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Glacial Geology and Petrography of Erratics in the Shackleton Range, Antarctica

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Abstract: Studies were made of the glacial geology and provenance of erratics in the Shackleton Range during the German geological expedition GEISHA in 1987/88, especially in the southern and northwestern parts of the range. Evidence that the entire Shackleton Range was once overrun by ice from a southerly to southeasterly direction was provided by subglacial erosional forms (e.g. striations, crescentic gouges, roches moutonnées) and erratics which probably orriginated in the region of the Whichaway Nunataks and the Pensacola Mountains in the southern part of the range. This probably happened during the last major expansion of the Anarctic polar ice sheet, which, on the basis of evidence from other parts of the continent, occurred towards the end of the Miocene.

Till and an area of scattered erratics were mapped in the northwestern part of the range. These were deposited during a period of expansion of the Slessor Glacier in the Weichselian (Wisconsian) glacial stage earlier. This expansion was caused by blockage of the glacier by an expanded Filchner ice shelf which resulted from the sinking of the sea level during the Pleistocene, as demonstrated by geological studies in the Weddell Sea and along the coast of the Ross Sea. Studies of the erratics at the edges of glaciers provided information about rock concealed by the glacier.

Zusammenfassung: Die glaziologische Geschichte und die Herkunft erratischer Gerölle in der Shackleton Range wurde - besonders in dem südlichen und nordwestlichen Teil des Gebirges - während der deutschen geologischen Expedition GEISHA 1987/88 untersucht. Daß die gesamte Shackleton Range einst aus südlicher bis südwestlicher Richtung vom Eis überfahren wurde, konnte anhand subglazialer Erosionsformen (wie Kritzungen, Sichelmarken und roches moutonnées) bewiesen werden, sowie durch erratische Gerölle im Südteil des Gebirges, die von den Whichaway Nunataks und den Pensacola Mountains abstammen. All dies geschah während der letzten großen Ausdehnung des antarktischen Eisschildes, die nach Erkennsnissen aus anderen Regionen des Kontinentes am Ende des Miozäns stattfand.

Moränen und ein Gebiet mit verstreuten erratischen Blöcken konnte im nordwestlichen Teil des Gebirges kartiert werden. Diese wurden während einer Periode abgelagert, in der der Slessor Gletscher einen Hochstand erreichte, der in die Weichsel- (Wisconsian) oder eine ältere Kaltzeit zu stellen ist. Dieser Hochstand wurde durch ein ausgedehntes Filchner Schelfeis verursacht, das den Abfluß des Gletschers blockierte. Die Ausdehnung des Schelfeises ist durch die Absenkung des Meeresspiegels während des Pleistozäns bedingt, wie durch geologische Studien in der Weddell See und entlang der Küste des Ross Meeres belegt werden konnte. Untersuchungen der erratischen Gerölle an den Rändern der Gletscher brachten Aufschluß über Gesteine, die subglazial anstehen.

1. MORPHOLOGY AND GLACIATIONS OF THE SHACKLETON RANGE

Stephenson (1966) and Skidmore & Clarkson (1973) have published very good descriptions of the physiography and glacial morphology of the Shackleton Range; thus only a brief introduction to the morphology of the range will be given here.

The Shackleton Range trends E-W at the east edge of the Filchner ice shelf. It is 170 km long and up to 70 km wide. The highest peaks (1800-1950 m) are the Read Mountains at the SE edge of the range (Fig. 1); the lowest peaks (700-900 m) are along the north edge of the range, which is bounded by Slessor Glacier.

Slessor Glacier is about 50 km wide and has an elevation of more than 800 m at the east end of the range, dropping to an elevation of about 200 m at the west end where it flows into the Filchner ice shelf (Marsh 1985). The flow rate in the centre of the glacier is so high that there are many crevasses and zones of chaotic ice.

Recovery Glacier, flowing along the south side of the range, is about 80 km wide and has an elevation of about 1200 m at the east end of the range, dropping to an elevation of about 800 m at the west end. It has a lower gradient and thus a lower flow rate than Slessor Glacier; there are few crevasses and the glacier is therefore easily traversable.

Aerial photographs of the Shackleton Range at a scale of 1 : 53,000, made in 1986 by the Institute for Applied Geodesy of Frankfurt, Germany, showed that the central part of the range is covered by an elongated ice cap (Fuchs Dome in the west and Shotton Snowfield in the east, Figs. 1 and 2). There are flat rocky areas at the edges of these caps, mostly only several metres wide, bound by cliffs up to 400 m high. In the Read Mountains in the southeast part of the range, large cirques up to 7 km wide are bounded by high cliffs (Fig. 1). The steep ridges between adjacent cirques extend more than 10 km into the area to the south, often branching. Seven of these ridges widen into flat-topped buttes. There are table mountains also in the western and northwestern parts of the Shackleton Range (e.g. in the Otter and Haskard highlands), as well as in the northern part (e.g. Lister Heights and Flat Top; Fig. 1). Towards the north and northwest the range consists increasingly of small table mountains and solitary mountains (e.g. Mount Provender, Mount Skidmore, Herbert Mountains). Table mountains are no

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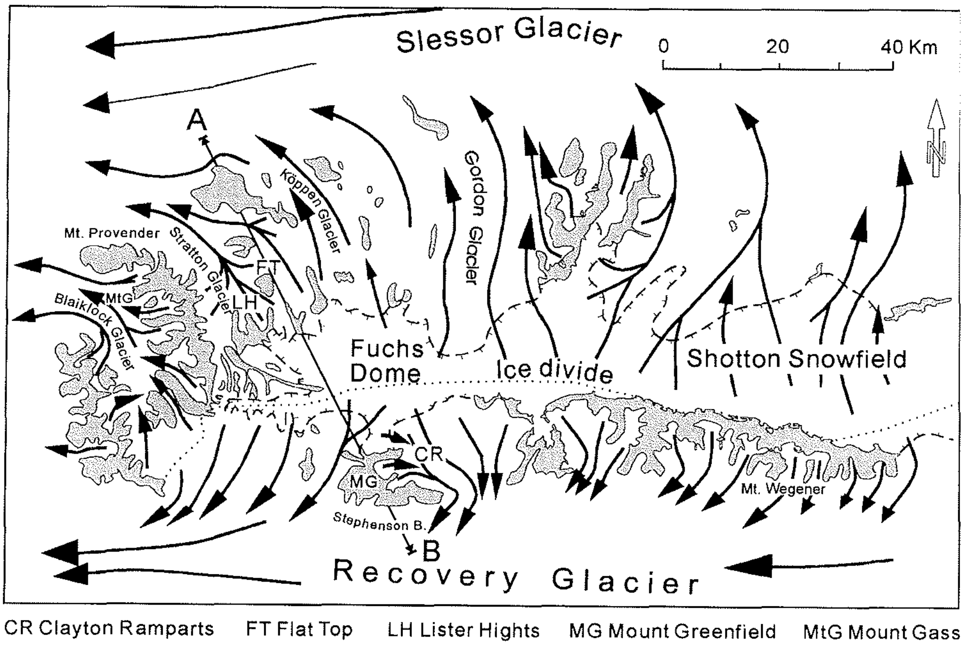

Fig. 1: General map of the Shackleton Range showing the present directions of ice flow.

Abb. 1: Übersichtskarte der Shackleton Range mit der derzeitigen Fließrichtung des Eises.

longer to be expected in this part of the range because erosion has reduced the level of the mountains here below the level of the original peneplain after uplift.

Comparison of the elevations and slopes of the tops of the table mountains leads to the conclusion that these are the remains of a peneplain. The question arose early on, during the interpretation of the aerial photographs, as to whether the mountains are an uplifted, dissected peneplain or whether they have been molded by an ice sheet and at present are subject to strong erosion.

SKIDMORE & CLARKSON (1972) consider the Shackleton Range to be a horst between two grabens filled by glaciers flowing parallel to the range. They viewed the range essentially as a peneplain that has been strongly dissected by faults, resulting in different levels molded by the ice. On the basis of the youngest rocks in the area, it could also be an old (pre-Beacon?), exhumed peneplain from which the younger cover had been eroded.

Because most of the peneplain slopes downwards towards the north, most of the ice on the range flows northwards and the divide is close to the southern edge (Fig. 1). The larger glaciers (e.g. Blaiklock, Stratton, Köppen, and Gordon glaciers) flow into the rapidly flowing Slessor Glacier. This is most probably the reason for the high rate of erosion of the northern part of the Shackleton Range.

2. METHODS

Most of the table mountains and large areas around Mount Provender and Mount Skidmore in the northwest part of the range (Fig. 1) were investigated with special emphasis on the subglacial erosional forms such as

- glacial polish,
- striations,
- crescentic gouges and lunate fractures,
- roches mountonnées,
- over-deepened valleys, and
- U-shaped valleys.

All kinds of glacial deposits were investigated, especially on the table mountains (Fig. 3) and on the gentle slopes in the northwest

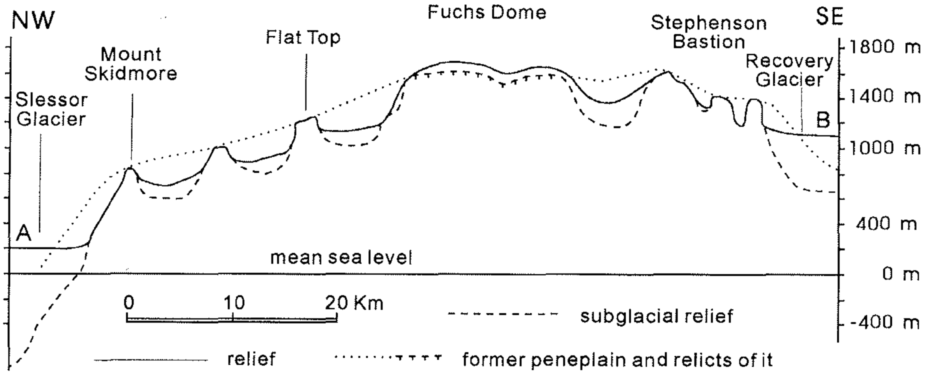

Fig. 2: Morphological profile through the Shackleton Range; see Fig. 1 (A-B) for profile location.

Abb. 2: Morphologisches Profil durch die Shackleton Range. Zur Lage siehe Abb. 1 (A-B).

part of the range. The erratics were subjected to petrological examination to obtain information about their origin. Erratics from within the Shackleton Range had to be distinguished from those transported from considerably further away. The terminal moraines in the northwestern part of the area are probably related to the adjacent till and abundant scattered erratics.

Mapping of the state of weathering of the till and the rock surfaces on the old peneplain, together with the morphological and geological data, were undertaken to reconstruct the glacial history of the area.

3. GLACIAL HISTORY OF THE SHACKLETON RANGE

3.1 *Pre-Quaternary*

Evidence for early glacial history can be expected only where more recent events can be excluded, especially at the edges of present glaciers. This was the situation at the edges of the Shackleton Range peneplain (Fig. 2) and therefore that is where the investigations were begun.

3.1.1 Weathering on the table mountains

Fuchs Dome and Shotton Snowfield and the surrounding table mountains represent remaining parts of a peneplain (Fig. 1). Along the southern margin of the range there are 15 table mountains (some of which have an area of several km^2), in the southwest there are seven, and in the north there are only three (one of which is smaller than 1 km^2). The former peneplain can be reconstructed (Fig. 2) from these table mountains and the flat, ice-free areas at the edges of Fuchs Dome and Shotton Snowfield.

The rocks making up the table mountains differ considerably. The rocks range from fossiliferous Cambrian shale and sandstone to amphibolite-facies gneiss containing some granite intrusions.

The most important forces that shape the morphology of the table mountains are alternating freezing and periods of thawing, abrasion by drifting snow in high winds (Fristrup 1952), and the removal of fine material from the top layer of the soil. Some table mountains in the Read Mountains area that are particularly exposed to the prevailing winds are almost completely free of debris (e.g. Mount Wegener and Trueman Terraces). In those areas the absence of even a thin cover of debris prevents the formation of polygonal ground.

