PHYSIOGRAPHY AND GLACIAL GEOMORPHOLOGY OF THE THERON MOUNTAINS

By D. Brook

Abstract. The physiography of the Theron Mountains is described with particular reference to weathering processes, glacial activity, melt phenomena and patterned ground.

This paper presents the results of physiographical and geomorphological observations made during geological and topographical surveys of the Theron Mountains in 1966–67. Glaciological and biological observations were also made, and these aspects of the field work have already been discussed by Wornham (1969), Lindsay and Brook (1971) and Brook and Beck (1972).

Localities mentioned in the text are shown in Fig. 1.

Physiography

Forming the southern margin of a lobe of the Filchner Ice Shelf, the main feature of the Theron Mountains is the steep north-east-facing scarp which was considered by Stephenson (1966) as a fault scarp on the basis of its marked linearity and constant trend. The presence of a similar south-west-facing crevassed ice scarp apparently parallel to the range and about 50 km. to the north-west suggests the possibility that these mountains form the southern edge of a graben occupied by a major ice stream (here called "Main Glacier") flowing south-westwards into the Filchner Ice Shelf.

No direct evidence of major faulting was found and little can be inferred of tectonic events since the end of the Jurassic. The Theron Mountains could have been uplifted prior to the last glaciation of Antarctica, and the present landforms may have been created under quite different conditions and only modified subsequently by the action of ice.

The frontal scarp of the mountains is backed by a broad undulating ice plateau (Fig. 2), which descends southward gently at first and then more steeply culminating in the ice-cliff margin of Slessor Glacier. The scarp is cut by three narrow glaciers flowing approximately in a northerly direction (p. 32).

Area north-east of Goldsmith Glacier

The escarpment of the Theron Mountains can be traced as an ice-covered scarp for several kilometres north-east of Tailend Nunatak. It consists of a series of approximately north-west to south-east-trending snow ridges which terminate abruptly against "Main Glacier". Tailend Nunatak and the small outcrops to the south of it are narrow irregular arêtes which break through the crests of the ridges; they terminate sharply against "Main Glacier" but do not possess the cliff form typical of most of the escarpment.

Farther south-west, the escarpment is more continuous, although rock outcrops are sparse until the long cliff immediately north-east of the mouth of Goldsmith Glacier. Over 300 m. high, the profile of this cliff is dictated by the vertical jointing in the two dolerite sills forming it. The lower sill (here called the scarp-capping sill), which can be traced through most of the mountain range, is over 200 m. thick and the upper one is about 30 m. thick; the top of the cliff generally follows the upper contact of either sill. Ice flows almost to the edge of the cliff except near station Z.487 where roughly triangular peaks of sediments, intruded by dolerite dykes, form a cliff-and-ledge ice-free capping at about 860 m. a.s.l.

There is a gently undulating snow-covered area with only minor rock outcrops south-east of the scarp front; small snow hills rise to over 1,000 m. The north-eastern margin of Goldsmith Glacier is formed by a steep ice scarp with rock cliffs near the mouth at stations Z.466 and 487. Small tributary glaciers descend steeply between the rock outcrops and between the snow ridges farther south.

