.10
K_2O	2.35	4.40	3.98	1.67	0.17	0.44	1.50	2.29	0.89	0.02	0.01	0.16	0.11	0.08
P_2O_5	0.10	0.10	0.12	0.43	0.15	0.15	<0.01	0.13	0.08	0.06	0.02	0.14	0.06	0.02
(SO_3)	0.08	<0.05	<0.05	0.09	<0.05	0.17	0.13	<0.05	<0.05	0.07	0.16	0.11	0.23	0.08
LOI	0.97	0.99	1.13	1.17	0.90	0.98	1.36	1.12	0.88	41.77	29.49	14.30	45.96	20.31
Ba	1443	1282	1248	1044	81	<50	155	512	125	<50	88	<50	53	<50
Bi	<10	11	<10	17	<10	<10	12	<10	<10	<10	<10	<10	<10	<10
Ce	188	227	255	88	49	<35	52	37	<35	<35	<35	<35	<35	<35
Co	<7	<7	<7	62	69	55	55	53	51	<7	<7	<7	<7	<7
Cr	<7	<7	<7	717	993	280	402	65	32	<7	<7	<7	<7	<7
Cu	<10	<10	<10	45	78	33	<10	72	<10	<10	<10	<10	<10	<10
Ga	16	23	21	15	14	15	17	17	17	<5	<5	<5	<5	<5
Nb	33	44	36	11	12	7	10	8	12	<5	7	5	6	9
Ni	7	<7	8	199	581	91	195	50	98	<7	<7	<7	<7	<7
Pb	22	36	32	<10	<10	<10	<10	19	20	<10	<10	11	<10	<10
Rb	97	140	126	101	7	7	81	62	16	<5	5	7	7	7
Sr	128	67	71	1083	339	127	116	95	144	60	52	58	39	76
Th	42	30	30	<10	25	11	<10	14	14	<10	<10	<10	<10	12
U	<5	<5	6	14	<5	<5	<5	<5	6	9	<5	6	<5	<5
V	65	13	<10	246	233	404	165	379	252	<10	<10	18	<10	24
Y	91	109	114	12	18	36	7	40	32	<5	<5	<5	<5	13
Zn	89	119	117	72	85	104	83	104	101	<7	16	26	<7	16
Zr	824	773	875	113	110	102	27	92	73	8	6	17	<5	16

Acid volcanic gneisses: 29 (HR 065) Meade Nunatak; 30 (HR 170) Hollingworth Cliffs; 31 (HR 171) Mount Beney.

Amphibolites: 32 (HR 009) Lindqvist Nunatak.; 33 (HR 023) Lord Nunatak; 34 (HR 039) Rileyryggen; 35 (HR 049) Mount Dewar; 36 (HR 066) Meade Nunatak; 37 (HR 172) Mount Beney.

Marbles, metalimestones, etc.: 38 (HR 029) Jackson Tooth; 39 (HR 044) Chevreul Cliffs; 40 (HR 051) Aronson Corner; 41 (HR 054) Weissenstein; 42 (HR 056) Whymper Spur.

Appendix 3 Geochemical analyses of mafic dykes from the Shackleton Range

by K.S. Techmer and P.T. Leat

Geochemical analyses of a selection of mafic dykes from different parts of the Shackleton Range are given in Tables A3.1–3. Samples with the prefix 'Z' were analysed by standard XRF procedures and published by Clarkson (1981). Other samples were analysed at the Geochemisches Institut, Göttingen, by the methods described in Chapter 11 (Table 11.1). A location map for the samples analysed is given in Fig. A3.1.

