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ABSTRACT

THE geomorphology of a large ice-free part of South Georgia is described. Pre-glacial erosion surfaces at 20–75, 600–650 and 1,700–2,000 m. a.s.l., and at 100–200 m. below sea-level, have been severely modified by glacial erosion which has also produced impressive cirques, troughs and submarine basins, as well as *roches moutonnées* and knob-and-tarn topography. Glacial erosion was effective as far as 12 km. beyond the eastern coastline and to a depth of 270 m. below sea-level. The deposits of four glacial stages are recognized; two of these are probably older than 5,500 yr. B.P. and the other two date from the late eighteenth to nineteenth centuries and the early twentieth century. South Georgia was probably completely covered by an ice cap during the oldest stage. Conspicuous terminal- and lateral-moraine complexes and contiguous outwash gravels are typically associated with the three youngest stages. The processes forming contemporary moraines at the ice margins are discussed. Adjacent landforms, such as ice-dammed lakes, raised beaches and patterned ground, are also described.

CONTENTS

I. INTRODUCTION AND METHODOLOGY

A PROGRAMME of geomorphological research was undertaken on South Georgia during January–March 1968. This was planned at short notice when summer field work arranged for Deception Island was abandoned because of the volcanic eruption there in December 1967.

An existing 1 : 50,000 topographical map of the Stromness Bay–Cumberland Bay area of South Georgia was enlarged to a scale of 1 : 25,000 using a ½ in. square grid system and this was suitable as a base for field mapping. Employing a system of symbols modified from those drawn up by the I.G.U. Sub-Commission on Geomorphological Mapping, all of the landforms were plotted as accurately as possible in the field. 5 to 10 day camps were made at Husvik, Cumberland West Bay, Moraine Fjord and on the Barff Peninsula; further work was done in the vicinity of King Edward Cove.

In addition to the basic morphological mapping, which served to make a complete inventory of the landforms and an analytical framework, other field techniques employed include the following: the measurement of the dip and orientation of stones in exposures of ground-moraine and raised beach deposits, and in trenches dug through moraine ridges. The field procedure used was similar to that described by Kirby (1969). Analyses of stone shapes in various morainic deposits were made according to the method discussed by Reichelt (1961). 1 m.^{2} of ground was randomly chosen at each locality and a random sample of 50 stones was examined from each site. Two raised beaches were levelled with a Wild T2 theodolite. Peat overlying one of the raised beaches was probed for depth and sampled for analysis and ^{14}C dating; a chambered, graduated peat borer was used to obtain samples.

Apart from assistance by R. J. Henry in the levelling traverses, all of the field work was done alone.

II. GEOLOGY AND TOPOGRAPHY

SOUTH GEORGIA (lat. 54°–55° S., long. 36°–38° W.) is a rugged island with a central mountain range rising to about 2,800 m. The island has a length of over 160 km., a breadth of 5–30 km. and is the largest in the Scotia arc. Elongated in a west-north-west to east-south-east direction, South Georgia lies south of the Antarctic Convergence.

The work of Trendall (1953, 1959) and others (e.g. Holtedahl, 1929) on the structure and geology of the island (Fig. 1) has recently been summarized by Adie (1964*a*). Consisting mainly of Palaeozoic–Mesozoic sediments (greywacke facies and coarse-bedded tuffs) deposited under geosynclinal conditions, and a small igneous complex, the rocks of South Georgia bear an affinity to those of the Antarctic Peninsula and the South Orkney Islands. The widespread occurrence of folded, fine-grained greywackes and tuffs in the Stromness Bay–Cumberland Bay area has probably facilitated the work of glacial erosion and of frost shattering.

There are several well-defined levels in the landscape of South Georgia. Holtedahl (1929) concluded that the prominent submarine platform surrounding the island at a depth of 100–200 m. was cut by a former lower sea-level. Adie (1964*b*) referred to the two principal coastal features—the strandflat close to present sea-level and "wave-cut platforms" at heights of 2·0, 4·8, 6·0–7·0 and 20–50 m. a.s.l. The sea-level abrasion platform is normally backed by a steep rock cliff which marks the front edge of the sloping coastal foreland above. The latter slopes gently but irregularly inland from an altitude of about 20 m., and frequently terminates against a steep mountain front at about 50–75 m. The foreland is well developed on the Barff Peninsula, on the peninsulas between Husvik Harbour and Leith Harbour, and in sheltered bays such as at Sphagnum Valley, Maiviken and Hound Bay; it seems to correlate with remnants of sloping valley benches at similar altitudes in King Edward Cove and Cumberland East Bay. Glacial erosion has severely roughened the foreland into knob-and-tarn topography. The foreland has been differentially eroded by marine action, sea cliffs having eaten further into it on exposed coastlines and in areas of weak bedrock. The cliff edge fronting the feature thus appears at various altitudes.