The highest table mountains have been ice-free the longest and thus have been exposed to weathering the longest. On these table mountains, chemical and mechanical weathering of most of the surfaces is so advanced that no subglacial erosional forms and glacial deposits are recognizable. The most intensive weathering was where winds seldom permit snow cover to form.

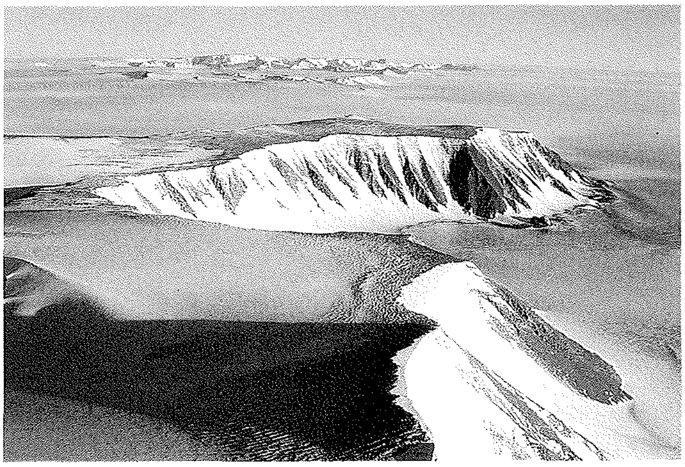

Fig. 3: Stephenson Bastion as an example of the table mountains in the southern part of the Shackleton Range remaining from the erosion of a former peneplain; Read Mountains in the background

Abb. 3: Stephenson Bastion: Ein Beispiel eines Tafelberges im südlichen Teil der Shackleton Range als Erosionsrest einer alten Peneplain, im Hintergrund die Read Mountains.

Weathering of the phyllites in the Read Mountains, for example, has led to the formation of a 20-30 cm layer of slightly clayey silt containing some sand and gravel; 5-10 cm of debris protects this fine material from being blown away. The debris derives mainly from the numerous quartz veins in the bedrock. Two profiles of soil on amphibole schist in the southwestern part of the range are shown in Fig. 4. Similar profiles were observed in the eastern part of the range.

Not all of the rocks are weathered to a particle size as small as silt. Quartzites and coarse-crystalline rocks, for example, have been weathered only as far as fine to medium-sized sand, sometimes only as far as fine gravel. Samples were taken from the debris layers at eight sites. The grain-size distributions in these samples are shown in Tab. 1.

To determine whether the fine-grained material is cryoclastic or whether clay minerals were formed by other weathering proces-

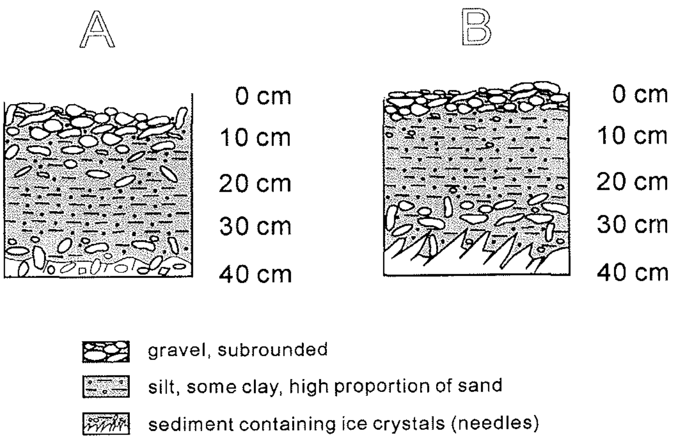

Fig. 4: Two soil profiles in the southwestern part of the Shackleton Range. (A) = Turnpike Bluff (elevation 1250 m); (B) = Wyeth Heights (elevation 1300 m).

Abb. 4: Zwei Bodenprofile im südwestlichen Teil der Shackleton Range. (A) = Turnpike Bluff (1250 m NN), (B) = Wyeth Heights (1300 m NN).

Sampling site	Turnpike Bluff						Mount Pivot		Wyeth Heights		Trueman Terraces
Sample no.	1A	1B	2A	2B	5A	5B	3A	3B	6A	6B	7
Underlying rock	schist										
Sampling depth (cm)	3-5	5-10	3-5	5-10	10-15	20-30	5-10	10-15	5-10	15-20	10-15
Gravel	16	37	10	20	48	45	41	57	5	1	25
Coarse sand	12	18	13	14	20	31	21	17	6	3	23
Medium sand	15	12	9	7	9	9	19	12	7	6	17
Fine sand	15	8	10	7	6	4	8	6	22	29	9
Silt	38	22	56	49	15	10	8	6	50	53	20
Clay	5	4	2	2	3	2	3	2	9	8	6

Tab. 1: Grain-size distribution (wt.%) in samples from eight profiles on table mountains in the southwestern part of the Shackleton Range. Sampling site locations are marked in Fig. 6.

Tab. 1: Korngrößenverteilung (Gew.%) in Proben von acht Profilen von Tafelbergen im Südwest-Gebiet der Shackleton Range. Probenpunkte sind in Abb. 6 markiert.

ses, XRD analyses were made of the clay and silt fractions. The results are shown in Tab. 2. The main components are muscovite-illite, chlorite, quartz, and mica. Traces of a non-swelling mixed-layer mineral were observed in only a few of the samples. Thus, this material is cryoclastic, disintegrated by freezing and thawing to the smallest possible particle sizes.

Despite weathering to clay and silt, little material has been removed from the top of the table mountains. The very compact, homogeneous, slowly weathering rock (e.g. quartzite) is seldom more than a metre higher than the surrounding inhomogeneous, easily weathered rock (e.g. phyllites). The reason for this may be assumed to be the fact that the cryoclastic debris is removed only by the wind. On the steep slopes that surround the table mountains, production and removal of the cryoclastic debris is much faster by at least two orders of magnitude.

Another indication of the intensive weathering over a long period of time is the presence of salt crusts, up to 2 cm thick, below the debris, particularly in the areas with little snow. These crusts are formed by physical and chemical weathering of crystalline and sedimentary rocks (e.g. schists) over long periods

Sample No.	sampling site	main components	main/sec. components	secondary components	sec./trace components	trace component	underlying rock
1A	south edge	muscovite/	quartz	chlorite	feldspar	-	schist
of	illite						
1B	Turnpike Bluff	muscovite/	quartz	-	feldspar	-	schist
		illite					
2A	east edge	muscovite/	quartz	-	feldspar	-	schist
of	illite						
2B	Turnpike Bluff	muscovite/	quartz	-	-	-	schist
		illite					
3A	Mount Pirot	mica	-	-	-	quartz / feldspar	gneiss
3B						chlorite	
5A	east edge	muscovite/	-	quartz	chlorite	-	schist
	of	illite			feldspar		
5B	Turnpike Bluff	muscovite/	quartz	quartz	feldspar	-	schist
		illite					
6A		muscovite/	-	quartz	feldspar	-	amphibolite
	Wyeth	illite		chlorite			schist
	Heights						
6B		muscovite/	-	quartz	feldspar	gypsum	amphibolite
		illite		chlorite			schist
7	Trueman Terraces	-	muscovite/	quartz	feldspar	-	-
			illite	chlorite			

Tab. 2: XRD analyses of the clay and silt fractions of soil samples collected in the southwestern part of the Shackleton Range.

Tab. 2: Röntgendiffraktionsanalysen der Ton- und Siltfraktionen von Bodenproben aus dem Südwestbereich der Shackleton Range.

of time. Thick salt crusts of this kind have been studied in the dry valleys of the Transantarctic Mountains, being the thickest crusts found in the areas that have been ice-free the longest (MIOTKE & HODENBERG 1980). Similarly long periods may be expected for higher parts of the Shackleton Range. Analyses of seven salt samples and the rocks below which they were found are given in Tab. 3 (Note: H.-C.H. did not complete this section).

Polygons are found on the table mountains only where the ground is moist in the summer, i.e. at the edges of snow and ice fields or where drifting snow collects in hollows or the lee of higher ground. The polygons are 3-12 m in diameter and commonly 50 cm high in the middle. The large polygons almost everywhere contain smaller ones with diameters of several decimeters up to about one metre.

The salt crust and the weathering of the rock to silt-size particles are evidence for a long period of time in the ice-free parts of the peneplain. Only in the dry valleys of the Transantarctic Mountains (which have been ice-free for more than 1.5 million years and for more than 3.5 million years in the central parts; for review see HÖFLE 1980) has such intensive disintegration of the rock and comparably thick salt crusts been previously observed. A comparably age may be at least initially assumed for the Shackleton Range; the areas exposed to weathering probably became ice-free during the Neogene.

The field work was aided by the fact that there was very little snowfall during the 1987/88 summer. The snow fields observed in the aerial photographs from the 1986/87 summer were smaller by 30-50 % in January-February 1988; the smaller ones had disappeared entirely. Less weathered rocks were found in the areas newly free of snow and ice and in some places subglacial erosional forms were found.

3.1.2 Subglacial erosional forms on the table mountains

Subglacial forms are seldom preserved under the weathering conditions described above. Nevertheless, such forms were found at four sites in the Read Mountains: (1) areas of glacial polish containing closely spaced striations of different depths. In particular, (2) crescentic gouges, which were used to determine the direction of ice flow (the points of the crescent point in the direction the ice came from). At all four sites (Murchison and Escola cirques), the erosional forms indicate that the ice crossed the Read Mountains from the SSW/SW. The highest site was in the Murchison Cirque at an elevation of 1750 m.

Striations, crescentic gouges (Fig. 5), and a roche moutonnée were observed on Stephenson Bastion . These erosional forms indicated the glacier came from the SSE to SW. Rock fragments with a polished side showing striations were observed on several other table mountains in the western part of the range (e.g. Wedge and Guyat ridges), indication that the entire peneplain was probably covered by ice.

Fig. 5: Striations and polish on sandstone erratics from the Stephenson Bastion Formation found at point C9 at an elevation of 1390 m on Stephenson Bastion.

Abb. 5: Gletscherschrammen und Schliff auf einem erratischen Sandstein von Stephenson Bastion (Fundpunkt C9 auf 1390 m NN).

Fig. 6: The over 250 m high Murchinson Cirque with a hanging U-shaped valley (in the centre) seen from the south .

Abb. 6: Blick von Süden auf den über 250 m hohen Murchinson Cirque mit U-förmigem Hängetal in der Bildmitte.

A U-shaped valley cut in a steep side of the Murchison Cirque 250 m above the floor of the cirque is evidence of former glacial acitivity (Fig. 6).

3.1.3 Till deposits on the table mountains

Except for Stephenson Bastion and surrounding area, and Flat Top in the north (Fig. 1), there were no glacial deposits on any of the table mountains studied. Striations and crescentic gouges found in places on these table mountains, however, indicate the former occurrence of glacial activity. It must be assumed that any till that may have been present has been eroded away during the long period that this area has been ice-free.

Large areas covered with erratics or till were discovered in places protected from erosion on Stephenson Bastion, neighboring Mount Greenfield (MG in Fig. 1), and on the adjoining Clayton Ramparts (CR in Fig. 1) to the north. The degree of weathering differs greatly. On Stephenson Bastion there are areas in which only a few erratics were found in the frost-shattered rock debris. A few tens of metres from these, a dense cluster of erratics was found, consisting of only the most resistent rocks (e.g. Beacon Sandstone and silicified conglomerate). Most of the erratics were fragmented by frost action. The erratics grade into till, sometimes more than 5 m thick. The distribution of till and abundant erratics on Stephenson Bastion and surrounding area is shown in Fig. 7.