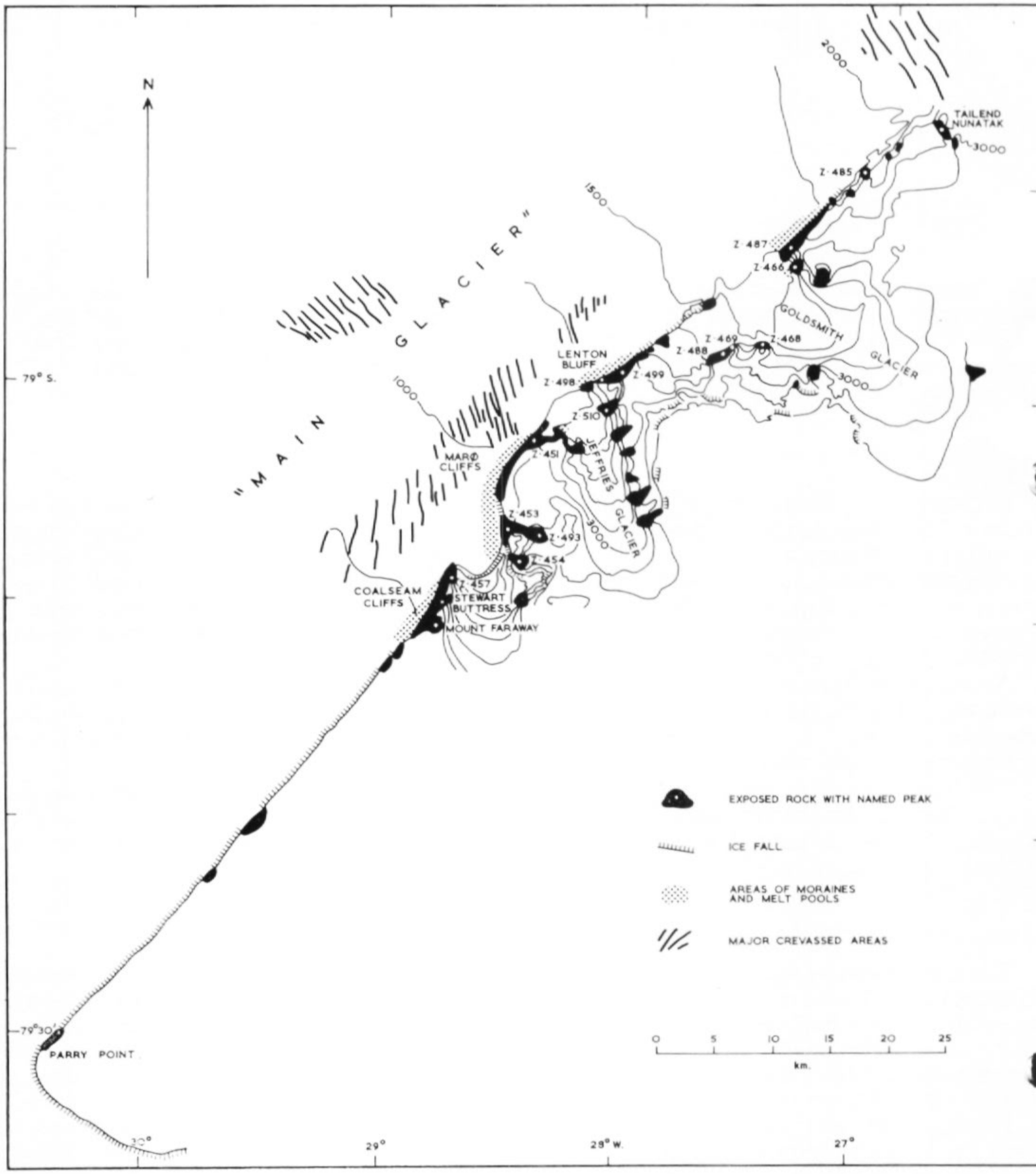

Fig. 1. Sketch map of the Theron Mountains showing the positions of localities mentioned in the text. The form lines are at 250 ft. [76 m.] intervals.

Area between Goldsmith and Jeffries Glaciers

The scarp front is continuous in this area, consisting of an ice cliff at about 600 m. a.s.l., which is breached by occasional rock outcrops, and the long cliff surmounted by the scarp-capping sill of Lenton Bluff.

Lenton Bluff rises rapidly from the ice cliff to over 950 m. a.s.l. at station Z.499, where it is about 580 m. above the surface of "Main Glacier". Strong vertical jointing in the scarp-capping sill results in a near-vertical cliff and the sediments below it receive considerable

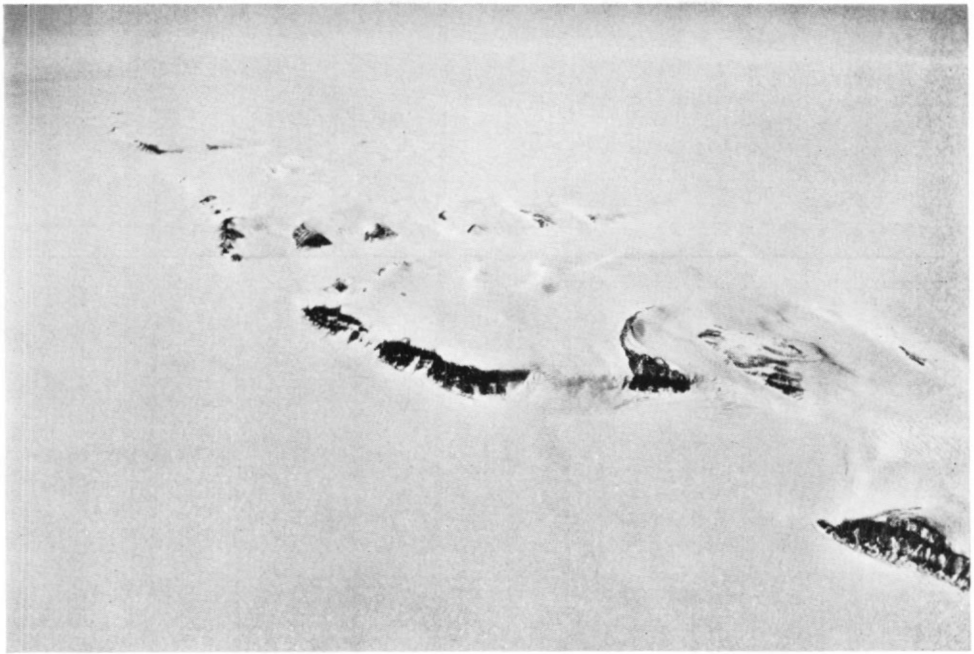

Fig. 2. Air photograph of the Theron Mountains from 8,000 m. a.s.l., facing east. Marø Cliffs are at centre. (Photograph by U.S. Navy for U.S. Geological Survey.)