The next pronounced level in the South Georgian landscape lies at 600–650 m. Rising abruptly above the coastal foreland, this surface is represented by the accordance of mountain tops over wide tracts of land, not only in the Stromness Bay–Cumberland Bay area but also to the north-west and south-east. Cut across a variety of structures, the surface appears to rise gently landwards until it is surmounted by the precipitous front of the Allardyce Range soaring to an array of summits between 1,700 and 2,000 m. Even higher residual mountains rise like monadnocks to altitudes of over 2,150 m.; the plateau summit of Mount Paget at 2,960 m. forms the highest ground.

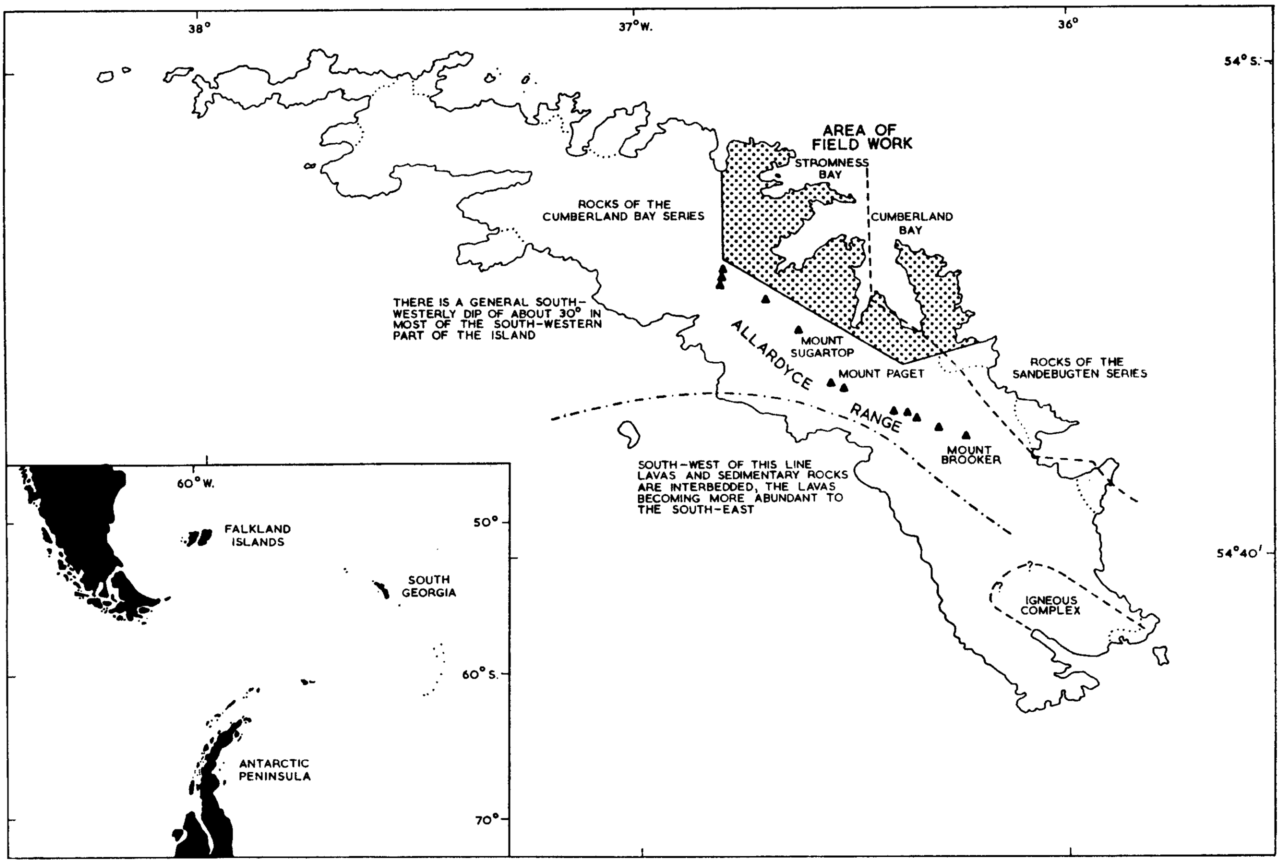

FIGURE 1

Sketch map of South Georgia showing the location of the field-work area and the general outlines of the geology (after Trendall, 1959). The inset shows the relation of South Georgia to South America, the Falkland Islands and the Antarctic Peninsula.