Samples showing little weathering were taken at four sites (C1, C2, C4, and C5 in Fig. 7) for grain-size analysis and lime content determination (Tab. 4). No lime was found in the samples. The proportions of the various grain-sizes differed greatly, e.g. the gravel fraction varied from 0 to 57 %, the clay fraction varied between 2.0 % and 20.5 %. The highest proportion of clay was in a sample of little weathered till taken from the bottom of the hollow shown in Fig. 8. The clay fraction in the other samples ranged from 2 to 8.6 %. The clay in the upper part of the till profile was probably blown out by the wind.

Several small hollows, probably caused by dead ice, were found in till on Stephenson Bastian. These hollows, 8-20 m across and a maximum of about 1.5 m deep, contained snow that in normal years filled them, protecting the clasts from wind erosion. In contrast to the surrounding area, the erratics in the hollows were little weathered by frost action. Quartzitic sandstone commonly showed striations. The erratics in the hollows included easily weathered Palaeozoic archaeocyathid limestones, which occur nowhere else on Stephenson Bastian. On Mount Greenfield, at a somewhat lower elevation and in an area with more snow, these limestones were also found in wide depressions. They are much smaller, however, due to frost action and wind abrasion. A cross section through a hollow (site C5) in the central part of Stephenson Bastion is shown in Figure 8. The rock types in the assemblage of slightly weathered erratics in a square metre at the bottom of the hollow were determined (C5 in Tab. 5).

Reddish-brown sandstones of the Beacon Formation, and an achaeocyathid reef limestone do not occur as bedrock anywhere in the Shackleton Range. They must have been transported from somewhere else. The subglacial erosional forms associated with these erratics indicate ice movement from the SW to SE. According to Stephenson (1966), the nearest outcrops of Beacon Sandstone are in the Whichaway Nunataks, 80 km south of the Shackleton Range. Archaeoycathid limestones occur there only as erratics (Hill 1965). Outcrops of these limestones (Nelson Limestone) occur in the Pensacola Mountains (Stephenson 1966).

Erratics at the southern edge of Clayton Ramparts (Tab. 5, site

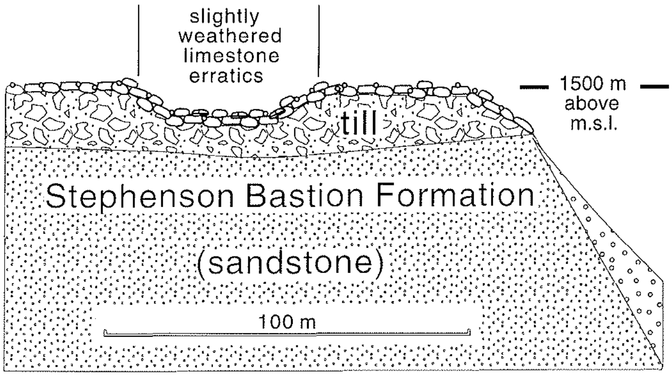

Fig. 8: Cross section through a depression in the till at point C4 (see Fig. 7) on Stephenson Bastion.

Abb. 8: Querschnitt durch eine Depression in der Moräne an Fundpunkt C4 (siehe Abb. 7) auf Stephenson Bastion.

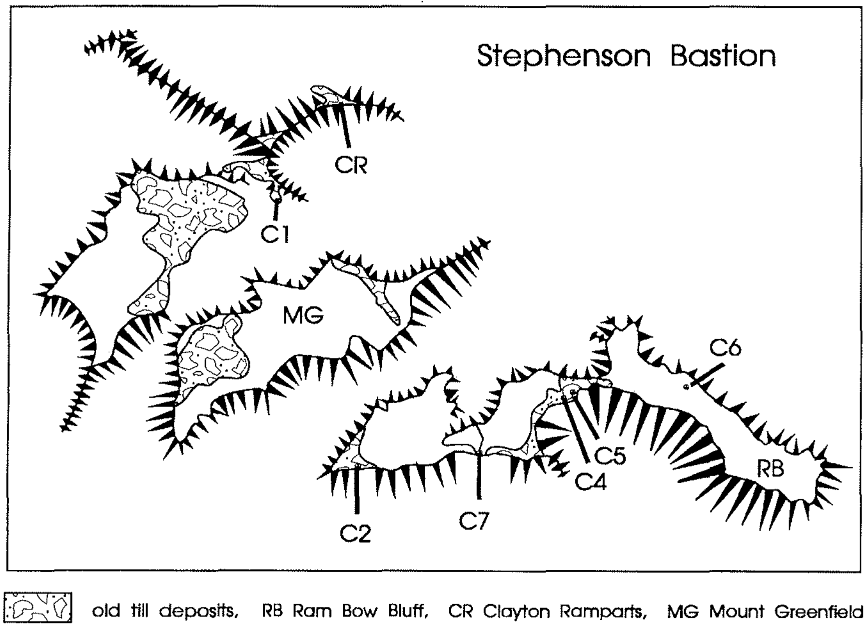

Fig. 7: Areas of erratics and till on and around Stephenson Bastion.

Abb. 7: Gebiete mit erratischen Geröllen und Moränen um Stephenson Bastion.

C1, 1 m^2) are abundant and have a maximum diameter of several decimetres. They lie on schists containing quartzite interbeds assigned to the Stephenson Bastion Formation. The highest elevation at which erratics were observed (Beacon Sandstone, 1780 m) was on Clayton Ramparts. An inventory of erratics on Mount Greenfield to the southwest showed little differences from the results for Clayton Ramparts. In places, locally the erratics are so abundant as to form till several metres thick containing rounded cobbles of Beacon Sandstone 50-80 cm in diameter. Individual striated boulders were also observed.

Several sandstone erratics were found on Flat Top (elevation 1400 m, northwest of Fuchs Dome). These were identified by thin-section analysis to be Beacon Sandstone, which is consistent with the hypothesis that the entire range was covered by an ice sheet flowing from the south.

3.1.4 Characterization of erratics collected on table Mountains

I. Carbonates

About half of the carbonate rocks contained identifiable fossils whose Early to Middle Cambrian ages are in agreement with the age of the rocks in the probable source area. The most prominent is archaeocyathid limestone. The archaeocyathids are in a fine-grained matrix now recrystallized with spots of sparite. The matrix consists of particles several millimetres across, indicating local reworking of the material not involving large transport distances. Accordingly these rocks are archaeocyathid bearing floatstones Fig. 9a and 9b). The associated fauna and flora are mainly trilobites (Fig. 9c) and algae (Fig. 9e, 9f and 9g). In particular the ?red algae or ?cyanobacterium *incertae sedis*, *Epiphyton sp.* formed archaeocyathid-epiphyte boundstones which, in the source area, developed into mud mounds

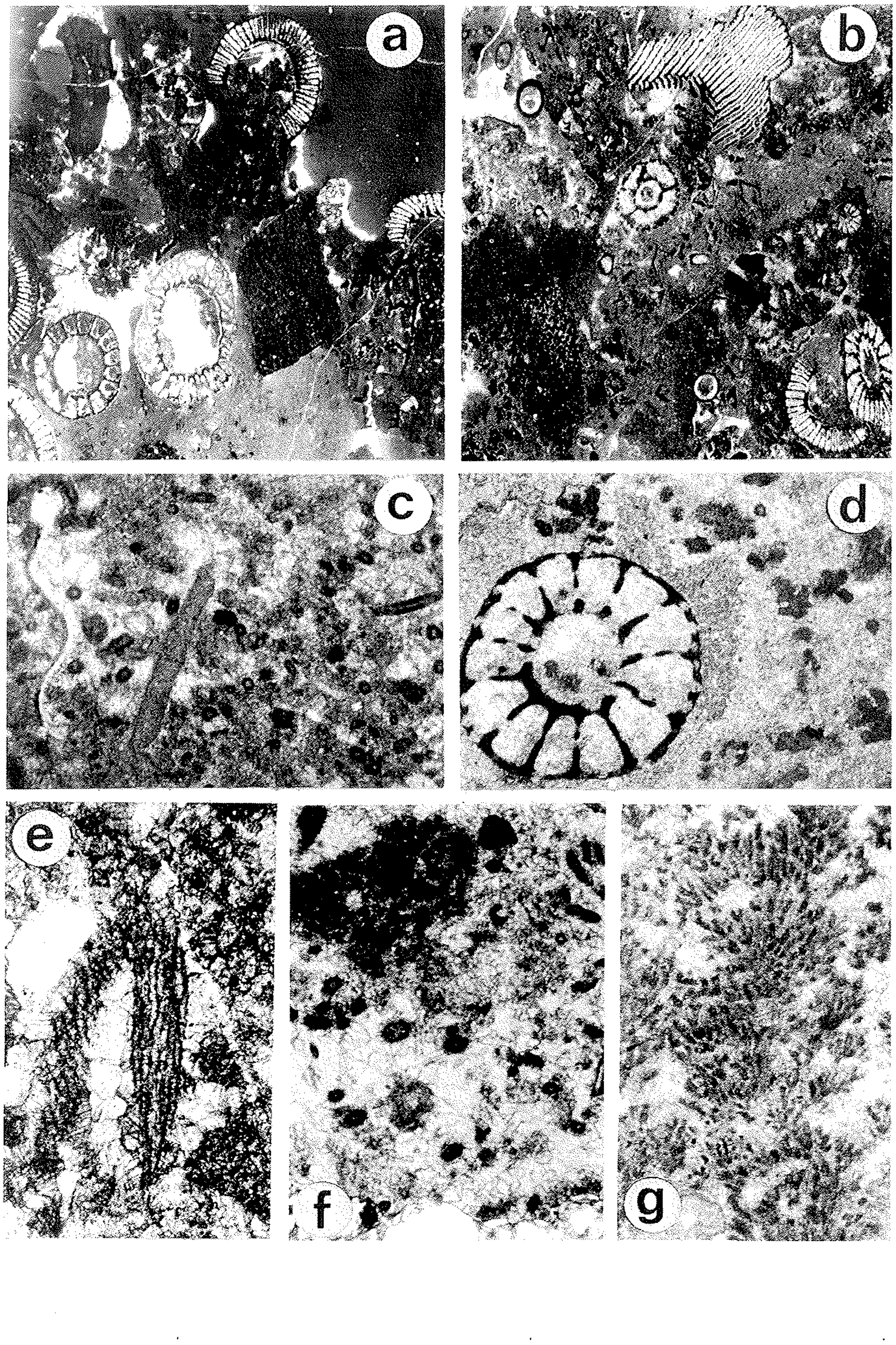

Fig. 9: Limestone clasts from till deposits on Mount Greenfield and C2 on Stephenson Bastion. (a) and (b): Archaeocyathid floatstone x2; (c): Pelsparite (grainstone) with abundant algal tubes and trilobites x5; (d): Archaeocyathid-*Renalcis* boundstone x5; (e): Bundled tubes of algae (probably *Batenivia ramosa* KORDE) x50; (f): Micritic tubes and fragments of *Epiphyton* and *Renalcis* in limestone clasts of a breccia, thin section 37998, Loc. C2 on Stephenson Bastion, x2; (g): *Epiphyyton* sp. x20.

Abb. 9: Kalkklasten aus den Moränenablagerungen von Mount Greenfield und Stephenson Bastion. (a) und (b): Archaeocyathinen -floatstone x2; (c): Pelsparit (grainstone) mit häufigen Algenröhren und Trilobiten; (d): Archaeocyathinen-*Renalcis* boundstone x5; (e): Röhrchenbündel von Algen, vermutlich *Batenivia ramosa* KORDE x50; (f): Mikriröhrchen und Bruchstücke von *Epiphyton* und *Renalcis* in Kalkklasten einer Brekzie x20; (g): *Epiphyton* sp. x20.

(bafflestones) or even small bioherms (framestones). *Epiphyton* formed also rocks by itself (Fig. 9g). Epiphyte fragments and *Renalcis* also appear between archaeocyathids (Fig.9d). Small, slightly curved, unbranched tubes with relatively thick micritic walls commonly occur among the algae (Fig. 9c).