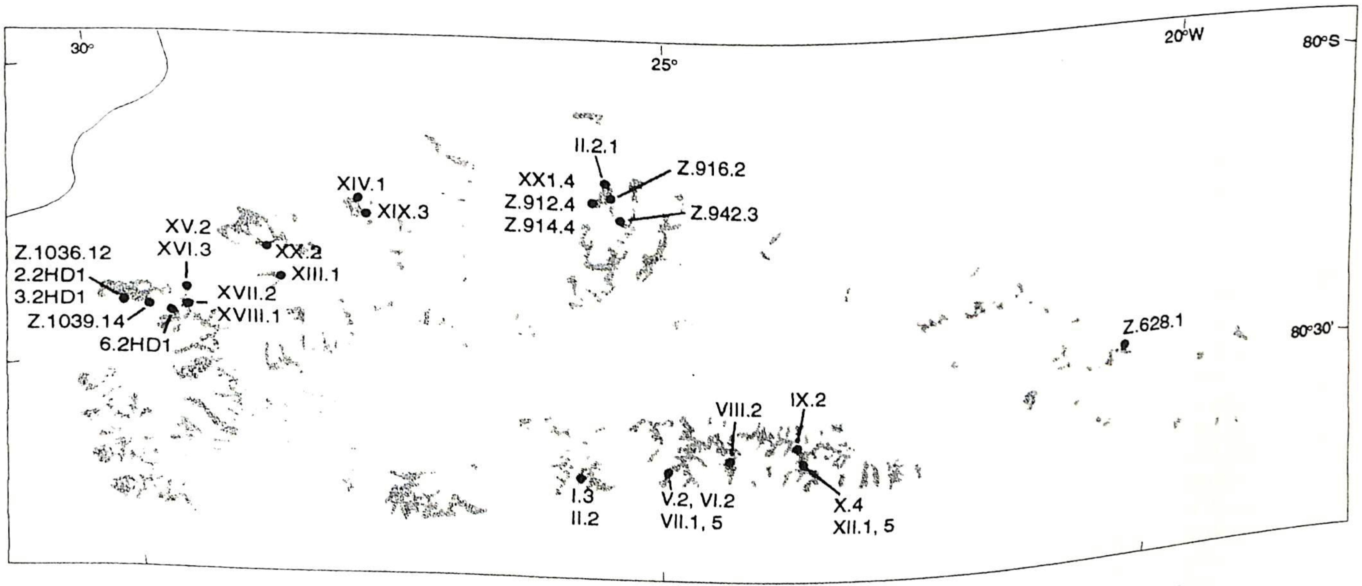

Fig. A3.1. Sketch map of the Shackleton Range showing the location of the mafic dykes analysed in Tables A3.1–3.

Table A3.1. Chemical analyses (wt.%, ppm) of mafic dykes, southern Shackleton Range (Read Mountains)

Sample	I.3	II.2	V.2	VI.2	VII.1	VII.5	VIII.2	IX.2	X.4	XII.1	XII.5
Group[1]	IV	V	V	V	IV	IV	IV	IV	IV	IV	IV
SiO_2	49.7	46.9	44.8	45.2	48.0	48.6	49.3	49.5	49.5	49.6	47.8
TiO_2	1.20	2.84	3.23	3.30	1.19	1.22	2.36	1.96	1.92	1.88	2.04
Al_2O_3	14.59	13.52	14.72	14.38	14.77	14.91	12.95	12.88	13.01	13.31	13.18
Fe_2O_3	3.41	4.01	5.22	3.56	3.08	3.09	4.64	3.55	4.06	4.30	4.86
FeO	7.65	10.00	10.21	11.60	7.91	7.48	10.06	10.66	10.00	9.06	8.92
MnO	0.19	0.24	0.22	0.22	0.18	0.19	0.26	0.24	0.24	0.24	0.48
MgO	7.95	6.43	5.83	5.75	8.54	7.96	5.82	5.89	6.00	6.54	6.57
CaO	10.92	9.70	9.04	8.86	11.14	11.31	10.65	10.69	10.30	10.93	10.22
Na_2O	2.22	2.31	2.81	2.74	2.11	1.87	2.13	2.33	2.50	2.33	3.09
K_2O	0.54	0.86	1.30	1.99	0.56	0.73	0.78	0.60	0.91	0.79	0.96
P_2O_5	0.10	0.36	0.57	0.62	0.09	0.10	0.23	0.19	0.18	0.16	0.14
CO_2	0.58	0.95	0.37	0.89	1.11	0.72	0.64	1.36	0.31	0.92	0.26
H_2O	1.49	3.09	2.28	2.19	2.87	2.75	1.58	2.25	2.29	1.36	2.27
S(ppm)	710	2260	690	1500	840	940	1150	1410	190	1260	570
Total	100.61	101.44	100.67	101.47	101.63	101.02	101.52	102.24	101.24	101.51	100.85
ΣFe_2O_3	11.91	15.12	16.57	16.45	11.87	11.40	15.83	15.40	15.17	14.37	14.77
Li	17	10	25	26	20	23.5	8	10	17	18	20
Sc	41	37	27	28	38	38	46	48	46	44	45
Cr	131	79	127	116	236	236	65	75	84	114	120
Co	45	43	45	51	49	47	49	51	46	48	47
Ni	118	38.5	92	93	151	145	60.5	63	64	80	81