protection from erosion for some distance beneath the sill. Farther down a cliff-and-ledge topography is developed between extensive talus slopes on the sediments due to the differential resistance to erosion of the sediments and the intervening thin dolerite sills. At station Z.498 (Fig. 3) the hardness of one dyke has resulted in a vertical "wall" up to 6 m. high projecting from the adjacent sediments.

The south-western margin of Goldsmith Glacier is an ice scarp with occasional small cliffs (Z.468), but near the mouth of the glacier it is less distinct because the area between the glacier and Lenton Bluff is relatively low-lying; it only rises above 700 m. a.s.l. in the narrow rock ridge of stations Z.469 and 488. South-east of Lenton Bluff and south of station Z.488 is an undulating snow-covered area devoid of rock outcrops at 800–900 m. with snow hills rising to over 1,000 m. a.s.l. The eastern margin of Jeffries Glacier is a distinct but interrupted scarp (Fig. 2) with short steep tributary glaciers descending between rock ridges from the plateau south-east of Lenton Bluff.

Area between Jeffries Glacier and the unnamed southern glacier

South-west of Jeffries Glacier, the scarp front is continuous but it swings round smoothly from Marø Cliffs, which are surmounted by the scarp-capping sill, to form the eastern margin of the unnamed southern glacier. Marø Cliffs rise steeply from Jeffries Glacier to over 920 m. a.s.l. at station Z.451 (Fig. 4) and the top of the cliffs generally follows the top of the scarp-capping sill, which is often surmounted by ice cliffs up to 20 m. high. The form of the cliff has been largely dictated by vertical jointing in the scarp-capping sill and other thick sills which intrude the sediments beneath it. Except near the ice fall which breaches the cliffs 2 km. south-west of the mouth of Jeffries Glacier, near-vertical buttresses are separated at wide intervals by steep talus and snow slopes. The eastern margin of the unnamed south glacier is formed by steep cliffs in the scarp-capping sill, above which is a cliff-and-ledge topography in the sediments and thin dolerite sills at stations Z.453 and 454. Ice cliffs separate these outcrops and only south

Fig. 3. The south-western end of Lenton Bluff (Z.498) viewed from the north. Dolerite dykes form wall-like projections from the intruded sediments; the cliff-forming basal sill is succeeded by cliff-and-ledge topography in both the sediments and the thin sills above it.

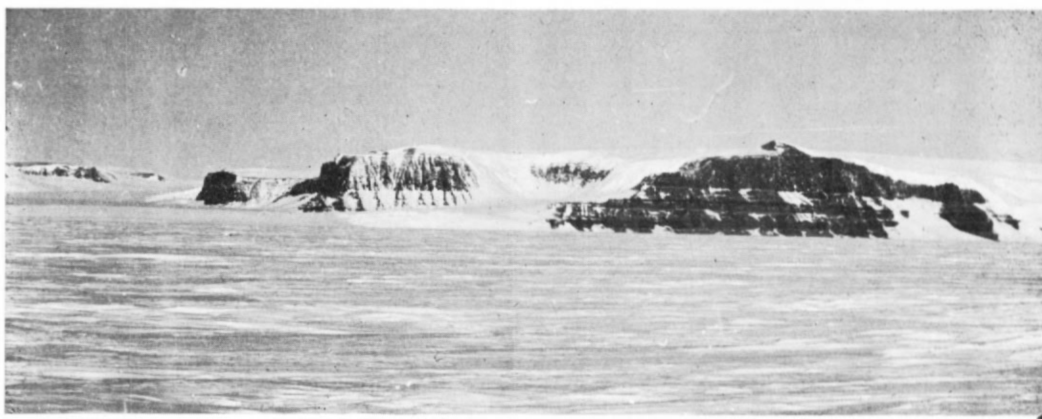

Fig. 4. Marø Cliffs, north-east of the central ice fall and the small cirque on the south-western margin of Jeffries Glacier, viewed from about 8 km. north-west of the scarp front.

of station Z.454 does a small tributary glacier descend gradually to the unnamed southern glacier.