Sampling sites: Numerous limestone clasts were collected from the moraines on Mount Greenfield (samples Mo3, 7, 19, 26, 31, 33, 35).
Source area: The nearest known outcrop of the limestone facies described above is the Nelson Limestone Formation in the Pensacola Mountains.

II. Breccia containing carbonate
The matrix is calcite. Breccia components include poorly rounded quartz grains, locally faintly showing undulose extinction, polycrystalline (quartzite), feldspar, biotite, garnet (very frequent), and carbonate (locally sandy). Micrite tubes and epiphytes occur in the carbonates (Fig. 9f), as known in the archaeocyathid limestone clasts on Mount Greenfield. In addition, *Girvanella* sp. and colonies of bundled tubes branching at acute angles (probably the alga *Batenivia ramosa* KORDE 1966 which is known from the Cambrian to the Silurian) are present (Fig. 9e).

Sampling site: C2 on Stephenson Bastion (thin section 37998).
Possible source area: Pensacola Mountains.

III. Chert
Fine-crystalline quartz containing rhombs of carbonate was sampled on Stephenson Bastion (site C2, thin section 37993).

IV. Siliciclastic rocks
Sandstone erratics can be divided into three types; the source area of one of these is the Shackleton Range itself (Blaiklock Glacier Group).

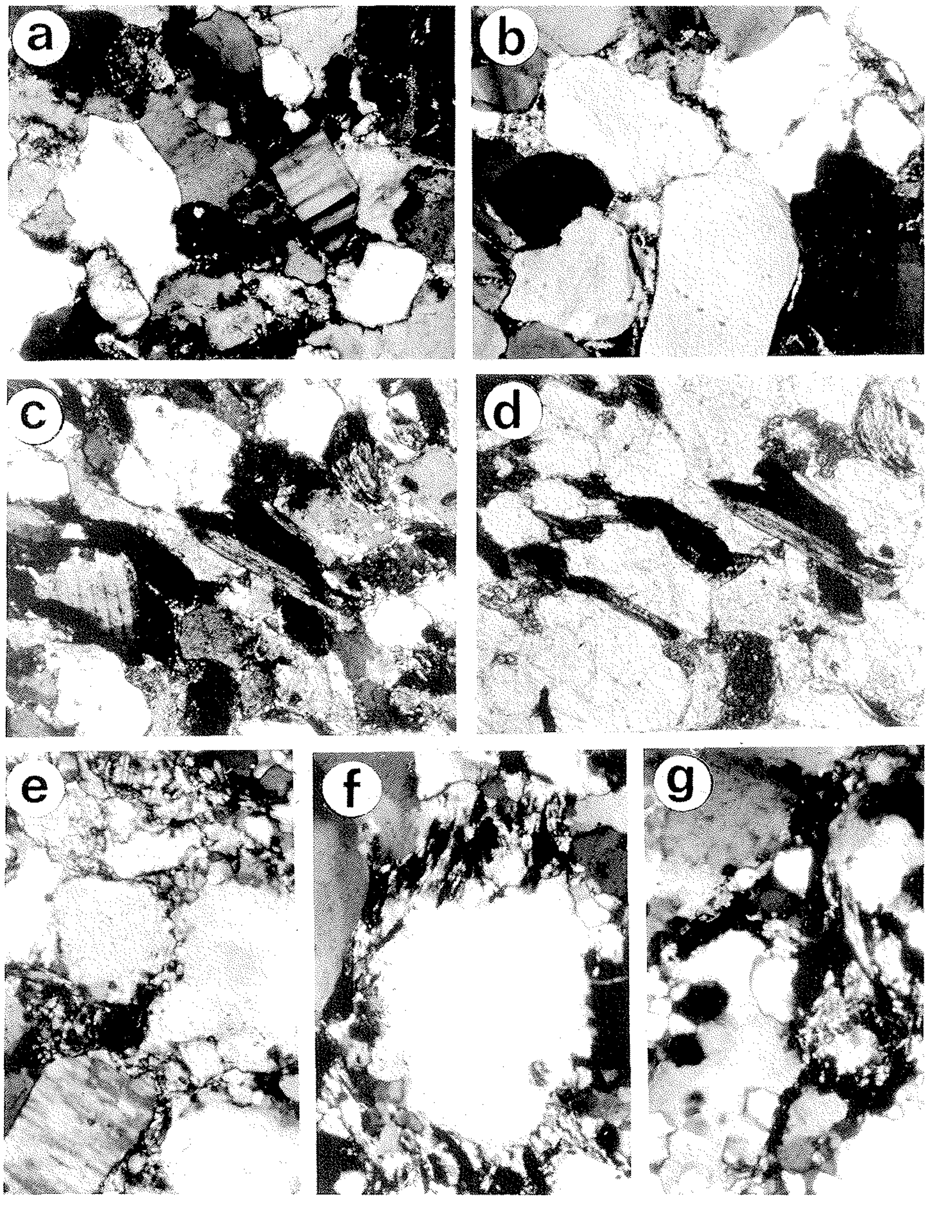

Fig. 10: Siliciclastic components of tills on Stephenson Bastion and Mount Greenfield; magnifications x75, except (g) = x200.
(a) and (b): Red Sandstone with up to 30 % of feldspar. Syntaxial overgrowth on quartz grains with „dirty rims". Thin sections 37999 and 38000. (c) and (d): Lithic arenites with large altered micas (Type Blaiklock Glacier Group sandstone). Thin sections 38002 (Fig. 10c) and 38003 (Fig. 10d). (e): Metaarenite with undulose, partly recrystallized quartz and brittle deformed feldspar. Thin section 38005. (f) and (g): Quartzite with chlorite-sericite-quartz beards (Fig. 10f). Quartz dynamically recrystallized (Fig. 10g). Thin section 38004.

Abb. 10: Siliziklastische Moränen-Komponenten von Stephenson Bastion und Mount Greenfield. Alle Vergrößerungen x75, nur (g) = x200.
(a) und (b): Rotsandsteine mit bis zu 30 % Feldspat. Syntaxialer Aufwuchs auf Quarz mit Schmutzrändern um die Altkörner. (c) und (d): Lithische Arenite mit großen verwitterten Glimmern (Typ Blaiklock-Glacier-Group-Sandstein). (e): Meta-Arenit mit undulös auslöschenden, teilweise rekritsallisierten Quarzen und spröd-deformiertem Feldspat. (f) und (g): Quarzite mit Chlorit-Serizit-Quarz-Faserbärten (Abb. 10f). Quarz ist dynamisch rekristallisiert (Abb. 10g).

(1) Arkosic and lithic arenites
Red sandstones and conglomerates are the most common type (Fig. 10a and 10b). They may be characterized as follows: a high feldspar content (up to 30 %), mainly orthoclase (+ microcline), but also plagioclase; chert fragments are common; quartz, locally in only small amounts, strong undulose extinction, locally polycrystalline (quartzite); distinctly old grains with „dirty rims" and syntaxial overgrowths; the quartz cement also shows undulose extinction; detrital white mica. Lithologically, the sandstones are arkosic and/or lithic arenites. The conglomerates contain more quartz, but probably come from the same source area. The grains show extensive pressure solution, resulting in interlocking dentate grain boundaries. No recrystallization of quartz was observed, but growth of phyllosilicates has begun.

Sampling sites: Stephenson Bastion area (C1, C2, C4, CR = Clayton Ramparts, see Fig. 7, thin sections 37987 to 38990, 37992, 37997, 38005 to 38011); also Flat Top (thin sections 37999, 38000, 38001).
Source areas: Similar rocks occur in the Beacon Supergroup; the nearest outcrops of Beacon Sandstone are in the Whichaway Nunataks 80 km to the south; Beacon Sandstone is not known in the Shackleton Range.

(2) Lithic arenites (Figs. 10c and 10d)
The matrix is carbonate. The detrital grains include angular to subrounded quartz with significant amounts of mica (biotite, white mica, chlorite), feldspar, heavy minerals (garnet, zircon). The high proportion of mica and the frequent pieces of biotite altered to iron oxide are characteristic. Pressure solution phenomena are present.

Sampling site: Mount Greenfield (samples MG, thin sections 38000 and 38002).
Source area: These erratics compare with the lithic arenites of the Blaiklock Glacier Group known only in the northwest part of the Shackleton Range. As there is no evidence for north to south transport this material must originate from an undiscovered sub-glacial occurrence in the southern part of the range.

(3) Quartzites
Two rock specimens are extensively recrystallized (up to 50 %) quartz arenite. Old quartz grains show strong undulose extinction; the recrystallized quartz also shows (weak) undulose extinction. The grain boundaries of the recrystallized quartz are locally straight; there are no triple points with 120° angles. The recrystallization was therefore dynamic, but locally almost static. Feldspars (up to about 10 %) are not recrystallized and are rarely broken (brittle deformation). Zircon occurs as accessory mineral. Whereas thin section 37991 shows only a weak indication of s_1 schistosity, the foliation in thin section 38004 is revealed by chlorite-sericite beards (Figs. 10e, 10f and 10g).

Sampling sites: Stephenson Bastion area (C1 and C3; thin sections 379911, 38004).
Source area: Metamorphic area of low greenschist facies (probably not in the Shackleton Range, since the meta-arenites of the so-called „Turnpike Bluff Group" (MARSH 1983) show a distinct s_1 schistosity.

3.1.5 When was the Shackleton Range last covered by ice?

The erratics and subglacial erosional forms on Stepheson Bastion and surrounding area and in the Read Mountains indicate ice flow from the south. There are several arguments for the hypothesis that the area has been ice-free for a considerable time, probably pre-Quaternary:

(1) For Antarctic conditions, the higher table mountains are unusually strongly weathered. The disintegration of rock to clay and silt particles requires a long time and similar soils are found in Antarctica only where the rock has been exposed for more than a million of years.

(2) The numerous table mountains are the remains of a former peneplain, moulded by the ice during the last major expansion of the Antarctic ice. As the ice sheet became thinner, parts of the mountains became exposed and, where there was no local snow or ice, the rock was subjected to intensive erosion. Exaration by rather fast moving glaciers in the north over a long period of time and the formation of cirques in the south have extensively dissected the peneplain. A more recent ice cap would have leveled the steep ridges in the north and the cirque walls in the south.

Because the ice at present flows from east to west on both sides of the Shackleton Range, the direction of flow from the south during the last major expansion of the Antarctic ice sheet is striking.The highest elevation at which subglacial erosional forms and erratics were observed was 800 m above the present level of Recovery Glacier. Neglecting any uplift of the Shackleton Range since the last retreat of the ice, the ice must have been more than 800 m higher than it is today. Even after taking a possible 100-300 m of uplift into account, the ice was considerably thicker at that time. The direction of flow must have been completely different from that of today since the morphology would have played a much lesser role.

According to DENTON et al. (1984), the thickness of the ice in the Transantarctic Mountains during the last major expansion of the Antarctic ice sheet was 1000 m greater than today, with the mountains in the area of the dry valleys covered with ice. The present ice divides did not exist at that time and the ice flowed northwards from the centers of the ice sheet. The maximum extent of this ice sheet as hypothesized by Denton et al. (1984) is shown in Figure 11. The ice sheet, particularly the ice shelves, advanced as much as 600 km further that at present. The northward flow of the ice is supported by our investigations.