Rb	30	33	40	71	37.5	48.5	49	21	49.5	47	56
Sr	167	215	370	370	170	187	183	146	160	170	200
Y	15	24	25	26	14	15	28	32	28	24	20
Zr	81	170	192	216	90	93	155	145	144	124	107
Nb	<8	12	20	16	<8	<8	11	<8	<8	<8	10
Cs	1.2	3.8	2.3	5.1	0.81	1.1	6.0	1.1	1.7	1.1	1.6
Ba	75	233	620	685	73	110	118	125	170	196	228
La	6.3	19.6	29.6	30.2	7.4	6.6	16.3	13.7	12.3	9.8	7.7
Ce	14.3	41.3	61.5	61	16.2	15.5	42.1	28.3	24	22.4	15
Sm	3.0	6.4	8.4	8.5	3.3	2.8	6.2	5.6	5.0	4.3	3.4
Eu	0.96	2.28	2.6	2.6	1.0	1.0	2.0	1.8	1.6	1.4	1.15
Tb	0.52	1.0	1.3	1.5	0.76	0.54	1.4	1.5	1.1	0.9	0.7
Yb	1.9	2.3	2.85	3.1	1.8	1.7	3.4	3.6	3.5	2.4	1.9
Lu	0.31	0.36	0.44	0.5	0.28	0.25	0.48	0.49	0.55	0.36	0.27
Hf	1.57	4.2	5.4	5.4	3.1	1.9	5	5.6	3.8	2.1	2.5
Ta	0.36	1.1	1.3	1.2	0.42	0.43	1.1	0.69	0.6	0.65	0.6
Th	1.3	2.0	2.6	3.5	1.6	0.7	3.1	3.9	3.8	n.d.	3.0
La/Nb		1.63	1.48	1.89			1.48				0.77
La/Yb	3.32	8.52	10.4	9.74	4.11	3.88	4.79	3.81	3.51	4.01	4.05
CIPW norm											
Q	1.63	6.82	0.00	0.00	0.00	1.23	4.85	4.28	1.91	3.22	0.00
Or	3.19	5.08	7.68	11.76	3.31	4.31	4.61	3.55	5.38	4.67	5.67
Ab	18.79	19.55	23.78	23.19	17.85	15.82	18.02	19.72	21.16	19.72	26.15
An	28.25	23.98	23.71	21.06	29.18	30.13	23.47	22.91	21.59	23.53	19.26
Di	17.48	12.29	12.30	10.91	14.96	16.80	19.54	16.75	21.68	19.44	23.52
Hy	20.94	10.32	6.79	3.57	22.73	21.22	16.12	20.24	16.56	17.23	4.87
Ol	0.00	0.00	8.18	13.73	1.19	0.00	0.00	0.00	0.00	0.00	7.22
Mt	4.94	5.48	7.57	5.16	4.47	4.48	6.73	5.15	5.89	6.23	7.05
Il	2.28	5.39	6.13	6.27	2.26	2.32	4.48	3.72	3.65	3.57	3.87
Ap	0.23	0.83	1.32	1.44	0.21	0.23	0.53	0.44	0.42	0.37	0.32
Cc	1.32	2.16	0.84	2.02	2.52	1.64	1.46	3.09	0.71	2.09	0.59