The south-western margin of Jeffries Glacier is formed by a steep ice scarp except near its mouth, where cliffs formed by the scarp-capping sill occur at the heads of small cirques north-east of station Z.451 (Fig. 4). South-east of Marø Cliffs is an undulating snow-covered area between the two glaciers at about 950–1,000 m. with snow hills rising to 1,100 m. a.s.l. The only rock outcrops (Figs. 2 and 5) are the arête east of station Z.453, rising to 1,091 m. at station Z.493, and the more rounded largely scree-covered outcrop at station Z.454 (1,081 m. a.s.l.).

Area south-west of the unnamed southern glacier

South-west of the unnamed southern glacier, the escarpment is continuous for a further 50 km. in the form of Coalseam Cliffs and ice cliffs (with occasional windows of dolerite

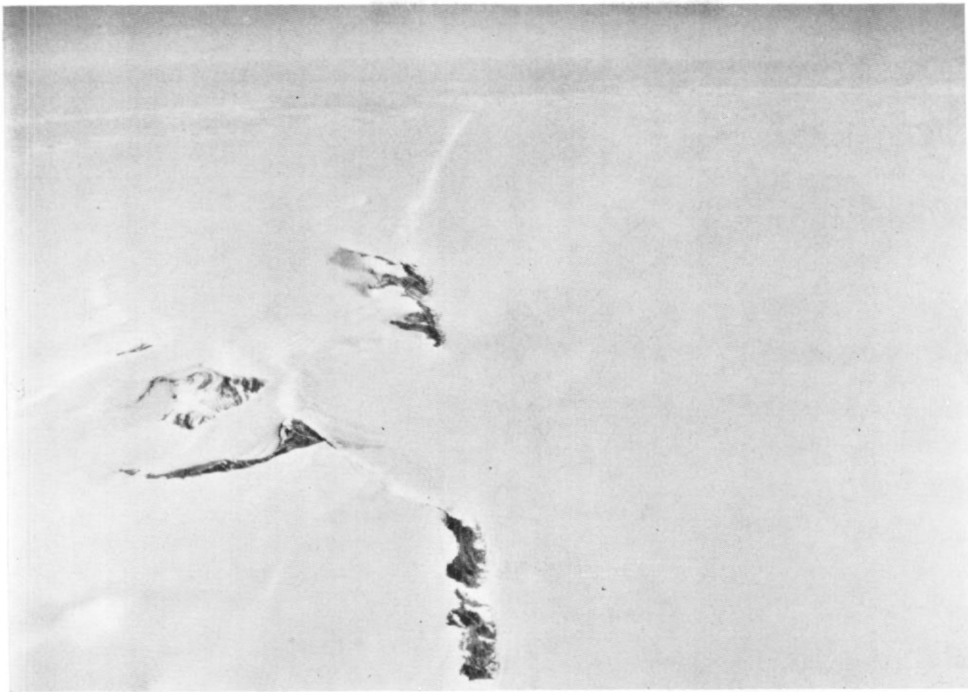

Fig. 5. Air photograph of the western end of the Theron Mountains from 8,000 m. a.s.l., facing south-west. Marø Cliffs are at the bottom centre and Parry Point is at the distant end of the escarpment. (Photograph by U.S. Navy for U.S. Geological Survey.)

(Fig. 5)), which decrease in height south-westwards before being swamped by the outflow of Slessor Glacier south-west of Parry Point. Coalseam Cliffs (Fig. 6) exhibit the effects of differential erosion of the sediments and dolerite sills, with three 30–60 m. thick sills forming near-vertical cliffs between which buttresses of sediments and thin dolerite sills with a cliff-and-ledge topography are separated by extensive talus slopes. The summits of the cliffs rise to almost 1,040 and 1,140 m. a.s.l. in Stewart Buttress and Mount Faraway, respectively; both are rounded summits with extensive *felsenmeere* and they are capped by exfoliated boulders of a dolerite sill. Between these two summits, and between station Z.457 and Stewart Buttress the rock cliffs are surmounted by ice cliffs. South of Mount Faraway (Fig. 5) is a gently undulating snow-covered area which decreases in height southwards and south-westwards to Slessor Glacier and the Filchner Ice Shelf. The south-western extremity of the mountain range is formed by a steep, moderately crevassed ice slope which becomes steeper eastwards to form the northern ice-cliff margin of Slessor Glacier.

Weathering and Erosion

The main detailed features of the landscape are caused by frost action but other agents appear to have had a considerable effect in local areas.