The results of borehole data from the continental shelf of the Amery Ice Shelf (HAMBREY et al. 1989) and in McMurdo Sound (BARRETT 1986) provide evidence for the time of the last major expansion of the Antarctic ice sheet. The shelf ice appears to have advanced much farther north in the late Miocene to Plio-

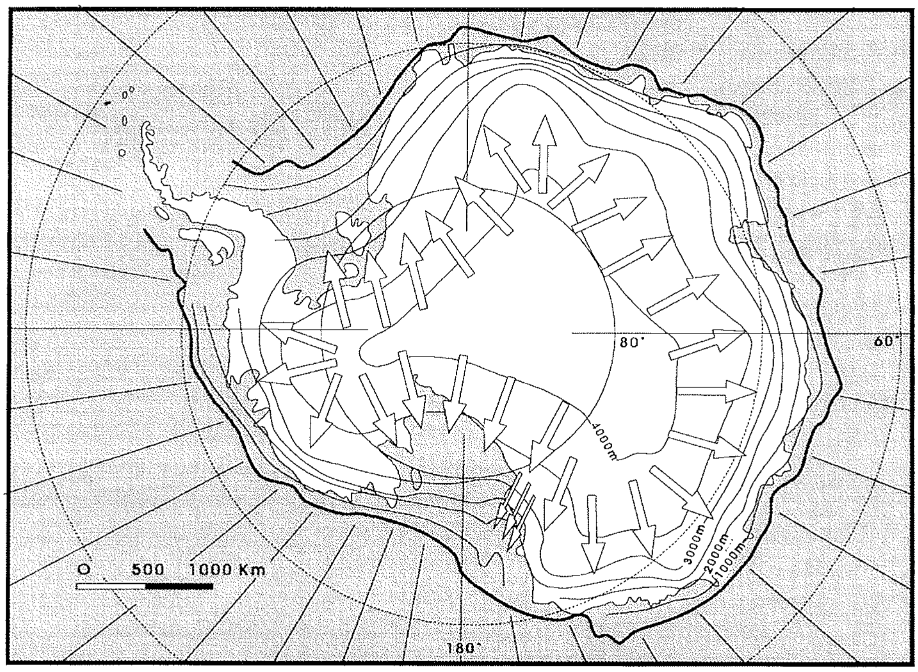

Fig. 11: Polar ice sheet during the last major expansion of the Antarctic polar ice (after DENTON et al. 1984).

Abb. 11: Der polare Eisschild während der letzten großen Ausdehnung des antarktischen polaren Eises (nach DENTON et al. 1984).

cene; this would have been a result of a thickening of the inland ice.

According to HARWOOD & WEBB (1991), the East Antarctic ice sheet retreated to a third of its present size in the Early Pliocene and expanded considerably in the Late Pliocene. Whether this increase in thickness was sufficient to cover the Shackleton Range is not known, however.

(3) An iron-nickel meteorite was found on the flat top of Mount Wegener in the southern Read Mountains (Fig. 12). On the basis of its shape and internal structure, this meteorite cannot have been carried by ice to where it was found but must have landed in snow at that site (80° 42' S, 23° 35' W), a wind exposed locality at an elevation of 1540 m, only 30 m away from a snowfield with a sastrugi about 5 m high. The bedrock is a greenish phyllite, covered by a thin layer of debris formed by weathering of interbedded metaquartzite and quartz veins in the schist. There are no glacial deposits on Mount Wegener, but there is no question that this table mountain was part of a peneplain formed by ice action.

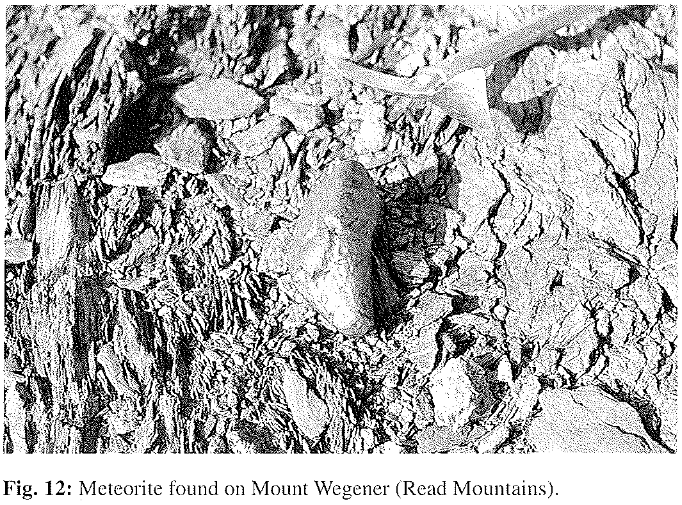

Fig. 12: Meteorite found on Mount Wegener (Read Mountains).

Abb. 12: Der Meteorit, der auf Mount Wegener (Read Mountains) gefunden wurde.

The meteorite was examined in detail by SCHULTZ et al. (1989). It is a „normal“, group IIIA iron meteorite with a kamacite bandwidth of 1.1 mm. The surface of the meteorite shows Widmannstätten structures enhanced by snow abrasion (they would otherwise be seen only on polished sections of the meteorite after etching). The meteorite consists of 91.9 % iron, 8.1 % nickel, and traces of gallium (21 ppm) and germanium (33 ppm). The isotope composition of the noble gases in the meteorite indicate that it was in interplanetary space for about 650 Ma. The ^{10}Be concentration (produced by cosmic rays) indicates a terrestrial age of about 415,000 years.

Passage of an ice sheet over Mount Wegener, or a local glaciation since its fall would probably have removed the meteorite and would have certainly disintegrated it, owing to the fractures in it. Because it was found about 350 m above Recovery Glacier, which flows along the southern side of Mount Wegener, it may be assumed that the site has not experienced any glacial activity since the fall of the meteorite. The last 415,000 years include the three coldest periods since the Permo-Carboniferous. These glacial periods apparently did not increase the thickness of the ice significantly in the higher parts of the Antarctic polar plateau.

3.2 *Glaciation in the Quaternary*

Study of the aerial photographs showed that the history of Quaternary glaciation could be studied only in the northwestern part of the Shackleton Range where there are several moraines and large areas of till cover in northern Haskard Highlands and on Lagrange Nunatak. Pleistocene deposits were expected along the edges of Slessor Glacier because it flows into the Filchner Ice Shelf just west of the range and the largest changes resulting from sea level changes during the Pleistocene were to be expected there.

3.2.1 Effects at the northwest end of the range resulting from sea level changes during the Pleistocene

Slessor Glacier flows past the foot of the gentle slopes of Mount Provender and Mount Gass, north of the Haskard Highlands, and of Mount Skidmore, west of the Lagrange Nunatak, both for the most part snow- and ice-free. In these two areas, Blaiklock and Stratton glaciers, respectively, flow into Slessor Glacier.

3.2.1.1 Mount Provender and surrounding area

Moraines

The lowest elevation in the Mount Provender (summit: 901 m) area is at Nostoc Lake (205 m) on the west side (Figs. 13-16). Bardin (1981) discussed the moraines that are present from this lake up to an elevation of 650 m. They range from scattered erratics to a continuous layer of erratics to till several metres thick containing relatively high proportions of clay and silt. The distribution of moraines on Mount Provender and in the surrounding area is shown in Fig. 14. The largest occurrences are in a wide valley opening to the southwest (Fig. 16).

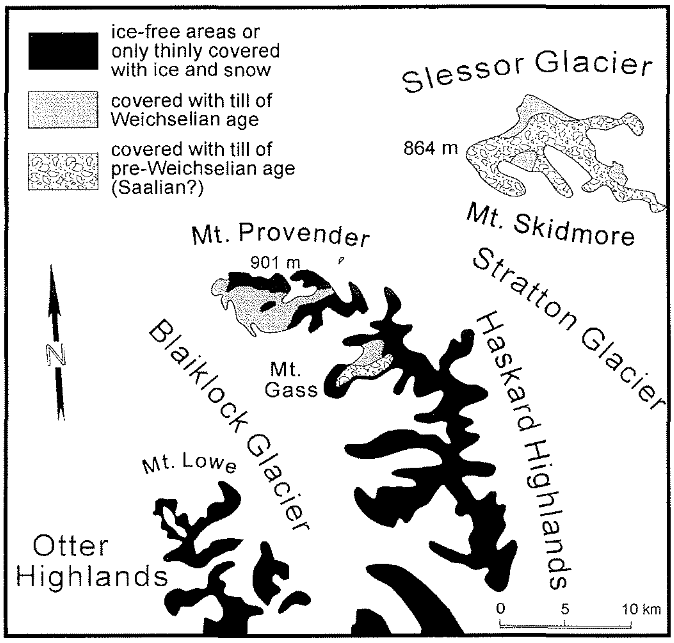

Fig. 13: The areas of Pleistocene till around Mount Provender and Mount Skidmore in the northwestern part of the Shackleton Range.

Abb. 13: Das Gebiet mit pleistozänen Moränen um Mount Provender und Mount Skidmore in der nordwestlichen Shackleton Range.

The till contains erratics showing a completely different composition and degree of weathering to those of the till in the Stephenson Bastion area. The range of rock types is much wider; the unusual sedimentary rocks found among the erratics in the southern part of the range (archaeocyathid limestone and Beacon Sandstone) are not found here. The erratics commonly include non-resistant rocks like semi-indurated sandstone, schists, and limestone that show little or no signs of weathering (e.g. frost shattering, snow abrasion). There are numerous erratics showing striations, especially on the west side of Mount Provender. In contrast to the erratics on the table mountains, the lower side of erratics at the surface of the moraines showed only a veneer of grey crystals. These rocks also show little frost shattering. Some 10-30 % of the erratics are fragmented into sever-

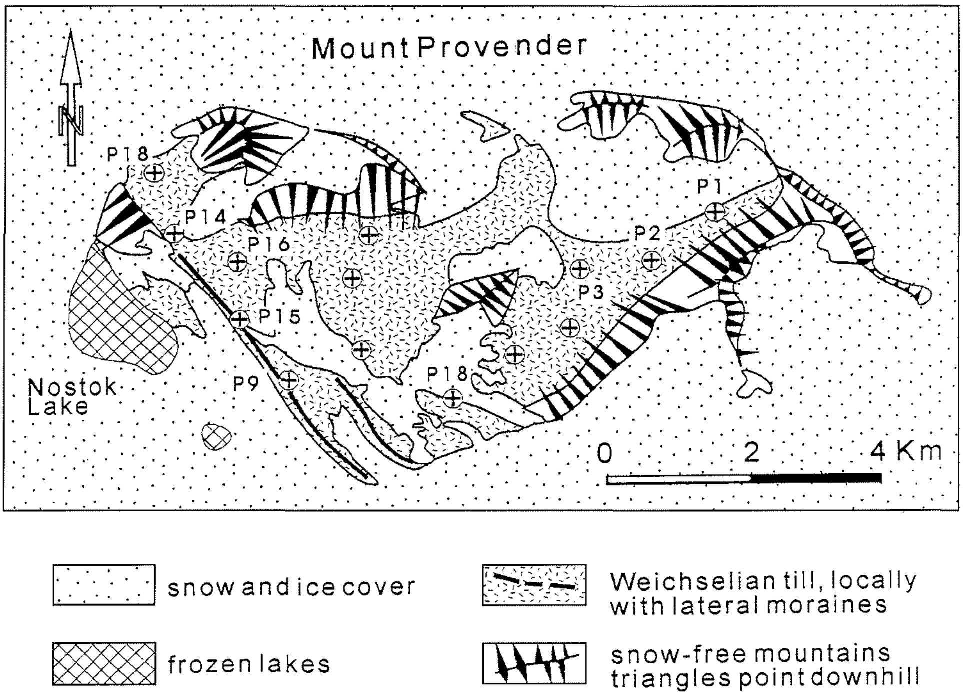

Fig. 14: Distribution of Weichselian till and moraines around Mount Provender.

Abb. 14: Verteilung der Weichsel-eiszeitlichen Moränen um Mount Provender.

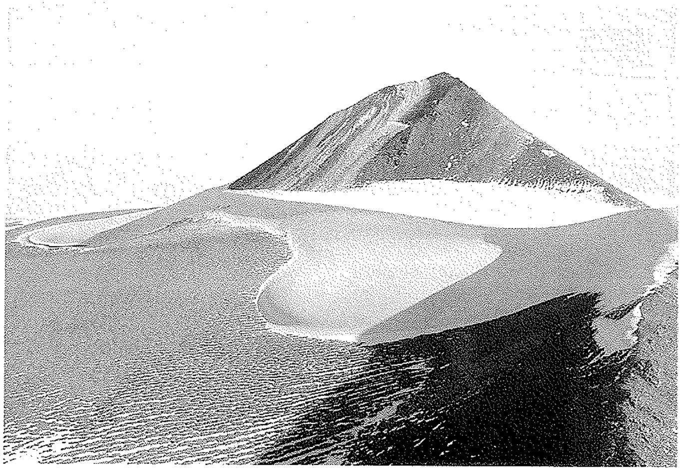

Fig. 15: Weichselian till on Mount Provender; in foreground polygonal ground and striped ground; Slessor Glacier in the background.