[1] Groups follow those of Hotten (1993), as modified in Chapter 11.

Table A3.2. Chemical analyses (wt-%, ppm) of mafic dykes, northern Shackleton Range (Haskard Highlands and La Grange Nunataks)

	Haskard Highlands									La Grange Nunataks	
Sample	XV.2	XVI.3	XVII.2	XVIII.1	6.2HD1	6.2HD2	3.2HD1	Z.1036.12	Z.1039.14	XIII.1	XIV.1
Group[1]	HAIII	HAIII	HAIII	HAIII	HAIII	HAIII	HAII	HAII	HAII	II	I
SiO_2	46.40	46.50	47.20	47.10	47.00	46.50	48.80	49.18	49.07	49.60	51.50
TiO_2	2.55	2.51	2.63	2.53	2.49	2.59	2.35	2.43	2.49	3.21	0.93
Al_2O_3	14.68	14.84	14.89	15.10	15.14	15.10	14.65	13.07	12.94	13.14	15.30
Fe_2O_3	3.22	2.58	2.38	3.07	3.55	3.01	4.88	6.41	6.35	3.43	2.64
FeO	10.76	11.12	11.36	10.39	10.21	10.77	7.14	6.34	6.65	10.10	7.94
MnO	0.21	0.21	0.22	0.21	0.20	0.21	0.18	0.23	0.26	0.20	0.17
MgO	6.45	6.47	6.35	6.65	6.34	6.26	5.34	5.85	6.38	4.52	6.82
CaO	9.30	9.15	9.31	9.31	9.20	9.33	7.81	7.92	7.53	8.25	10.25
Na_2O	2.75	2.85	2.86	2.78	2.76	2.85	2.21	3.04	3.62	2.55	2.22
K_2O	1.00	1.01	1.00	0.94	1.03	1.03	1.57	2.17	1.09	2.26	0.93
P_2O_3	0.50	0.48	0.51	0.49	0.47	0.50	0.97	0.99	1.05	1.43	0.15
CO_2	0.92	1.60	0.31	0.43	0.54	0.46	0.58	-	-	0.08	0.11
H_2O	2.04	1.39	1.76	2.19	1.77	1.89	2.53	2.23	2.31	1.53	1.73
S (ppm)	1380	1250	1350	1400	1500	1200	1830	-	-	1090	390
Total	100.92	100.84	100.92	101.33	100.85	100.62	99.19	99.86	99.74	100.41	100.73
ΣFe_2O_3	15.17	14.93	15.00	14.69	14.90	14.98	11.46	13.46	13.74	14.65	11.46
Li	8	6	9.5	13	7.3	6.2	16	-	-	19	8
Sc	35	33	35	34	34	34	33	-	-	34	38
Cr	93	79	88	83	90	85	61	61	50	42	170
Co	47	45	46	46	46	45	30	-	-	30	43
Ni	35	34	37	33.5	35.5	31	23	27	21	8	92
Rb	28	23	27	25	26	24	43	62	33	51	31
Sr	310	270	320	290	320	280	930	865	1104	470	180
Y	41	38	42	39	38	41	33	35	38	81	22
Zr	206	200	219	206	205	219	220	217	208	399	126
Nb	10	<8	11	10	8	9	37	36	42	17	<8
Cs	7.2	3.5	2.0	3.6	2.1	2.4	2.6	-	-	1.0	0.7
Ba	520	540	550	540	580	550	2000	1425	1928	1120	190
La	26.0	24.4	25.7	23.7	24.1	24.8	81.0	89	94	64	10.4
Ce	46.3	51.3	50.8	47	48.4	50.6	150	132	143	140	17
Sm	7.5	7.8	8.8	7.3	7.7	8.3	11.0	-	-	17.3	3.4
Eu	2.5	2.4	2.5	2.4	2.4	2.6	3.1	-	-	4.2	1.1
Tb	1.30	1.50	1.24	1.35	1.38	1.74	1.25	-	-	2.5	0.74
Yb	3.9	4.0	3.9	4.2	3.9	4.4	3.2	-	-	6.0	2.7
Lu	0.50	0.54	0.54	0.7	n.d.	0.68	0.47	-	-	1.0	0.39
Hf	4.8	6.4	4.9	5.14	5.4	5.2	5.3	-	-	10	2.5
Ta	0.65	0.57	0.62	0.62	0.55	0.58	2.00	-	-	1.46	0.32
Th	2.1	2.4	2.0	2.60	2.0	3.0	12.0	10	13	3.99	1.5
La/Nb	2.60		2.34	2.37	3.01	2.76	2.19	2.47	2.24	3.77	3.85
La/Yb	6.67	6.10	6.59	5.64	6.18	5.64	25.3			10.7	
CIPW norms											
Q	0.00	0.00	0.00	0.00	0.00	0.00	7.76	2.68	2.70	3.92	2.88
Or	5.91	5.97	5.91	5.56	6.09	6.09	9.28	13.11	6.60	13.36	5.5
Ab	23.27	24.12	24.20	23.52	23.36	24.12	18.70	26.29	31.36	21.58	18.79
An	24.76	24.72	24.84	25.95	25.88	25.37	25.42	15.96	16.22	17.73	29.04
Di	10.11	6.13	13.26	11.75	10.89	12.14	2.68	14.41	12.52	11.04	16.44
Hy	15.24	18.25	10.08	13.51	15.09	9.49	17.54	10.90	13.75	16.58	20.13
Ol	6.69	6.89	10.40	7.35	5.44	9.92	0.00	0.00	0.00	0.00	0.00
Mt	4.67	3.74	3.45	4.45	5.15	4.36	2.42	9.50	9.43	4.97	3.83
Il	4.84	4.77	5.00	4.81	4.73	4.92	1.39	4.72	4.84	6.10	1.77
Ap	1.16	1.11	1.18	1.14	1.09	1.16	0.37	2.40	2.54	3.31	0.35
Cc	2.09	5.91	0.71	0.98	1.23	1.05	0.32	0.00	0.00	0.18	0.25

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[1] Groups follow those of Hotten (1993), as modified in Chapter 11.