Frost action

The mean annual temperature in the Theron Mountains is about -22° to -26° C; the mean of over 200 measurements taken at different localities and at various times of day by A. Johnston and M. M. Samuel between November 1966 and February 1967 is $-9 \cdot 3^\circ$ C. However, in the immediate environment of rock outcrops the air temperatures commonly rise sufficiently to cause melting of snow and ice during the summer months. Consequently, water derived from melting snow is an effective fracturing agent when it freezes at night in cracks. Loud reports

Fig. 6. Stewart Buttress and part of Coalseam Cliffs viewed from the north-west. The three main cliff-forming sills are separated by more gentle slopes on sediments.

from falling blocks of rock and ice were not uncommon when the author was camped near rock outcrops.

The results of intensive frost action are different on cliff faces from those on top of the cliffs. Fractured material falls by gravity from the cliff faces, resulting in fresh joint-block faces with extensive screes and angular blocky weathering, particularly of the dolerite sills. Frost-shattered material remains *in situ* on the gentler slopes, resulting in large areas of *felsenmeere* which may then be exposed to such processes as frost heaving to form patterned ground (p. 34). Frost shattering may also have some effect in the exfoliation process, resulting in spheroidal weathering of dolerite on gentler slopes.

Wind action

The erosive power of wind carrying ice particles is significant at low temperatures, and sand-blasting can be effective near the surface in an arid area. Sand grains were observed on and in the snow up to several kilometres down-wind of the nearest rock outcrop. Though many

authors have described wind-eroded features from Antarctica, no particularly striking examples were seen in the Theron Mountains. However, wind erosion on snow is extremely effective, and sastrugi, windscoops, snow dunes and blue-ice areas are common. The main area where such features occur is on and alongside "Main Glacier", where air flow is channelled parallel to the scarp.

Running water

During the summer months there is considerable melting of the snow resting on rock and of ice cliffs above rock exposures and small streams are common. These streams are to some extent effective in eroding the rocks and transporting the resultant material. Though the streams are not generally highly charged with debris, mud slurries were occasionally seen on Coalseam Cliffs. Small gullies observed in moraines and *felsenmeere* are probably attributable to melt streams, possibly accentuated by nivation. Melt streams flowing from rock outcrops on to the glaciers commonly form large melt pools and these are often connected by streams (p. 32).

Although the overall effect of running water in the Theron Mountains is probably less than that of other agents, it is not insignificant in the summer months.

Chemical weathering

In an arid frigid climate, such as that of Antarctica, chemical weathering is restricted but it is not ineffective. Around the Antarctic petrel colony beneath Stewart Buttress there is quite deep weathering of the sedimentary mantle, which may properly constitute a true soil because of the amount of organic matter derived from the petrel colony. Elsewhere, chemical weathering is probably of increased effectiveness in restricted areas where other bird colonies and mosses occur in relative abundance. Exfoliation and spheroidal weathering of dolerite is also affected by chemical weathering; some exfoliated boulders may have weathered crusts up to several millimetres thick. Cavernous weathering (cf. Van Autenboer, 1964; Juckes, 1969) was not observed.

No evidence of chemical precipitation, such as that of gypsum (Van Autenboer, 1964; Stephenson, 1966) or calcite (Juckes, in press), was seen in the Theron Mountains. The only encrustations observed were of an organic origin, associated with bird colonies, but they are not as well developed as those in Heimefrontfjella (Ardus, 1964).

Glaciers

The main flow of ice in this area is from the polar plateau in the north-east towards the Filchner Ice Shelf and it is channelled in two large glaciers on either side of the Theron Mountains. In the plateau area of the mountains the ice flow is dominantly to the north-west or south-east towards these two major glaciers. Ice-movement vectors for "Main Glacier", Goldsmith Glacier and near the mouths of Jeffries Glacier and the unnamed southern glacier have been given by Wornham (1969).

Slessor Glacier

Slessor Glacier was not examined in detail but it appears to be a fast-moving ice stream over 60 km. wide and at least 160 km. in length bounded on each side by ice cliffs and extensive areas of crevassing. Stephenson (1966) suggested that it arose indefinitely from the margin of the Antarctic ice sheet and V. E. Fuchs (personal communication) thought its head region had a clover-leaf form. It flows westwards, only becoming a clearly defined glacier between the mountain ranges before merging with the Filchner Ice Shelf.

"Main Glacier"

About 50 km. wide and over 100 km. long, this glacier flows south-westwards parallel to the scarp of the Theron Mountains and descends from over 600 m. near Tailend Nunatak to under 200 m. a.s.l., merging imperceptibly with the Filchner Ice Shelf somewhere south-west of Mount Faraway. Its major crevasse zones, ice-movement vectors and blue-ice areas have been illustrated by Wornham (1969, fig. 1).