It is always difficult to assess the ages and modes of origin of ancient erosion levels, particularly in the absence of correlative and datable deposits. A combination of subaerial slope retreat and marine action in pre-glacial times has probably been of greatest importance in the development of most of the surfaces. Because the coastal foreland has been differentially eroded, some of the apparent wave-cut platforms at 2·0, 4·8, 6·0–7·0 and 20–50 m. may be degraded parts of the foreland and may not represent former sea-levels. The only conclusive evidence of higher Pleistocene sea-levels in South Georgia are the raised beaches.

III. CLIMATE AND GLACIOLOGY

THE climate of South Georgia is greatly influenced by the island's position south of the Antarctic Convergence and within the sub-Antarctic cyclonic zone. The mean annual temperature at Grytviken is +1·7° C and the mean annual precipitation is 1,395 mm. of water (Smith, 1960). Combined with the orographic effect of the island's mountainous backbone, frontal precipitation from prevailing westerly air masses nourishes large snow and ice fields. 58 per cent of South Georgia is covered by ice, the western windward side of the island being more extensively glacierized than the eastern side. Most of the ice-free terrain is thus located east of the mountains, where föhn winds can raise temperatures by over 12 deg. within 10 min. (Mansfield and Glassey, 1957).

There was little literature on the glaciology of South Georgia before the studies of J. Smith, R. Brown and M. J. Stansbury between 1957 and 1959. Their work on a cirque glacier (Hodges Glacier) and nearby valley glaciers (Hamberg, Harker and Nordenskjöld Glaciers) in Cumberland Bay suggested that all of the ice in South Georgia below an altitude of 1,000 m. is probably temperate; a map of interpolated isoglacihypses was drawn (Smith, 1960). Smith (1960, p. 710) also concluded that temperature is the most influential factor on the regime of Hodges Glacier and that an enlargement of the glacier "would most probably be caused by a northerly shift of the average track of depressions across the Scotia Sea, which, in turn, would result from a northerly extension of the Antarctic pack ice". This conclusion is probably valid for all of the glaciers in the Stromness Bay–Cumberland Bay area; there is certainly evidence that they were considerably larger in the past. From meteorological records at Grytviken, Smith noted that a deterioration in climate began in 1924; photographic records showed that, while large sea-calving glaciers had completed their advances between 2 and 5 yr. from that date, a cirque glacier with a land terminus took between 4 and 12 yr. to complete its advance.

The detailed geomorphological mapping of the Stromness Bay–Cumberland Bay area has provided additional information about former, more advanced positions of the glaciers.

IV. LANDFORMS OF GLACIAL EROSION

SINCE at least the beginning of the Pleistocene, glacial erosion has probably operated continually in the mountains and periodically on the lower ground of South Georgia. The most impressive landforms created by glacial erosion are the enormous cirques and troughs which fret the north-east flank of the Allardyce Range (Map). Other manifestations of this process, such as *roches moutonnées*, knob-and-tarn topography, glacially grooved and polished bedrock and rock steps, are equally abundant in the ice-free areas. Sometimes buried beneath expanded valley glaciers and sometimes beneath an ice cap, many of these landforms represent the effect of repeated glacial advances rather than only the most recent one.

1. *Cirques*

The north-east side of the Allardyce Range is scalloped by impressive cirques in which side walls rise to over 700 m. and precipitous back walls soar majestically above the glaciers for 700–2,000 m. A large number of cirques is also present on the lower ground where they vary in size from incipient semi-circular features to large embayments. Above 800 m. most of the cirques contain glaciers. The majority of the cirque floors below that altitude are presently ice-free but several are still occupied by glaciers, which in places terminate below 165 m. (e.g. at Leith Harbour and Stromness). The cirques lie at many different altitudes from sea-level upwards. The presence of a cirque-like bay at Godthul harbour led Holtedahl (1929, p. 76) to suggest the possibility of "a lower level of the shore-line during a time of more widespread glaciation". The configuration of other bays, such as Enten Bay, Jason Harbour, Allen Bay and King Edward Cove, suggests that they were also sculptured mainly by cirque glaciers at or near present sea-level. Since coastal cirques containing glaciers presently occur on some of the Antarctic islands, such as Clarence Island, lower sea-levels need not be invoked to explain those that are ice-free on South Georgia. They merely indicate a former firn line at or close to present sea-level.

The head walls of many of the lower cirques have been modified by the development of secondary ones, e.g. at Godthul and on Mount Hodges. Evidence of this nature suggests different generations of cirque development—as in Scotland (Godard, 1965; Sugden, 1969) and the Falkland Islands (Clapperton, 1971)—but the lack of large-scale topographic maps prevents an accurate study of this topic.

The preferred orientations of cirques in the Allardyce Range and the adjacent terrain are clearly linked with the alignments of the mountain range and the major peninsulas. Because the Allardyce Range trends approximately north-west to south-east and the major peninsulas project north-eastwards, the preferred orientations of the cirques are towards the north-west, north-east, south-west and south-east (Fig. 2).