Table A3.3. Chemical analyses (wt.%, ppm) of mafic dykes, northern Shackleton Range (La Grange Nunataks, Herbert Mountains and Pioneers Escarpment)

	La Grange Nunataks				Herbert Mountains					Pioneers Escarpment
Sample	XIX.3	XX.2	2.2HD1	XXI.4	11.2.1	Z.912.4	Z.914.4	Z.916.2	Z.942.3	Z.628.1
Group[1]	I	I	I	II	II	II	II	II	II	II
SiO_2	51.60	51.20	51.40	50.40	53.70	48.87	48.97	51.29	47.93	50.12
TiO_2	0.94	0.74	0.73	3.20	0.85	3.48	3.62	3.01	4.13	3.39
Al_2O_3	15.69	15.91	15.91	13.09	17.28	10.12	10.38	11.20	9.98	12.18
Fe_2O_3	3.14	1.64	1.67	4.60	0.64	7.00	6.04	5.46	7.57	8.99
FeO	7.47	7.24	7.02	8.17	6.39	9.60	10.39	7.64	8.20	6.30
MnO	0.17	0.15	0.15	0.20	0.12	0.28	0.27	0.21	0.25	0.28
MgO	6.50	8.74	8.77	4.35	5.07	4.65	4.88	5.11	6.44	4.36
CaO	10.63	10.10	10.00	8.20	6.38	7.18	7.15	7.01	8.00	7.22
Na_2O	2.21	1.73	1.82	2.53	3.50	1.95	1.96	2.05	1.61	2.62
K_2O	0.83	0.74	0.78	2.34	2.97	2.86	2.73	2.68	1.89	2.97
P_2O_3	0.15	0.16	0.16	1.36	0.74	1.75	1.66	1.33	0.93	1.11
CO_2	0.13	0.12	0.14	0.12	0.28	-	-	-	-	-
H_2O	1.48	1.67	1.71	2.40	1.77	2.50	2.15	2.21	2.62	1.40
S (ppm)	220	270	270	840	500	-	-	-	-	-
Total	100.96	100.17	100.29	101.04	99.74	100.24	100.20	99.24	99.55	100.94
ΣFe_2O_3	11.44	9.68	9.47	13.68	7.74	17.67	17.59	13.95	16.68	15.99
Li	7	10.5	10	15	26	-	-	-	-	-
Sc	37	39	40	33	17	-	-	-	-	-
Cr	173	659	638	26	60	n.d	5	19	56	1
Co	42	38	38	25	27	-	-	-	-	-
Ni	78	68	70	10	34	4	8	5	27	7
Rb	24	25	22	56	78	63	54	66	37	37
Sr	170	140	140	320	1210	430	398	369	429	517
Y	23	20	21	79	11	97	93	79	72	79
Zr	123	121	117	363	152	721	637	486	475	731
Nb	<8	<8	<8	19	<8	32	28	25	24	33
Cs	0.1	2.3	2.1	0.27	1.7	-	-	-	-	-
Ba	180	150	170	1230	1500	1738	1646	1468	1170	1570
La	11.6	10.1	10.4	70.7	81.8	120	108	90	91	152
Ce	19.9	19.6	16.4	153	153	191	174	146	126	239
Sm	4.3	3.2	3.3	19.2	8.9	-	-	-	-	-
Eu	1.1	0.98	1.1	4.3	2.1	-	-	-	-	-
Tb	1.09	0.59	0.71	2.84	0.79	-	-	-	-	-
Yb	3.0	2.4	2.4	6.2	1.5	-	-	-	-	-
Lu	0.45	0.41	0.42	0.94	0.24	-	-	-	-	-
Hf	6.3	2.6	2.7	13.9	5.2	-	-	-	-	-
Ta	0.35	0.31	0.27	1.44	0.39	-	-	-	-	-
Th	2.6	1.68	1.8	6.4	12.8	9	6	5	3	6
La/Nb				3.72		3.75	3.86	3.60	3.79	4.61
La/Yb	3.87	4.21	4.33	11.40	54.5					
CIPW norms										
Q	3.80	2.61	2.52	6.90	0.00	9.20	7.96	10.89	10.44	7.97
Or	4.91	4.37	4.61	13.83	17.55	17.24	16.44	16.29	11.50	17.59
Ab	18.70	14.64	15.40	21.41	29.62	16.83	16.90	17.84	14.03	22.21
An	30.44	33.46	32.94	17.45	22.67	10.62	11.68	13.83	14.85	12.73
Di	16.69	12.02	11.93	11.06	1.96	11.82	11.36	10.80	15.92	12.75
Hy	17.94	26.94	26.65	11.74	19.99	12.81	15.60	12.98	11.53	4.97
Ol	0.00	0.00	0.00	0.00	1.25	0.00	0.00	0.00	0.00	0.00
Mt	4.55	2.38	2.42	6.67	0.93	10.35	8.92	8.14	11.30	11.42
Il	1.79	1.41	1.39	6.08	1.61	6.74	7.01	5.88	8.08	6.45
Ap	0.35	0.37	0.37	3.15	1.71	4.23	4.00	3.24	2.27	2.63
Cc	0.30	0.27	0.32	0.27	0.64	0.00	0.00	0.00	0.00	0.00

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[1] Groups follow those of Hotten (1993), as modified in Chapter 11.