Goldsmith Glacier

Flowing north-westwards for 25–30 km., this glacier descends from the plateau at about 1,050 m. to "Main Glacier" at about 530 m. a.s.l. It is 5–7 km. wide and there are well-defined crevassed zones along its margins. It is fed by small tributary glaciers from the north-east and south-west. Blue ice and moraines were seen only at the foot of the truncated spur at station Z.466.

Jeffries Glacier

This glacier is 4–5 km. wide and flows north-north-westwards for over 20 km., descending from over 1,050 m. to about 370 m. a.s.l. Small tributary glaciers descend from the plateau, and on its south-western side small cirques near the mouth of the glacier (Fig. 4) are partly fed by ice from the plateau above. Extensive crevassing is present along the glacier margins especially on its eastern side. At the mouth of the glacier, a prominent ice tongue extends for over 1·5 km. into "Main Glacier". This is marked by pressure ridges, the crests and northern sides of which are bounded by blue ice. The blue ice could have been formed either by ablation (Wornham, 1969) or by horizontal compression under flow (Crary and Wilson, 1961).

Unnamed southern glacier

Flowing north-north-westwards, this glacier is about 4 km. wide and 13 km. long, descending from over 840 m. to under 300 m. a.s.l. An ice tongue extending from the foot of the ice fall half-way down is marked by a certain amount of blue ice. The main source of this glacier is to the south and east, for the catchment area on Mount Faraway is of limited extent. On its eastern side, three prominent tributary glaciers, each less than 5 km. long and 1·5–2·0 km. wide, meet this glacier in ice falls; these are followed down-stream by progressive waves of blue ice probably formed in the same manner as those described by Crary and Wilson (1961). Extensive moraines and ablation blue ice extend from the foot of the cliffs beneath station Z.453.

Moraines and Melt Pools

Moraines and melt pools are common along the margins of "Main Glacier" and in the lower reaches of its three tributary glaciers.

Moraines

At the foot of the scarp, frost-shattered debris extends as scree for several metres and as lateral moraines parallel to the scarp for several hundred metres (Figs. 7 and 8). They may consist either of debris ridges or isolated boulders, usually on the crest of a small snow ridge. Because talus slopes emerge at different points along cliff faces, moraines often form a series of parallel ridges varying in height from 1 m. to about 10 m. (Fig. 8). Inter-moraine depressions may be either snow-covered or infilled by melt pools.

The size of the morainic material varies from sand and silt to boulders a few metres across. Though its composition is variable, there is no material which could not have been locally derived. Many of the wind-formed features (p. 31) have developed on a small scale around individual boulders.

Lateral moraines occur alongside the four major cliffs of the scarp front, at the foot of the truncated spur at station Z.466, on the south-western margin of Jeffries Glacier and at the foot of the cliffs beneath station Z.453. Englacial moraine was seen in isolated areas in crevasses but only in "Main Glacier" and Jeffries Glacier.

There are no moraines in the plateau area of the Theron Mountains. Just south of Lenton Bluff, isolated boulders rest on the snow surface at about 670 m. a.s.l. but they have probably rolled from the cirque above; although they are several metres from the nearest rock outcrop, they are technically scree deposits.

Melt pools

Melt pools of varying sizes (Figs. 7 and 8) occur among the moraines. Even at the height of the summer their surfaces are usually thinly covered with ice but where rock debris forms the

Fig. 7. A moraine ridge (in the distance) which disappears beneath the snow surface at the south-western end of Lenton Bluff. At the foot of the scree (in the foreground) is a melt pool with ice mounds; the melt pool merges with blue ice, which has in parts a thin snow cover between the melt pool and the moraine ridge.

margin of the pool there may be an ice-free zone. One pool sounded by D. K. McKerrow was about 4 m. deep. Streams between pools are of varying sizes and some of them can be traced for several hundred metres. They are up to 1·0–1·3 m. deep and may be ice-free at the surface. They flow on a bed of ice (often fluted) or of moraine but the amount of debris carried is small.

Circular to elliptical ice mounds, similar to those in the Sør-Rondane (Van Autenboer, 1962) and the Shackleton Range (Stephenson, 1966) occur on many of the pools (Figs. 7 and 8). They vary in size but are generally 2–10 m. in diameter and 0·2–1·5 m. in height. Crevasses radiating from the centres of the mounds pinch out at the margins. The ice comprising the mounds is white with numerous air bubbles, and it is quite distinct from the bluer ice of the pools, but no cellular structure (Cailleux, 1962) was observed. They are considered to be expansion mounds caused by water freezing at depth.

Melt pools occur in all the places where moraines are present. Small insignificant pools in windscoops are often difficult to distinguish from the blue ice caused by ablation.