Cirques on the south-west side of the Allardyce Range are generally smaller than those on the north-east side. The reasons for this may include the following. The sunnier aspect of the north-east side of the mountains probably causes a greater number of freeze-thaw cycles, thus producing more rock shattering. Cirque development is therefore likely to be more active. Frequent avalanches and rock falls were observed in the cirques of the Stromness Bay–Cumberland Bay area during the summer of 1968. The regional bedrock dip in this part of South Georgia is generally from north-east to south-west. This may facilitate the exploitation of the strata by weathering and glacial plucking on the north-east side of the mountains.

2. *Bays*

The north and north-east coastline of South Georgia is indented by many sea inlets penetrating far inland. Stromness Bay, Cumberland West Bay and Cumberland East Bay are three of the largest. In

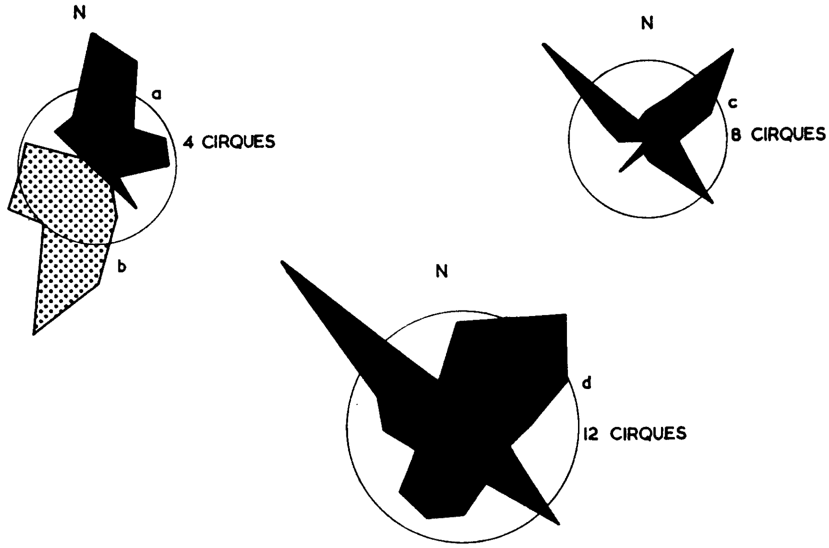

FIGURE 2

Preferred orientations of cirques in South Georgia.
a. Major cirques of the north-east side of the Allardyce Range.
b. Major cirques of the south-west side of the Allardyce Range.
c. Cirques in the Stromness Bay–Cumberland Bay area excluding the Allardyce Range.
d. Cirques in the Stromness Bay–Cumberland Bay area including the Allardyce Range.

accounting for such bays, Holtedahl (1929, p. 73) concluded "It is of course difficult to prove that there have not once existed river-cut valleys in at least some of the bay areas; I can, however, see no feature telling against a purely glacial origin of these bays . . .". Moraine Fjord, the Hamberg Lakes valley, King Edward Cove and Mercer Bay have clearly been severely widened and oversteepened by glacial erosion, but this is unlikely to be entirely responsible for the widths and irregular outlines of Stromness Bay, Cumberland West Bay and Cumberland East Bay. The well-developed abrasion platform at sea-level and the coastal foreland at 20–75 m. occurring in these bays suggest that the latter are quite ancient features. The larger bays have been modified only locally by glacial erosion.

Hydrographic details published in 1959 for Stromness and Cumberland Bays enable interpolated bathymetric contours to be drawn (Map). These indicate the presence of prominent basins varying in depth from 20 to 275 m., and the lowest points within some of them are from 7 to 190 m. below the levels of the thresholds. In the absence of unusual faults or tectonic subsidence, such basin forms can only have been created by glacial erosion. Other signs of glacial erosion are the profusion of shoals and rocky islets at the head of Husvik Harbour; these would probably appear as *roches moutonnées* similar to those west of Stromness and Husvik if sea-level fell by 15–25 m. Submarine hanging valleys are present in Cumberland West Bay and Cumberland East Bay. The most remarkable basin is in Moraine Fjord where the soundings prove a rock basin 190 m. deep. Situated close to the steep western shore of the fjord, the west side of the basin rises continuously from 190 m. below sea-level to the shoulder of the glacial trough 200 m. a.s.l. At least 390 m. of rock appear to have been removed by glacial erosion.

The bathymetry of Stromness and Cumberland Bays indicates that, during a period of more extensive ice cover, glacial erosion was effective for at least 12 km. beyond the outer coastline and to a depth of 270 m. below sea-level. Because glacial trenches have been cut into the submarine platform shelving from 20 to 150 m., the latter must pre-date the period of glacial erosion.