Abb. 15: Weichsel-eiszeitliche Moränen auf Mount Provender. Im Vordergrund: Polygone und Streifenböden, im Hintergrund der Slessor Gletscher.

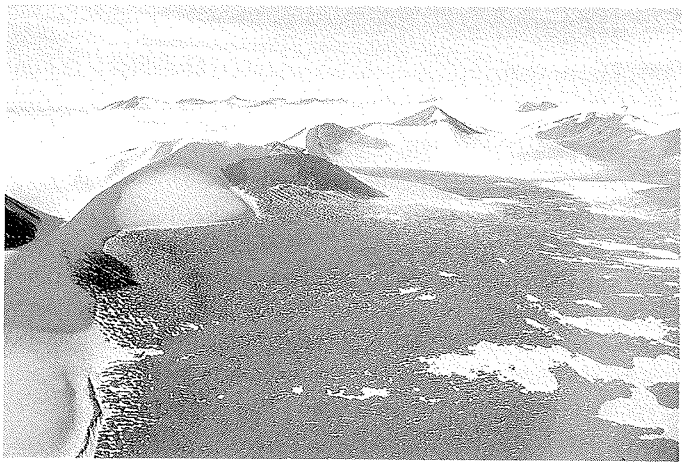

Fig. 16: Till-filled valley south of Mount Provender; in the background are Stratton Glacier and the Mount Skidmore area.

Abb. 16: Moränen erfülltes Tal südlich Mount Provender. Im Hintergrund der Stratton Gletscher und das Gebiet des Mount Skidmore.

al pieces; only the least resistant rocks (e.g. coarse-grained marble and amphibolites) have disintegrated to their constituent components and sandstones have been reduced to bizarre tafoni. There is till, probably several metres thick, at the open end of the valley. The proportion of clay and silt is so high that the matrix forms the surface of the moraine (Fig. 17). A thin calcareous crust covers the bottom surfaces of the erratics within the fine-grained till matrix. These crusts can have originated only from lime in the till. Remarkably high carbonate contents of 5-23 % were obtained for ten samples from five sites (Tab. 6). In contrast, the matrix of the considerably older till on Stephenson Bastion contains no carbonate. It is noticeable in the analyses that the carbonate content of the top 5 cm is higher than at a depth of 10-20 cm. The extreme dryness, with only occasional wetting of the surface during the short summer (as in hot, dry desert areas), is responsible for this concentration of carbonate near the surface.

Fig. 17: Till containing a high proportion of clay and silt just above Nostoc Lake on the south side of Mount Provender (see Fig. 14).

Abb. 17: Moräne mit hohem Anteil an Ton und Silt direkt oberhalb Nostoc Lake an der Südseite von Mount Provender (siehe Abb. 14).

There are two large, slightly curved lateral moraines, 3-6 m high, trending NW-SE across the open end of the valley (as far as is recognizable in the snow), as well as three or four smaller one partly burried under the snow.The valley ends with a relatively steep slope down to the Blaiklock Glacier and Nostoc Lake. Several channels (max. 1.5 m deep; Fig. 18) have been eroded into the moraine near the top of this slope (Fig. 14). In warmer years, large amounts of earth have been eroded from the till onto the steep slope, where it has formed talus fans. In the lower part of the steep sides of the channels, erratics are exposed that are still in the position where they were deposited, enabling the orientation of the long axis to be determined. Although only 34 measurements could be made, there was a distinct clustering of values between 150° and 170° (i.e. NNW-SSE). Aiignment of erratics is characteristic of lodgment till, strongly suggesting that the surface of Blaiklock Glacier, which flows NW, was once 100 m higher in this area. Near these erosion channels (points 9, 14 and 15 in Fig. 14) and at the top of the steep slope, the till reaches its maximum thickness of probably no more than 3-4 m. In this area there are sinkholes caused by melting of ice lenses in the till. These holes are 30-40 cm across and up to 40 cm deep; they usually occur singly.

A trench (80 cm deep) was dug at point 9 on one of the terminal moraines to examine the internal structure of the moraine and the transition to the permafrost zone. Below a horizon containing gravel and coarse sand (max. 18 cm) there is a layer of sand, gravel, silt, and needle-shaped crystals of ice. Permafrost begins abruptly at 50 cm. Below this depth, 50-60 % of the volume is clear ice containing almost no rock debris (Fig. 20). Clumps of till in this ice contain needle-shaped ice crystals.

Petrography of the erratics

An inventory was made of the erratics at 14 sites (Fig. 12) in the Mount Provender area. One of these was done at Lake Lundström at the foot of Mount Gass (Figs. 13 and 21). Erratics with a diameter of more than 2 cm were counted on the surface of

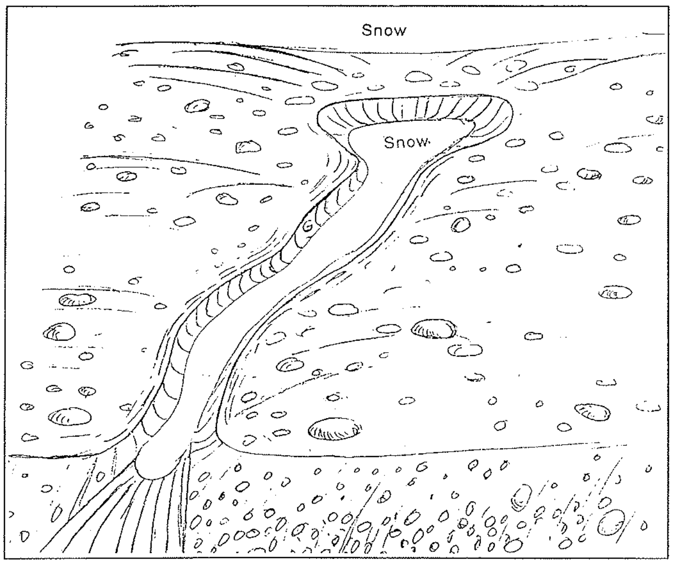

Fig. 18: Erosion channel at point 14 (see Fig. 14) above Nostoc Lake.

Abb. 18: Erosionskanal bei Fundpunkt 14 (siehe Abb. 14) oberhalb Nostoc Lake.

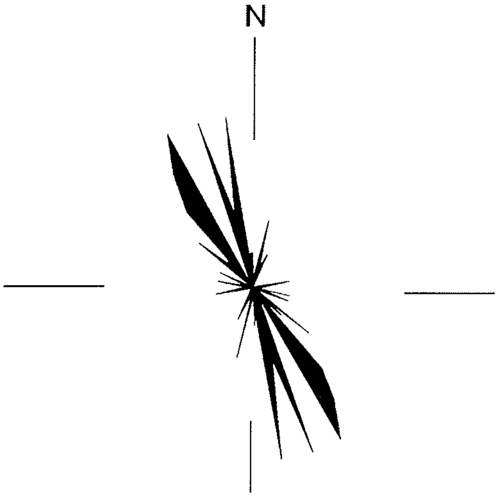

Fig. 19: Alignment of 34 clasts in till at Mount Provender. The length of the orientation lines represents the number of measurements in that direction.

Abb. 19: Orientierung von 34 Klasten in der Moräne am Mount Provender. Die Länge der Vektoren entspricht der Anzahl von Messungen in dieser Richtung.

areas of 1-2 m^2. The sampling sites are shown in Figure 14. The composition of the erratics is very close to the geology of the bedrock (BUGGISCH et al. 1990, 1994). Thus the rocks of the Blaiklock Glacier Group crop out in the area of the Blaiklock Glacier with the rocks of the Basement Complex adjoining to the east. A thrust fault between the rocks of these two areas crosses the till -filled valley on Mount Provender from SE to NW.

Except for the dolerite, the crystalline erratics listed in Table 7 are typical of the Pioneers and Stratton groups. The source rocks form the mountains east of the valley, i.e. these erratics are of local origin. The proportion of these rocks among the erratics decreases to the west (erratics inventories at points 1, 2,3, and 10 through 13); at the edge of Blaiklock Glacier there are little or no crystalline rocks among the erratics.

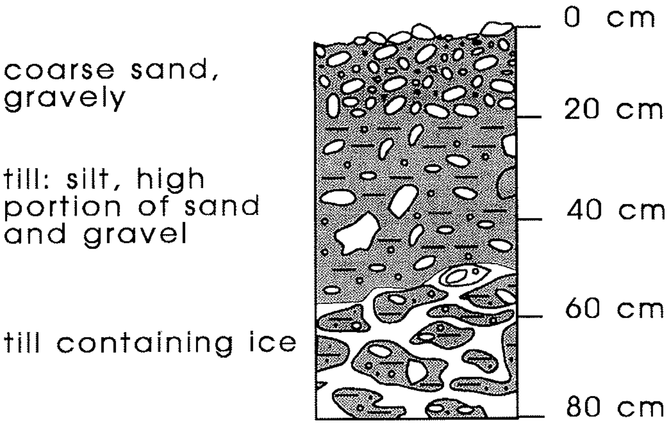

Fig. 20: Soil profile in a trench in Weichselian till at point 9 (see Fig. 14).

Abb. 20: Bodenprofil in einem Schurfgraben in Weichsel-zeitlicher Moräne bei Fundpunkt 9 (siehe Abb. 14).

The proportion of sedimentary rocks among the erratics increases as the number of crystalline rocks decreases. With respect to the dark shales (trilobite-bearing, Cambrian age), outcrops of shale were found at several till-free places (points 8, 11, 12); shale was encountered in the trench dug in the till at point 9 during the 1978/79 Soviet expedition. The other sedimentary erratics are rocks that must have been transported from the upper reaches of the Blaiklock Glacier.

The till at Lake Lundström on Mount Gass (Fig. 21) is similar to that at Mount Provender with respect to weathering and composition of the erratics and thus may be considered to be of the same age. Erratics of sedimentary rocks were observed on crystalline bedrock on the valley slopes up to an elevation of 750 m. Thus, at the height of the Weichselian, Blaiklock Glacier must have filled the valley. Individual erratics were observed above 750 m on Mount Gass as far as the summit. Poorly resistant rocks like limestone and shale were not found (with one exception), nor were striations observed at these elevations. These rocks have obviously been exposed for a much longer time and were probably deposited during an earlier Pleistocene glacial stage. The Weichselian was the warmest of the Pleistocene glacial stages and it is probable that the ice was much thikker during the earlier stages (e.g. Elsterian and Saalian). To overrun Mount Gass, Blaiklock Glacier must have been more than 500 m thicker than it is today, i.e. at least 160 m thicker than at the height of the Weichselian.

With such ice thicknesses, the Otter Highlands (Fig. 13) would also not have been a hindrance to the ice flow. Polished sandstone, striations and crescentic gouges observed at the summit of Mount Lowe (950 m) indicate ENE-WSW flow of the ice. These erosional forms were well preserved and were only partially erased by frost shattering. No erratics were found. It must be assumed that this area was overrun during an earlier Pleisto-

Sample no.	sampling site	main components	secondary components	sec./trace components	trace componont	rock below salt crust	underlying rock
1	Mount Wegener	thernardite	-	-	pyrophyllite? ± mirabilite	quartzite	mica schist
2	Mount Wegener	thernardite	-	-	pyrophyllite? ± mirabilite	quartzite	arkose
3	Escola Cirque	thernardite	daiapskite	muscovite/ illite	bloedite ± pyrophyllite	vein quartz	granite
4	Stephenson Bastion (C2)	bloedite	quartz	hexahydrite	calcite / gypsum polyhalite?	granite erratics	till matrix
5	SE Turnpike Bluff	thernardite	quartz	-	muscovite / illite kaolinite / mirabilite polyhalite	schist	schist
6	Mount Provender (P12)	thernardite	quartz	dolomite or polyhalite gypsum / mirabilite pyrophyllite	± kaolinite	gneiss erratics	till matrix
7	Mount Provender (P3)	thernardite	-	-	mirabilite ± kaolinite	granite erratics	till matrix

Tab. 3: Analyses of seven samples of salt crusts and the rocks below which they were found.