In the blue-ice area north-west of Marø Cliffs, cryoconite holes (cf. Crohn, 1959; Van Autenboer, 1962) are common. They have been formed either by isolated boulders or pockets of

Fig. 8. Melt pools and scree/moraine ridges viewed from the summit of Lenton Bluff (station Z.499). (Photograph by A. Johnston.)

wind-blown sand sinking through the ice. They are typically circular patches of darker blue ice in the surrounding blue ice which is richer in air bubbles, and some of them may have a small amount of water resting on and around the contained debris.

Other Glacial Features

Stephenson (1966) noted abundant ice striations on the shoulders of the ridge rising to Mount Faraway from the east. Although ice flows over the scarp in many places and the smooth profiles of other parts strongly suggest bevelling by ice, no indications of similar striations were seen. The ice has probably retreated since the last glaciation but the absence of trim lines noted by Wornham (1969) and extensive *felsenmeere*, which would have destroyed any original striations, does not indicate very recent retreat. There is no evidence of multiple glaciation such as that described from Victoria Land (Péwé, 1960; Bull and others, 1962).

On several ridges, isolated blocks of dolerite rest on top of sedimentary rocks, though the nearest dolerite outcrop is several tens of metres distant. These could be glacial erratics but, since they appear to be identical to nearby dolerite, they are considered to be residual blocks.

The snow slope which breaches the middle sill of Coalseam Cliffs below Mount Faraway and other snow-filled depressions on cliff faces are similar to the type III niche glaciers described by Groom (1959). The funnel-shaped hollow beneath Stewart Buttress (Fig. 9) was probably formed by a niche glacier.

Patterned Ground

Patterned ground is common on the tops of cliffs but none was observed in front of the cliffs, either on scree or moraine. It is more abundant and more noticeable on the mantle formed of fissile sandstones and siltstones but it is also present on the mantle formed of dolerite. Much of the following description is based on information provided by A. Johnston and C. M. Wornham.

On top of the cliff at station Z.485, a small flattish area is partially covered by sorted polygons (Washburn, 1956) 2–3 m. across with a border of large stones and a central area of small ones. On top of Lenton Bluff at station Z.499, stripes of material about 25 cm. in diameter are separated by material about 10 cm. in diameter. The ridge at station Z.510 (Fig. 10) is marked

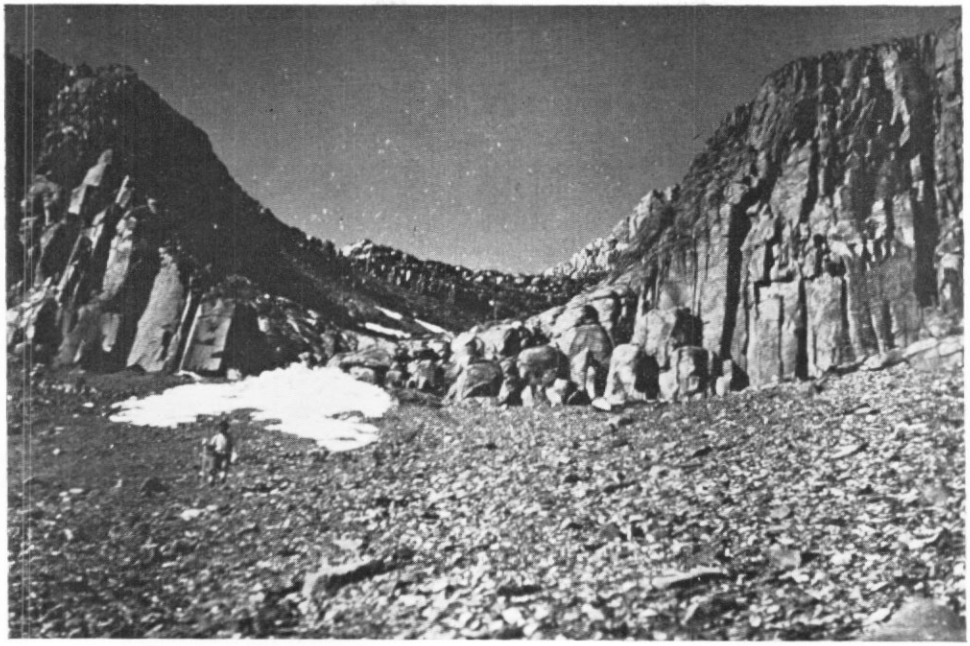

Fig. 9. A funnel-shaped hollow below Stewart Buttress which was probably formed by a niche glacier. This is the site of the Antarctic petrel colony described by Brook and Beck (1972).