V. GLACIAL DEPOSITS

THE glacial deposits of South Georgia include till, fluvio-glacial sand and gravel, and raised beach sand and shingle. The till occurs as ground moraine and as lateral- and terminal-moraine ridges. Outwash plains of fluvio-glacial sand and gravel are associated with the moraines in some places.

1. *Ground moraine*

The ground moraine varies considerably in thickness from less than 1 m. to over 8 m., and it is generally a well-compacted mass of boulders and gravel in a clayey matrix. Measurements made in the till near Dartmouth Point in Cumberland Bay indicate that stones from 1 to 10 cm. long and with a length : breadth ratio of about 2 : 1 tend to have a preferred dip and orientation (Fig. 3). Aligned roughly parallel with the valley, the long axes of most stones dip up-valley, suggesting that they were deposited by a glacier flowing out of Moraine Fjord. Stone-shape analyses for the ground moraine indicate that the majority of stones are sub-rounded or sub-angular.

The ground moraine creates gently undulating topography on the lower slopes of some valleys but west of Stromness and Husvik it has been ice-moulded into conspicuous mounds and ridges. Some of the ridges may be composed entirely of till but others seem to be attached to *roches moutonnées* and other

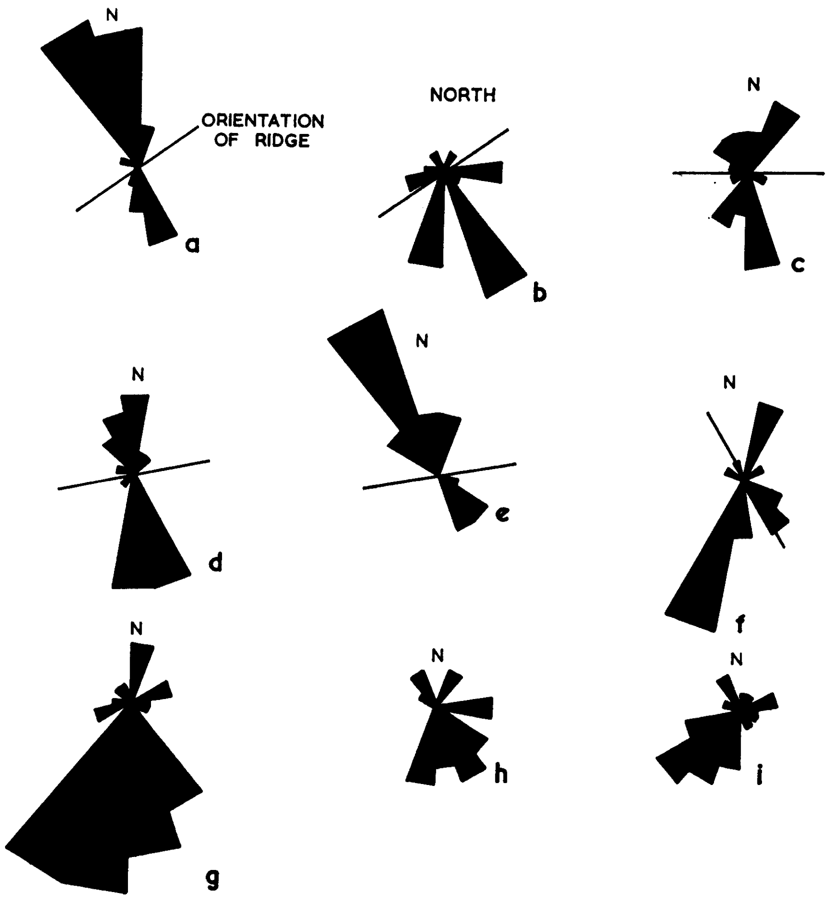

FIGURE 3

Preferred orientations of stones in glacial deposits, Cumberland Bay. 25 stones were examined at each site except site g.

a. Hodges cirque. Group 1 terminal moraine 50 m. from glacier; trench in proximal side of ridge.
b. Hodges cirque. Group 1 terminal moraine 50 m. from glacier; trench in distal side of ridge.
c. Hodges cirque. Group 1 terminal moraine 120 m. from glacier; surface stones.
d. Hodges cirque. Group 1 terminal moraine 120 m. from glacier; surface stones.
e. Hodges cirque. Group 2 terminal moraine.
f. Glacier Col. Group 1 terminal moraine 1 m. from glacier.
g. King Edward Point. Raised beach; 100 stones.
h. Moraine Fjord. Till exposed south of Dartmouth Point.
i. Moraine Fjord. Till exposed east of Dartmouth Point.

ice-worn knolls of bedrock. A stream-cut section in an ice-moulded mound near Stromness exposes 7 m. of apparently homogeneous till, the upper 1 m. of which is considerably weathered.