Appendix 4 Gazetteer of the Shackleton Range

by S. King

The gazetteer below includes all place-names referred to in this volume, and also all features within the map area (80°–81°S, 19°–31°W) that have been named officially by the relevant authorities of Germany, Norway, Russia and the UK. The place-names in this composite gazetteer are as published in the original gazetteers (see references) and their listing below does not necessarily imply acceptance by all Antarctic Treaty Contracting Parties.

Argentina Range	82°20'S 42°00'W
Absalom, Mount	80°24'S 25°24'W
ANARE Mountains	70°55'S 166°00'E
Anastasa Mikojana, Skal	80°32'S 20°30'W
Angelinoj, Pik	80°42'S 22°40'W
Ark, The	80°43'S 24°47'W
Arkell Cirque	80°42'S 24°08'W
Aronson Corner	80°29'S 20°56'W
Baines Nunatak	80°19'S 23°58'W
Baltijskil, Kupol	80°37'S 25°02'W
Beche Blade	80°43'S 24°19'W
Berkner Island	79°30'S 47°30'W
Belgrano I (Argentina)	77°58'S 38°48'W - station destroyed
Belosnežka, Gora	80°35'S 30°10'W
Beney, Mount	80°16'S 27°45'W
Bergan Castle	80°36'S 21°22'W
Bernhardi Heights	80°20'S 25°00'W
Blaiklock Glacier	80°35'S 29°40'W
Blanchard Hill	80°26'S 21°56'W
Bol'šakova, Gora	80°18'S 25°23'W
Bonney Bowl	80°22'S 25°36'W
Bowen Cirque	80°43'S 23°27'W
Brjusova, Nunataki	80°39'S 28°32'W
Brunt Ice Shelf	74°45'S 22°30'W
Bubnoffnunatakker	80°43'S 23°46'W
Butterfly Knoll	80°21'S 28°09'W
Caird Coast	75°25'S 20°00'W to 76° 40'S 28°20'W
Carterknattane	80°40'S 19°05'W
Charlesworth Cliffs	80°14'S 25°18'W
Charpentier Pyramid	80°16'S 25°37'W
Chevreul Cliffs	80°32'S 20°36'W
Clarkson Cliffs	80°28'S 27°04'W
Clayton Ramparts	80°44'S 27°25'W
Coats Land	South of Luitpold and Caird coasts, north of 82°S and west of 20°W.
Cornwall Glacier	80°44'S 26°30'W
Crossover Pass	80°38'S 26°30'W
Deržavina, Lednik	80°35'S 28°28'W
Dewar, Mount	80°32'S 21°11'W
Dragons Back, The	80°23S 28°33'W
Dronning Maud Land	Between 20°00'W and 44°38'E
Družnaja 1 (Russia)	77°34'S 40°13'W - abandoned station
Du Toit Nunataks	80°44'S 25°50'W
East Antarctica	The major region of Antarctica lying on the Indian Ocean side of the Transantarctic Mountains.
Ellsworth Mountains	78°45'S 85°00'W
Enderby Land	Land between 44°38'E and 59°34'E
Eskola Cirque	80°43'S 23°49'W
Etchells, Mount	80°18'S 28°21'W
Filchner Ice Shelf	Between Coats Land and Berkner Island westward to 50°W.
Flat Top	80°27'S 28°23'W
Flett Crags	80°39'S 23°35'W
Folkertssee	80°16'S 28°47'W
Freshfield Nunatak	80°28'S 24°53'W
Fuchs Dome	80°36'S 27°50'W
Gallsworthyryggen	80°40'S 19°25'W
Gass, Mount	80°27'S 29°30'W
Gavrilova, Gora	80°23'S 29°40'W
Geikie Nunatak	80°24'S 25°52'W
Gelnhausental	80°45'S 27°00'W
Genghis Hills	80°44'S 28°02'W
Glen Glacier	80°42'S 25°20'W
Goldschmidt Cirque	80°44'S 22°48'W
Gordon Glacier	80°25'S 26°10'W
Greenfield, Mount	80°46'S 27°36'W
Grigor'eva, Utës	80°37'S 29°30'W
Gureviča, Nunataki	80°39'S 19°48'W
Guyatt Ridge	80°38'S 29°27'W
Halley (UK)	75°35'S 26°19'W - permanent station
Harold Byrd Mountains	85°26'S 146°30'W
Haskard Highlands	80°30'S 29°15'W
Haslop, Mount	80°36'S 30°16'W
Hatch Plain	80°44'S 25°43'W
Herbert Mountains	80°20'S 25°30'W
Höflegletscher	80°20'S 27°10'W
Högbom Outcrops	80°15'S 24°52'W
Hollingworth Cliffs	80°26'S 25°33'W
Holmes Summit	80°40'S 24°40'W
Homard, Mount	80°40'S 29°50'W
Honnywill Peak	80°31'S 29°08'W
Horlick Mountains	85°23'S 121°00'W
Il'jušina, Gora	80°31'S 19°11'W
Jackson Tooth	80°25'S 23°16'W
Jamieson Ridge	80°27'S 25°53'W
Južnye, Skaly	80°44'S 25°39'W
Karbyševa, Gora	80°30'S 28°09'W
Kelsey, Mount	80°27'S 22°19'W
Kendall Basin	80°15'S 25°39'W
Kol'cova Nunataki	80°34'S 28°30'W
Köppengletscher	80°18'S 28°00'W
Kraulberga	73°10'S 13°45'W
Krebsnunatak	80°38'S 24°02'W
Kuno Cirque	80°41'S 24°55'W
La Grange Nunataks	80°18'S 27°50'W
Lapworth Cirque	80°44'S 23°08'W