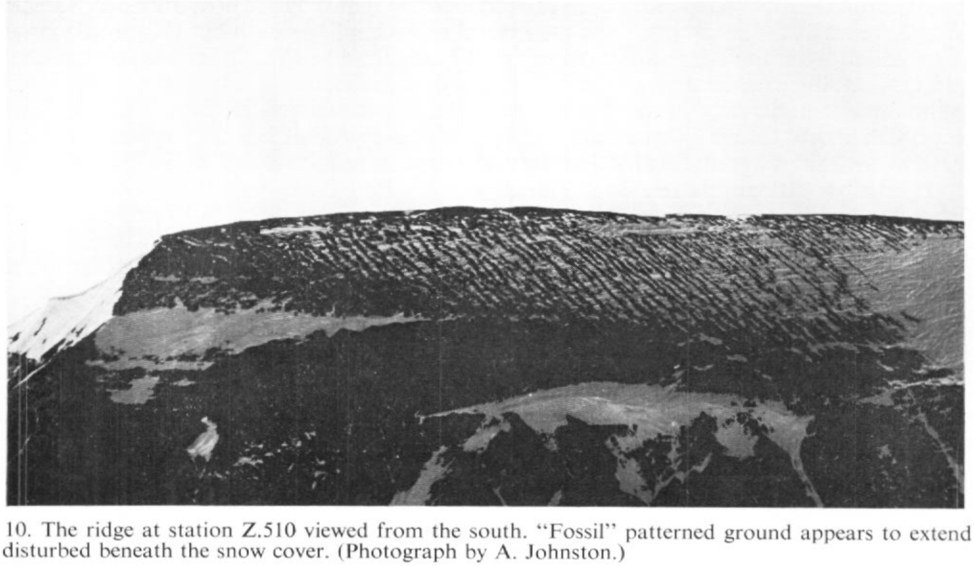

Fig. 10. The ridge at station Z.510 viewed from the south. "Fossil" patterned ground appears to extend undisturbed beneath the snow cover. (Photograph by A. Johnston.)

by stripes trending down the slope but it is uncertain whether these are sorted or non-sorted. The southernmost outcrop alongside Jeffries Glacier has sorted polygons about 4 m. across; the stones are about 25 cm. in diameter and fines are of gravel size. On top of Marø Cliffs sorted polygons 0·2–1·0 m. across have tabular siltstone fragments horizontal in the centres and dipping inwards parallel to the margins in the borders. The ridge east of station Z.453 has

large irregular polygons or circles (probably more properly termed sorted nets) with stripes on steeper slopes. On the ridge of station Z.457, stripes on a 25–30° slope are marked by the sorting of coal and sandstone fragments, the latter being of coarser grade (5–6 cm. compared to <1 mm.).

Stephenson (1961, 1966) has recorded "fossil" patterned ground in the Shackleton Range, 130 km. to the south. These examples are on a relatively large scale compared to most of those in the Theron Mountains, where areas of suitable gradient for patterned ground formation are less extensive. The occurrences in the Shackleton Range are of non-sorted polygons and stripes, and only the stripes at station Z.510 which seem to disappear beneath the snow cover and to be perfectly formed at the snow margin (Fig. 10) are likely to be of a similar form. Other occurrences in the Theron Mountains are of sorted polygons, nets and stripes and they are similar to the sorted circles described by Juckes (in press) except that they usually occur as a network and not singly.

The absence of patterned ground on transported material, such as scree or moraine, in front of the cliffs is probably due to instability because of their rapid rate of transport, though the difference in altitude and consequently in micro-climate may be significant. There appears to be no particular variation in patterned ground with aspect.

Melt-water gullies similar to those described from Heimefrontfjella by Worsfold (1967) have been seen on some of the screes and moraines and in a small dry valley on top of Lenton Bluff. Their somewhat erratic pattern and consequent lack of symmetry excludes them from Washburn's (1956) definition of patterned ground.

Summary

The main physiographical feature of the Theron Mountains is the undulating snow-covered plateau area with isolated nunataks which terminates abruptly to the north-west in the frontal scarp of the Theron Mountains and to the south in the ice-cliff margin of Slessor Glacier. Although there is no direct evidence of major faulting, these features are considered to be fault scarps but there is no evidence as to their age except that they are post-Jurassic. Stephenson (1966) inferred that the sharp profile of the frontal scarp implied youth but this profile may have simply resulted from the dominant erosion agent being frost action. Other erosion agents, such as water, wind and chemical weathering, are locally significant.

The main glacial activity in the Theron Mountains is restricted to "Main Glacier" and its three principal tributaries. Cirque and niche glaciers are present but they are not particularly important. Moraines are all locally derived and they are restricted to "Main Glacier" and the lower reaches of its tributaries. Melt pools, which often have expansion mounds on their surfaces, are similarly restricted. There is little evidence of recent glacial retreat and none of multiple glaciation.

Patterned ground is restricted to the cliff tops but it is present throughout the mountain range. One possible example of "fossil" patterned ground was observed.

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