A thin scattering of ablation debris, mostly in the form of isolated boulders or clusters of gravel, overlies bedrock and the ground moraine in places.

2. *Moraine ridges*

Moraine ridges are present beyond all of the glaciers; they also occur in cirques and valleys that are now ice-free. Ridges are actively forming at the snouts and lower margins of the glaciers but much more impressive are the groups of older ridges at various distances away from the contemporary ridges. The ridges vary considerably in shape and size from sharp-crested narrow forms 0·5 m. high to steep-sided massive features up to 30 m. high. The moraines sometimes occur as groups of tightly packed, interconnected ridges and form disorganized topography. In many places the ridges are spaced clearly apart and trend almost parallel to one another. Individual ridges and groups of ridges are normally aligned crescentically across valley, approximately parallel to the glacier snouts, and they clearly mark former terminal positions of the glaciers. The terminal ridges often merge imperceptibly with lateral moraines which occur as ridges, terraces and trimlines.

The moraines vary in composition from loose accumulations of gravel and boulders to masses of gravel and boulders firmly held in a clayey matrix. Stones from the four categories of roundness suggested by Reichelt (1961) are present in most ridges, but the percentage of each type of stone seems to differ between different groups and types of moraine ridge. In general, lateral moraines contain a higher percentage of angular and sub-angular stones than the terminal moraines (Fig. 4).

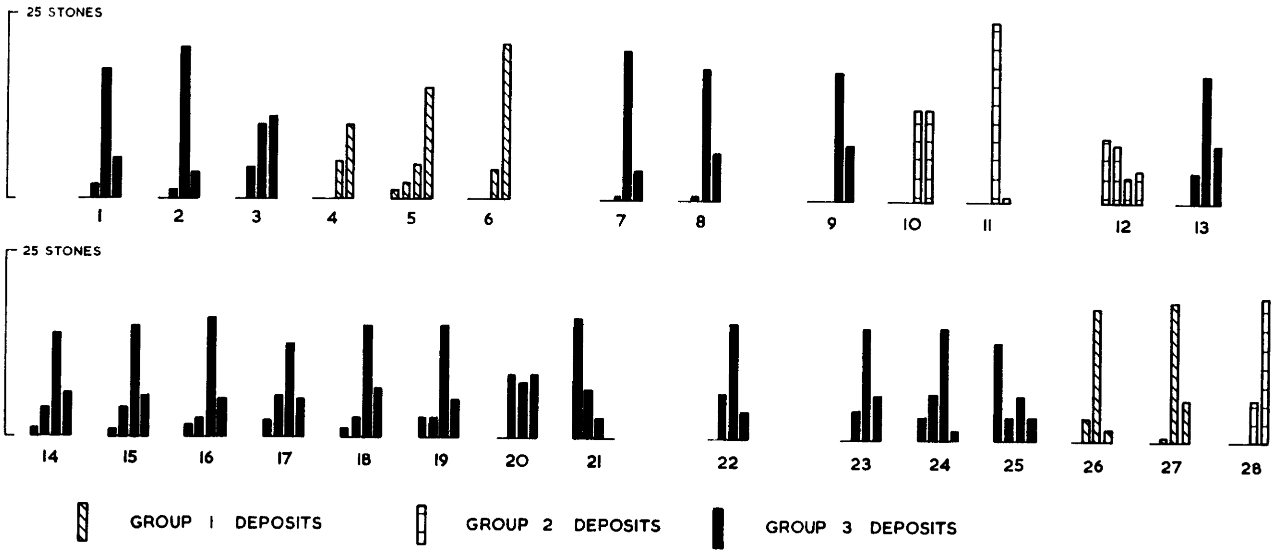

FIGURE 4

Morphometric analyses of stones in glacial deposits. The four columns from left to right represent stones which are rounded, sub-rounded, sub-angular and angular, respectively. Random samples of 50 stones in 1 m.^{2} were examined at each site.