Tab. 3: Analysen von sieben Salzkrusten und den in der Unterlage der Fundorte anstehenden Gesteinen.

Sampling site	Stephenson Bastion					
Sample no.	C2A	C2B	C2B	C4A	C4B	C5
Sample depth (cm)	5-10	10-20	10-20	3-6	10-20	10-20
Gravel	21	35	20	47	57	38
Coarse sand	9	9	13	16	14	5
Medium sand	11	9	12	11	9	6
Fine sand	22	18	20	11	9	8
Silt	34	25	28	11	8	23
Clay	3	4	8	5	3	21

Tab. 4: Grain-size distribution (wt.%) in six samples of till from Stephenson Bastion. Sampling site locations are marked in Fig. 7.

Tab. 4: Korngrößenverteilung (Gew.%) in sechs Proben aus Moränen von Stephenson Bastion. Probenpunkte sind in Abb. 7 markiert.

cene glacial stage. A reliable age determination could not be obtained.

3.2.1.2 Mount Skidmore and surrounding area

There are large flat areas free of ice and snow covered with till showing various degrees of weathering around Mount Skidmore, which is 20 km NE of Mount Provender. Numerous moraines cross these areas. The results of four days of mapping these areas are compiled in Fig. 22.

The till in the area around Mount Skidmore is quite different from that in the Mount Provender area. It contains more debris (pebbles and larger clasts >50 %) and the matrix consists mainly of sand (all particle sizes) with a small amount of silt. The erratics are considerably less rounded (commonly only at the edges) and seldom show striations. The grey salt crusts on the undersides of the clasts are very thin, similar to those on Mount Provender. There are considerable differences, however, in the degree of weathering of the till within the moraines. Between

Sampling site	C5	C2	C1
Site elevation (m)	1485	1350	1470
Number of erratics counted	260	119	120
Reddish-brown Beacon Sandstone			
fresh faces mostly reddish-violet	61	51	54
Light-grey archaeocyathid and other usually fossil-bearing limestones	2	0	0
Metaquartzite, breccia and conglomerate	3	9	10
Igneous rocks (granite, gneiss)	4	10	11
Greenish-grey quartzite from the Stephenson Bastion Formation (local origin)	30	30	16
Schist (local origin)	0	0	9

Tab. 5: Results of an inventory of erratics (%) on Stephenson Bastion and Clayton Ramparts. Sampling sites are marked in Fig. 7.

Tab. 5: Geschiebeanalyse (%) auf Stephenson Bastion und Clayton Ramparts. Probenpunkte sind in Abb. 7 markiert.

Fig. 21: Lundström Lake on Mount Gass.

Abb. 21: Der Lundström-See am Mount Gass.

the edge of Slessor Glacier (elevation ca. 250 m) and elevations of about 450 m, the degree of weathering is very similar to that on Mount Provender. From 450 m to 650 m, the till is considerably more weathered (more frost shattering, marble erratics completely disintegrated, granite and sandstone tafoni). The boundaries between the weathered areas are mostly marked by moraines 2-5 m high (Fig. 22).

The younger, less weathered moraines include the Blaiklock Drift on Mount Provender, which was most likely deposited during the Weichselian. The moraines at higher elevations are more weathered and may be assumed to have been deposited during an earlier Pleistocene glacial stage (?Saalian). The small ice tongues extending from the south side of Stratton Glacier (A and B in Fig. 22) must have moved in their present direction during the Weichselian since the moraines in front of them are little weathered.

Petrography of the erratics

In contrast to the Mount Provender area, the erratics in this area are mostly igneous and metamorphic rocks (Fig. 6, Tab. 8). The source area for Köppen Glacier (on the east side of Mount Skidmore) is mainly in the Shackleton basement outcrop area. The sedimentary erratics probably derive from the Blaiklock Glacier Group, which must crop out at the west edge of the Köppen Glacier. This is supported by the presence of rocks of this formation just south of Mount Skidmore in The Dragon's Back area.

Age of the Moraines

The only slight weathering of the moraine material on Mount Provender and surrounding area is evidence that it was deposited relatively recently. In contrast to the old moraines on Stepheson Bastion, a wide range of non-resistent rocks are preserved, some showing striations. The matrix has a high carbonate content, which in the old till is no longer present (Tabs. 4 and 6). Chemical weathering has produced only a thin veneer of salt crystals on the undersides of the clasts, in contrast to the salt crust up to 2 cm thick in the old moraines.

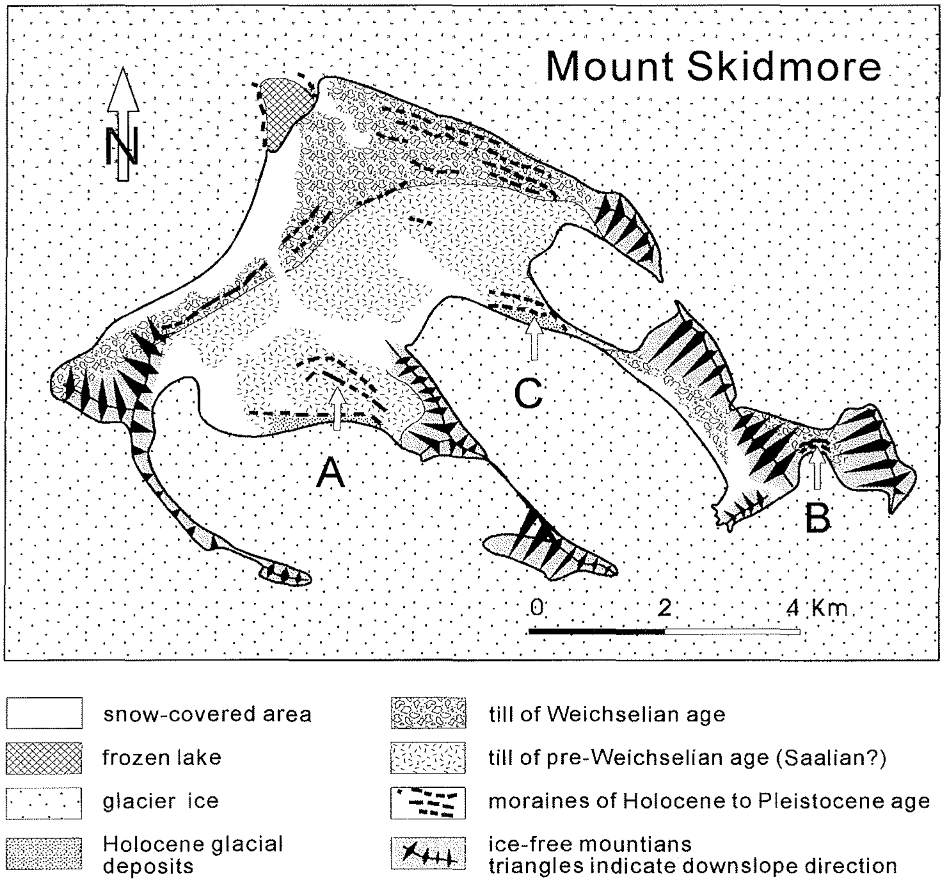

Fig. 22: Quaternary deposits on and around Mount Skidmore.

Abb. 22: Quartäre Ablagerungen auf und um Mount Skidmore.

Sampling site	Mount Provender										Du Toit Nunatak	
Sample no.	P1A	P1B	P2A	P2B	P3A	P3B	P13A	P13B	P16A	P16B	DT1	DT2
Sampling depth (cm)	1-5	10-20	5-10	15-22	1-5	10-20	0-5	10-20	0-5	10-20	10-15	10-15
Gravel	22	47	31	11	47	3	26	1	25	29	13	31
Coarse sand	28	10	27	27	19	13	15	9	19	15	23	21
Medium sand	20	12	20	31	12	11	10	11	25	21	14	13
Fine sand	15	8	11	16	7	10	8	13	12	12	15	12
Silt	13	14	5	10	9	23	19	37	12	14	25	16
Clay	3	0	4	5	7	23	19	37	12	14	25	16
Carbonate	16	13	16	23	10	5	1.7	1.6	3.3	3	8	8

Tab. 6: Grain-size distribution (wt.%) and carbonate content (wt.%) in ten samples of till from five sampling sites just south of Mount Provender (Fig. 14) and two samples from Du Toit Nunatak.

Tab. 6: Korngrößenverteilung (Gew.%) und Karbonatgehalt (Gew.%) in 10 Moränenproben von fünf Probepunkten unmittelbar südlich des Mount Provender (Abb. 14) sowie zwei Proben vom Du Toit Nunatak.

Sampling site	P1	P3	P5	P6	P7	P8	P9	P10	P11	P12	P13	P15	P17	P18	GASS
Number of erratics counted (Ø >2 cm)	137	126	74	104	89	67	101	114	102	99	75	156	127	132	74
Quartzite	12	10	8	5	.	.	.	.	.	.	.	.	.	.	30
Limestone conglomerate and breccia	7	7	1	.	2	.	1	.	.	.	.	1	2	.	.
Reddish-brown and ??? limestone)	3	12	.	2	.	.	3	4	.	1	.	4	.	.	14
Marble	6	8	.	1	.	1	.	.	.	.	.	.	.	.	.
Sandstone	23	25	35	53	40	46	38	23	55	22	15	49	56	19	.
Conglomerate and breccia	1	.	.	.	.	.	.	.	.	.	.	1	2	.	3
Dark grey schist	4	11	4	14	44	39	30	7	5	57	73	12	23	3	24
Reddish-brown schist	.	6	4	.	.	4	4	5	5	.	1	1	2	.	.
Total sedimentary rocks	56	79	53	75	90	91	75	39	65	80	89	60	83	22	.
Granite	6	1	.	.	.	.	.	.	.	.	.	.	.	.	.
Garnet gneiss	14	7	9	.	.	.	.	26	.	.	.	.	.	.	.
Garnet-mica schist	4	.	5	.	.	.	.	.	.	.	.	.		.	.2
Mica schist	8	2	8	.	.	.	.	.	.	.	.		.	.	.
Gneiss	11	12	16	.	.	.	.	.	.	.		.	.	.	.
Amphibolite schist	9	.	7	.	.	.	.	.	.	.	.	1	.	.	.
Dolerite	1	.	1	.	.	.	.	.	.	.	.	.	.	.	.
Total non-sedimentary rocks	44	21	47	25	10	9	25	61	35	20	11	32	17	110	27

Tab. 7: Results of an inventory of erratics (%) in the Mount Provender area and at Lake Lundström on Mount Gass.

Tab. 7: Geschiebezählungen (%) im Bereich Mount Provender und am Lundström-See am Mount Gass.

Till with a similar degree of weathering, and thus assumed to be of similar age, has been studied along the coast of Victoria Land (e.g. DENTON & HUGHES 1981, CHINN et al. 1989), where it was demonstrated that the Ross Ice Shelf at the height of the Weichselian about 18,000 years ago advanced more than 600 km farther north than today. This was due to a sea-level lowering of up to 150 m (DENTON & HUGHES 1981) resulting from the tying up of water in continental ice sheets, mainly in the Northern Hemisphere. The ice shelves were grounded on the sea floor and the ice flow slowed. This led to an increase in the thickness of the ice. Thus, along the present ice-free coast of Terra Nova Bay, the moraines of the part of the Ross Ice Shelf that advanced during the Weichselian are as much as 350 m below present sea level.