Lavočkina, Gora	80°32'S 19°35'W
Leskova, Obryv	80°30'S 28°22'W
Lewis Chain	80°23'S 26°50'W
Lindqvist Nunatak	80°39'S 20°38'W
Lister Heights	80°31'S 28°35'W
Lord Nunatak	80°21'S 24°01'W
Lowe, Mount	80°33'S 30°16'W
Luitpold Coast	Between Caird Coast and the eastward edge of Filchner Ice Shelf
Lundström Knoll	80°31'S 20°25'W
Lundströmsee	80°27'S 29°29'W
M'Clintock Bastion	80°28'S 22°28'W
Maclaren Monolith	80°20'S 25°23'W
MacQuarrie Edge	80°32'S 30°03'W
Majkova, Obryv	80°30'S 28°30'W
Mantell Screes	80°38'S 24°26'W
Markova, Gora	80°43'S 27°25'W
Mathys Bank	80°19'S 28°30'W
McMurdo Sound	77°30'S 165°00'E
Meade Nunatak	80°23'S 21°58'W
Morris Hills	80°22'S 27°26'W
Mummery Cliff	80°27'S 21°23'W
Murchison Cirque	80°42'S 24°33'W
Nekrasova, Utësy	80°28'S 27°45'W
Neptune Range	83°40'S 56°00'W
Nicol Crags	80°44'S 24°05'W
Niggli Nunataks	80°38'S 23°20'W
Nobleknausane	80°40'S 19°45'W
Nostoc Lake	80°24'S 30°05'W
Novatorov, Otrog	80°43'S 23°00'W
Oleschnunatak	80°26'S 21°41'W
Otter Highlands	80°38'S 30°00'W
Pensacola Mountains	83°45'S 55°00'W
Petersen Peak	80°27'S 27°57'W
Petljakova, Nunatak	80°39'S 19°23'W
Pioneers Escarpment	80°28'S 21°50'W
Pivot, Mount	80°41'S 30°10'W
Pjatnenkova, Pik	80°43'S 24°45'W
Pleščeeva, Pik	80°19'S 28°35'w
Pointer Nunatak	80°37'S 29°00'W
Poldervaart Edge	80°44'S 25°57'W
Polonskogo, Gora	80°21'S 28°15'W
Pratts Peak	80°25'S 29°22'W
Provender, Mount	80°23'S 29°55'W
Ram Bow Bluff	80°47'S 26°43'W
Ramsay Wedge	80°26'S 25°43'W
Read Mountains	80°42'S 24°15'W
Recovery Glacier	81°10'S 25°30'W
Reilly Ridge	71°32'S 163°18'E
Rileyryggen	80°35'S 19°35'W
Rogers, Mount	80°33'S 29°26'W
Sauria Buttress	80°32'S 20°24'W
Schimper Glacier	80°20'S 25°12'W
Ščuseva, Gora	80°38'S 25°06'W
Sergienko, Gora	80°38'S 29°24'W