1. Group 3 hummocky moraine, Lyell Glacier.
2. Group 3 ground moraine, Lyell Glacier.
3. Group 3 terminal moraine, Lyell Glacier.
4. Group 1 end moraine, Lyell Glacier.
5. Group 1 terminal moraine, Lyell Glacier.
6. Supraglacial debris on Lyell Glacier.
7. Group 3 terminal moraine west of Grytviken.
8. Group 3 ground moraine, Gull Lake.
9. Group 3 ground moraine, Hodges cirque.
10. Group 2 terminal moraine, Hodges cirque.
11. Group 2 outwash, Hodges cirque.
12. Group 2 end moraine, Nordenskjöld Glacier.
13. Group 3 moraine, near Nordenskjöld Glacier.
14. Group 3 end moraine, Hestesletten.
15. Group 3 terminal moraine (second ridge), Hestesletten.
16. Group 3 terminal moraine (third ridge), Hestesletten.
17. Group 3 terminal moraine (third ridge), Hestesletten.
18. Group 3 terminal moraine (third ridge), Hestesletten.
19. Group 3 terminal moraine (third ridge), Hestesletten.
20. Group 3 terminal moraine (fourth ridge), Hestesletten.
21. Group 3 terminal moraine (fourth ridge), Hestesletten.
22. Group 3 end moraine, Hamberg Lakes.
23. Group 3 lateral moraine, Moraine Fjord.
24. Group 3 ground moraine, Moraine Fjord.
25. Group 3 ground moraine, Moraine Fjord.
26. Group 2 terminal moraine, Harker Glacier.
27. Group 2/1 lateral moraine, Sutton Crag Glacier.
28. Group 1 terminal moraine, Sutton Crag Glacier.

The detailed mapping of all of the moraine ridges has shown that in nearly every valley in the Stromness Bay–Cumberland Bay area they occur as three distinct groups. The characteristics of each group of ridges down-valley from the glaciers and cirques will be discussed in turn.

a. *Group 1.* The first group of moraines includes the ridges currently forming at the glacier margins and varying numbers of contiguous moraine ridges occurring at distances of between 50 and 500 m. in front of the glaciers. Small areas of adjoining outwash deposits are sometimes present. The moraine ridges of this group are sharply defined fresh forms and are completely free of vegetation. The surface stones have not yet become discoloured with lichens and retain either a rusty brown or dark grey colour. There is little evidence of frost action either on individual stones or on the deposit as a whole. It is very noticeable that moraines of this group are much more numerous and extensive in front of cirque and col glaciers than in front of the large valley glaciers.

i. *Cirque and col glacier moraines.* In the Stromness Bay area 13 parallel terminal ridges can be identified in front of the glacier west of Leith Harbour. At the glacier west of Stromness, 15 parallel ridges, 0·5–1 m. high, are spaced 1–15 m. apart over a distance of 80 m. on a reverse slope in front of the ice. By far the most remarkable series of such small terminal moraines occurs in the valley south-west of Husvik. The outermost ridge is over 500 m. from the glacier snout which is receding up a 5° slope. On the north side of the main melt stream, 38 parallel ridges lie in front of the glacier snout (Plate Ia). Most of them are from 0·3 to 1 m. high, but the third ridge from the distal one is 6 m. high and another one is 3 m. high. The smaller ridges are composed of grey clayey till containing small stones, whereas the larger ridges have a large number of surface stones from 5 to 50 cm. in size. Similar forms are present at Glacier Col on a concave reverse slope behind the large rock step in front of the glacier (Plate Ib); the ground slopes at an angle of 16° to 8° down towards the small lake at the ice front. At least 20 ridges, all less than 0·6 m. high, cross the slope almost parallel to the glacier's snout. They are all composed of grey till. At Hodges Glacier, the inner two moraine ridges are similar to those at Glacier Col but the others are up to 6 m. high and consist predominantly of a mixture of clayey till and loose angular debris.

ii. *Valley-glacier moraines.* The large valley glaciers, such as König, Neumayer, Geikie, Lyell and Nordenskjöld Glaciers, are bordered by well-defined lateral and terminal moraines, but more than three separate ridges seldom occur at any one place. Furthermore, they are normally very close to the present glacier, the outermost moraine being rarely more than 50 m. distant (Plate Ic). The main exception to this is König Glacier, where group 1 lateral moraines occur up to 70 m. above the eastern margin of the glacier. Fragments of low terminal moraines lie approximately 400 m. in front of the glacier's snout, at the eastern margin of which are extensive areas of ice-cored moraine up to 10 m. above the glacier and 40 m. from it. It forms a unique zone of dead and decaying ice where supraglacial, englacial and subglacial melt streams abound; kame terraces and poorly defined eskers are also present.

b. *Group 2.* A second group of moraine ridges is always present down-valley from the group described above. In some places the second group is located a few tens of metres beyond the first, but in other places the two groups are contiguous. The composition and topography of the two moraine groups are quite similar, but ridge crests in the second group are less sharp than those in the first. Vegetation grows on the group 2 moraines but it is very sparse and occurs only in sheltered places and as little clumps and solitary plants. Nowhere is there a dense or complete vegetation cover. The surface stones are nearly always light grey or pink in colour because of the lichens growing on them. Some of the surface boulders have been split by frost action and, in places, the surface stones have been frost-heaved and are arranged as small stripes. The second group of moraines can thus be clearly distinguished from the first group. Where the two groups are contiguous, there is normally a sharp boundary between them (Plate IIIb) and in some places it is evident that the first group of deposits overlies part of the second group. The sparsely vegetated surface of the latter was found beneath debris at the fringes of the former.