Because the sea level lowering was worldwide, the Filchner and Ronne Ice shelves must have been affected in the same way. The northwestern part of the Shackleton Range is adjacent to where Slessor Glacier enters the Filchner Ice Shelf. Any increase in thickness of the ice shelf would cause a backing up of the ice at the mouth of the glacier. The young moraines occur up to an elevation of 640 m. Slessor Glacier and its tributary Blaiklock Glacier must have increased in thickness by about 350 m in order to deposit material at this elevation (Fig. 23); this corresponds to the increase in thickness determined for the Ross Ice Shelf.

Sampling site	sk1	sk2	sk11
Quartzite, green, light grey, grey, brown	5	20	30
Sandstone greenish grey dark grey, black	5	10	5
Conglomerate and breccia	5	.	.
Limestone	.	2	2
Marble	5	3	.
Total sedimentary rocks	20	35	37
Amphibolite, sometimes with garnet	35	20	10
Garnet-muscovite gneiss	15	5	.
Quartz-rich foliated gneiss	30	.	40
Quartz-rich gneiss, amphibole layers	.	35	10
Green-mica schist	.	5	3
Total metamorphic rocks	80	65	63
Number of erratics counted	115	122	118

Tab. 8: Results of an inventory of erratics (%) in the Mount Skidmore area. Sampling sites are marked in Figure 24.

Tab. 8: Geschiebezählungen (%) im Bereich Mount Skidmore. Probenpunkte sind in Abb. 24 markiert.

The backing up of the glacier at its mouth had less effect in the Mount Skidmore area, 20 km upstream, where the glacier increased in thickness by only 200 m. On the basis of the „old“ moraines, the surface of the glacier must have been at least 400 m higher during the earlier Pleistocene glacial stages.

As the global sea level rose again, the level of the glacier ice on the northern side of the range became lower. Gradually the area around Mount Provender became free of ice, probably during the early Holocene. During the middle Holocene, the level of the ice was probably even lower than at present. The evidence for this (Fig. 24) is provided by the presence of lake-bottom algae above the present shore of Lake Lundström near Mount Gass (southeast of Mount Provender). The lake is in a depression with no exit, mostly surrounded by glaciers. The lake level must have risen above the present level at least twice due to increased input of meltwater during warm periods of the Holocene. The lake extended to the foot of cliffs on one side from which falling debris covered aögae on th lake floor, preserving them when the lake level dropped again (Figs. 21 and 24). Radiocarbon dating of the algae from the foot of the cliff 2 m above the present lake level yielded an age of 2808 ±100 years; for the algae from the foot of the cliff 20 above present lake level, an age of 4630 ±150 years was obtained. Since the algae lie on Blaiklock Drift, the moraine material must be older than the higher occurrence of algae.

3.2.2 The Holocene glaciers

Information about glacier movements during the Holocene was obtained mainly in the Mount Skidmore area. Slightly weathered till was found in the ice- and snow-free areas in front of three glaciers (A, B, C in Fig. 22). This material covers an area 100-300 m wide in front of the present glaciers. The fresh till is quite distinct from the Weichselian till. Only in front of glacier C are there three separate moraines; in the other cases, the till is not separated into several terminal moraines. Lateral moraines are present along all three glaciers; these moraines are 2-4 m high. In some places fresh debris is being added to the lateral morai-

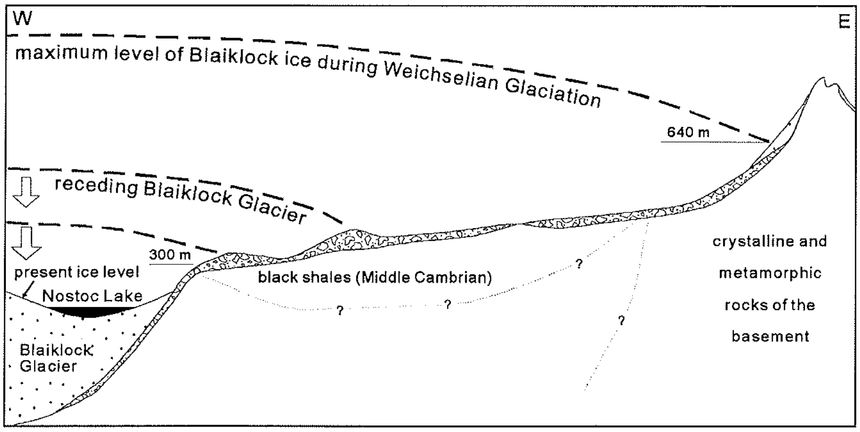

Fig. 23: Cross section through Blaiklock Glacier and underlying bedrock at the time of the Weichselian maximum and at the time of deposition of the lateral moraines during the Wechselian Late Glacial.

Abb. 23: Querschnitt durch den Blaiklock-Gletscher und unterlagernde Gesteine während des Weichsel-eiszeitlichen Maximums und zur Zeit der Ablagerungen der Seitenmoränen während der späten Weichsel-Eiszeit.

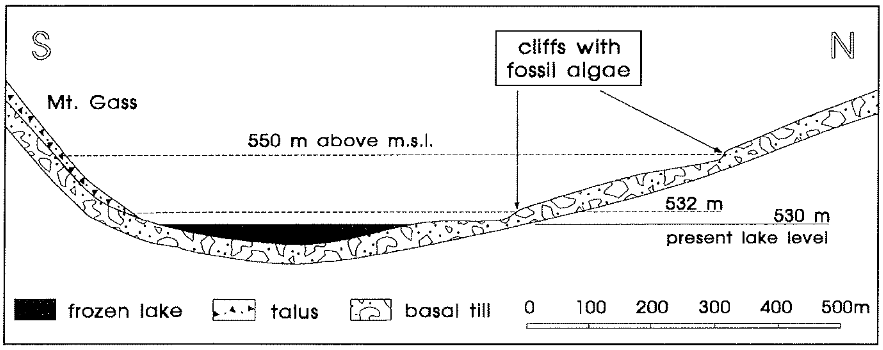

Fig. 24: Section through Lake Lundström on Mount Gass showing earlier, higher lake levels.

Abb. 24: Schnitt durch den Lundström-See am Mount Gass mit früheren höheren Seespiegel Ständen.

Fig. 25: Subrecent moraine in front of glacier B (marked in Fig. 24) in the Mount Skidmore area.

Abb. 25: Subrezente Moränen vor Gletscher B (markiert in Abb. 24) im Mount Skidmore Gebiet.

nes from the zone of shearing at the base of the 8-10 m high, cliff-like glacier sides (Fig. 24). For the most part, the glaciers have retreated several metres from the lateral moraines.

The algae 2 m and 20 m above the present lake level on Mount Gass are evidence of a warm period at the beginning of the Subboreal (4630 ±150 B.P.) and one just before its end (2782 ±145 B.P.), during which the lake was filled with meltwater.

Dead ice was observed in Brown Cirque on Mount Wegener in the Read Mountains. It has obviously had no new input of ice for a long time: A typical dead ice landscape has formed consisting of ridges and hills up to 12 m high covered with a thin layer of debris up to 20 cm thick. There is more evaporation and melting in the areas containing no debris, leading to more rapid sinking of the surface in those areas. A small stream leading to a lake more than 1 m deep was observed to originate in one of these areas.

4. INFORMATION FROM ERRATICS ABOUT SUBGLACIAL BEDROCK

An inventory was made of erratics in subrecent till on a local glacier at Du Toit Nunataks, western Read Mountains. There is a terminal moraine 50-250 m wide at the end of the glacier; the till in this moraine is little weathered and contains some limestone boulders. Analysis (grain size and carbonate) of two samples of matrix material showed it to contain a high proportion of fine gravel, sand, silt and little clay (Tab. 6).

On the bedrock of dark grey amphibole schists with aplite veins, the till was only several decimetres to somewhat more than 1 mm thick. It could be seen that numerous rocks in the till were not derived from the underlying bedrock. An inventory of the erratics yielded the results given in Tab. 9.

The glacier flows from the southern end of a plateau about 10 km long and 5 km wide, with numerous cirques on three sides. The southern end of the plateau divides into two branches. Ice from the eastern one flows onto Hatch Plain. The source area for the till on this plain is thus very small. It is unlikely to be reworked old till, like on Stephenson Bastion, because the characteristic Beacon Sandstone is not present. The fossil content of fourteen limestone clasts was analyzed. Three of them contained abundant fossils: an *Epiphyton* wacke to floatstone and two archaeocyathid-epiphyte boundstones. The barren limestone and sandstone clasts could be derived from the Watts Needle Formation, whose type locality is only 13 km to the east. The fossil-bearing limestone clasts do not fit any source area in the Shackleton Range, although limestone clasts with *Epiphyton* (but without archaeocyathids) were found in the Mount Wegener Formation. If these clasts are from a source area to the south, by comparison with the situation on Mount Greenfield other material from the south should also be present (e.g. Beacon Sandstone). Since this is not the case, the source area must be considered to be unknown.

Number of erratics counted	112
Limestone	2
Dark quartzitic sandstone or quartzite	63
White sandstone	11
Schist (local origin)	4
Metamorphic rocks	20

Tab. 9: Results of an inventory of erratics (%) in 1 m^2 of Holocene till on Du Toit Nunatak.

Tab. 9: Geschiebezählung (%) auf 1 m^2 holozäner Moräne auf Du Toit Nunatak.

5. CONCLUSIONS

Subglacial erosional forms and till found in the Shackleton Range indicate that the range was overrun by ice during a glacial stage. This ice flowed from the south, in contrast to the present westerly ice flow direction, leaving its traces at elevations as high as 1750 m. Neglecting any uplift of the range, the ice was at least 650 m thicker, with respect to the present level of Recovery Glacier. This can have occurred only during an increase in thickness of the entire Antarctic ice sheet, in which case the local morphology would no longer have affected the ice flow. An old peneplain was probably incised and molded by the ice sheet, leaving a new morphology when the level of the ice sank again.

A late Tertiary age (end of the Miocene or Late Pliocene) for this extensive ice sheet is suggested by the advanced state of weathering of the rocks in the high parts of the range that are not covered by ice and by the almost complete denudation of the peneplain in the north, as well as by the advanced development of cirques in the south. Slightly weathered till was observed in the northwestern part of the range; on the basis of a comparison with till on the west coast of the Ross Sea, we infer that this till was deposited during the last Pleistocene glacial stage. The level of the ice on Mount Provender rose about 340 m during the Weichselian due to the damming up of Blaiklock Glacier by the Filchner Ice Shelf.

6. PROPOSALS FOR FUTURE RESEARCH

The results of six weeks of field work provide important insight into the glacial history of the Shackleton Range. An initial survey of the glacial deposits and erosional forms, as well as the degree of weathering, had to be done first, leaving little time for detailed studies. It was not possible to search the table mountains, relics of the peneplain, for old till and erosional forms. Trenches were dug in the till on Stephenson Bastion to determine whether older till was present.

With respect to the recent till along the northern margin of the range, the nunataks at the eastern end of the range should also be investigated to confirm whether the rise in the level of the ice at the end of the Weichselian became less towards the east. Under the till from the last Pleistocene glacial stage on Mount Provender, even older till might be found which would provide information about the earlier Pleistocene glacial stages. There was also insufficient time to investigate Holocene glacial history. Hopefully there will be a glacial geologist on a future expedition to delve further into the difficult glacial history of the Antarctic.

REMARKS

Hans-Christian Höfle died suddenly in 1993. He left an almost complete manuscript about the glacial geology of the Shackleton Range, including sedimentary petrographic data provided by Werner Buggisch. The latter tried to complete the unfinished drafts of the figures and the manuscript. In some cases he was not able to reconstruct the position of sample sites and other localities precisely. Nevertheless - in memory of Hans-Christian Höfle - this paper was presented to the publisher.

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