Shackleton Range	80°30'S 25°00'W
Shaler Cliffs	80°17'S 25°29'W
Sheffield, Mount	80°10'S 25°42'W
Shotton Snowfield	80°35'S 23°40'W
Skidmore, Mount	80°19'S 28°57'W
Skiltvakta	80°30'S 19°15'W
Slessor Glacier	79°50'S 26°00'W
Solov'ëva, Nunataki	80°16'S 27°00'W
South Pole	90°00'S
Spath Crest	80°39'S 26°12'W
Stahanova, Gora	80°43'S 23°02'W
Stephenson Bastion	80°46'S 27°12'W
Strachey Stump	80°41'S 23°10'W
Stratton Glacier	80°25'S 28°50'W
Sumgin Buttress	80°18'S 25°44'W
Swinnerton Ledge	80°43'S 22°28'W
Šolohova, Gora	80°39'S 23°55'W
Theron Mountains	79°02'S 28°05'W
Tjutčeva, Nunataki	80°37'S 28°15'W
Touchdown Hills	78°20'S 35°01'W
Transantarctic Mountains	Transcontinental mountain range which extends from Victoria Land to the Pensacola Mountains.
Trey Peaks	80°36'S 28°52'W
True Hills	80°13'S 26°51'W
Trueman Terraces	80°43'S 22°41'W
Turnpike Bluff	80°44'S 30°04'W
Vahsel Bay	77°49'S 35°10'W
Venetz Peak	80°23'S 25°30'W
Vestfjella	73°35'S 14°30'W
Victoria Land	That part of Antarctica lying to the west of the Ross Sea, and extending from 70°30'S to 78°00'S
Vindberget	80°30'S 19°15'W
Voejkova, Gora	80°22'S 25°10'W
Warden Pass	80°28'S 28°20'W
Watts Needle	80°44'S 24°59'W
Weddell Sea	72°00'S 45°00'W
Wedge Ridge	80°38'S 29°12'W
Wegener, Mount	80°44'S 23°31'W
Weissenstein	80°26'S 21°24'W
West Antarctica	The minor region of Antarctica lying on the Pacific Ocean side of the Transantarctic Mountains.
Weston, Mount	80°28'S 29°10'W
Whichaway Nunataks	81°33'S 28°26'W
Whymper Spur	80°25'S 21°29'W
Wiggans Hills	80°11'S 27°03'W
Williams Ridge	80°30'S 29°20'W
Wyeth Heights	80°45'S 29°33'W
Zavrajskogo, Gora	80°38'S 29°05'W
Zelënoe, Ozero	80°28'S 29°31'W
Zittel Cliffs	80°40'S 25°59'W

REFERENCES

ANENBERG, L.I., SAVINA, T.V. and MAKEEVOI, L.C., compilers. 1987. *Slovar' geograficheskikh nazvanii Antarktiki* [*Dictionary of geographical names of the Antarctic*]. Moscow, Tsniigaik, 406 pp.

HATTERSLEY-SMITH, G. 1991. The history of place-names in the British Antarctic Territory. Parts 1 and II. *British Antarctic Survey Scientific Reports*, No. 113, 670 pp.

HATTERSLEY-SMITH, G. and ROBERTS, A., compilers. 1993. *Gazetteer of the Antarctic*. London, Her Majesty's Stationery Office, 45 pp.

HELLE, G. 1992. *Preliminary lists of Norwegian place-names of Bouvetøya, Dronning Maud Land, Peter I Øy*. Bærum, Norsk Polarinstitutt, 36 pp.

SIEVERS, J. 1993. *Nachrichten aus dem Karten- und Vermessungswesen* [*Index of German-language Antarctic place-names*], 2nd edn. Frankfurt am Main, Institut für Angewandte Geodäsie, 30 pp.

UNITED STATES, DEPARTMENT OF THE INTERIOR. 1989. *Gazetteer of the Antarctic. Names approved by the United States Board of Geographic Names*. Washington, DC, National Science Foundation, 145 pp.

Appendix 5 Acronyms & abbreviations

by S. King

AES	Atomic emission spectrometry
AWI	Alfred-Wegener-Institut
BAS	British Antarctic Survey
BGG	Blaicklock Glacier Group
BGR	Bundesanstalt für Geowissenschaften und Rohstoffe
BIF	Banded iron formation
BVAC	Bimodal volcanics-arkose-conglomerate
CAR	Committee of Antarctic Research
DFG	Deutsche Forschungsgemeinschaft
EDX	Energy dispersive X-ray
EUROSHACK	European Expedition to the Shackleton Range
GEISHA	German Geologische Expedition in die Shackleton Range
HREE	Heavy rare earth elements
ICP-AES	Inductively coupled plasma-atomic emission spectrometry
INAA	Instrumental neutron activation analysis
IR	Initial ratio
KFMASH	K_2O-FeO-MgO-Al_2O_3-SiO_2-H_2O
LREE	Light rare earth elements
MORB	Mid-ocean ridge basalts
MSWD	Mean square weighted deviates
NSRMC	North Shackleton Range Metamorphic Complex
OIB	Ocean island basalt
QPC	Quartzite-pelite-carbonate
REE	Rare earth elements
RFA	German abbreviation for X-ray fluorescence
SCAR	Scientific Committee on Antarctic Research
SEM	Scanning electron microscope
SRMC	Shackleton Range Metamorphic Complex
XRF	X-ray fluorescence