The second group of moraines also indicates that the cirque and col glaciers attained positions much farther down-valley from their present snouts than the large valley glaciers. Small till ridges, similar to those in the group 1 moraines near Stromness, Husvik and Glacier Col, are absent from group 2. The group 2 moraines in front of Nordenskjöld Glacier provide interesting information about their mode and relative age of origin. On the western side of the glacier, two ridges 2 to 3 m. high gradually merge into one as they curve into the lateral moraine; they are 300–450 m. from the present snout. Close to the shore the moraines are composed mainly of beach sand, shingle and cobbles, and these have either been pushed into position by the advancing glacier or else were incorporated as ground moraine and re-deposited in ridge form. A number of the smoothly rounded stones are striated. Whale bones (a vertebra and small bone fragments) were found embedded 7·5 to 15 cm. in the crest of the inner ridge and on its flanks, approximately 80 m. from the shore and 4 m. above the base of the ridge. Closer to the valley side, the beach debris composing the moraine is mixed with angular and sub-angular stones, some of which are nearly 2 m. in size. On the eastern side of the glacier, eight ridges mostly 1–2 m. high curve from the shore to the lateral moraine. The outermost ridge is 5 m. high and is largely composed of beach material at its seaward end. The proportion of angular, sub-angular and sub-rounded stones increases towards the side of the valley. Near its junction with the lateral moraine, the outer terminal ridge contains large masses of contorted peat which has evidently been stripped off the small spur of land immediately behind the moraine.

c. *Group 3.* A third group of moraines is present at higher altitudes and at greater distances down-valley than the previous two groups. The size and extent of ridges in the third group are considerably greater than those of the other groups. Occurring as lateral and terminal ridges and mounds, the moraines vary in height from 1 to 35 m. and are generally more massive features than the group 1 and group 2 moraines. The forms are well preserved and sharply defined but the slopes and crests of the ridges are more degraded by gullying and slope movements than those of groups 1 and 2. A dense cover of vegetation grows on many of the ridges and frequently forms a continuous cover in the low coastal areas. Patches bare of vegetation occur in places exposed to strong winds and above the upper limit of continuous vegetation. The vegetation cover is probably a sub-climax association for the Stromness Bay–Cumberland Bay area.

Beyond the limits of continuous vegetation, surface stones on the moraines are arranged as large stripes, polygons and other periglacial landforms which are discussed later (p. 18). Similar forms may also be present beneath the vegetation cover. The number, variety, size and extent of the frost-heaved phenomena on the ridges of the third group are much greater than those on ridges in the second group. Thus, in terms of their relative position, morphology, vegetation cover and the extent to which they have been affected by periglacial activity, the third group of moraines is distinct from the other two groups.

Moraines of group 3 clearly indicate a phase of glacierization considerably more extensive than the present. They also show that substantial glaciers were present at that time in areas which are now ice-free. The limits of the group 3 stage are shown in Fig. 5. Because the moraines and contiguous landforms are so complex, in places it has not been possible to show all of the details on the geomorphological map. Selected areas are therefore described below.

i. *Cumberland West Bay.* Geikie Glacier deposited the low promontory between Mercer and Harpon Bays. The moraine complex forming this promontory consists of at least seven prominent terminal ridges linked by short cross ridges and is strewn with kettle holes. Rising 1–5 m. above adjacent depressions, the ridges are only superficial forms overlying a much greater thickness of till. An active sea cliff on the north side of the ridge complex exposes up to 8 m. of apparently homogeneous till beneath the ridges.

East of Lyell Glacier, moraines of the third group create equally complex topography and they are associated with landforms produced by contemporaneous melt-water activity. The latter landforms include three impressive, rock-cut melt-water channels, one of which breaches a col in the bedrock spur east of Lyell Glacier as a steep-sided gorge 8 m. deep. The dry floor of this channel leads out onto the apex of an extensive fan of correlative outwash gravels. The fan has an area of about 0·25 $km.^2$ and bears a braided pattern of dry channels. At the mouth of an adjacent valley, the fan truncates the distal end of a smaller fan which appears to have been deposited by melt water which had been flowing earlier from a higher channel in the lateral moraine.

The lateral and terminal moraines in the embayment containing Sphagnum Valley show that confluent glaciers emanating from the six cirques at the head of the embayment probably terminated just offshore. The altitude of the eastern lateral moraine indicates that the glacier was at least 60 m. thick near its snout.

ii. *Cumberland East Bay.* The presence and alignment of moraines in King Edward Cove and Junction Valley suggest that at the time of their deposition substantial valley glaciers were being nourished

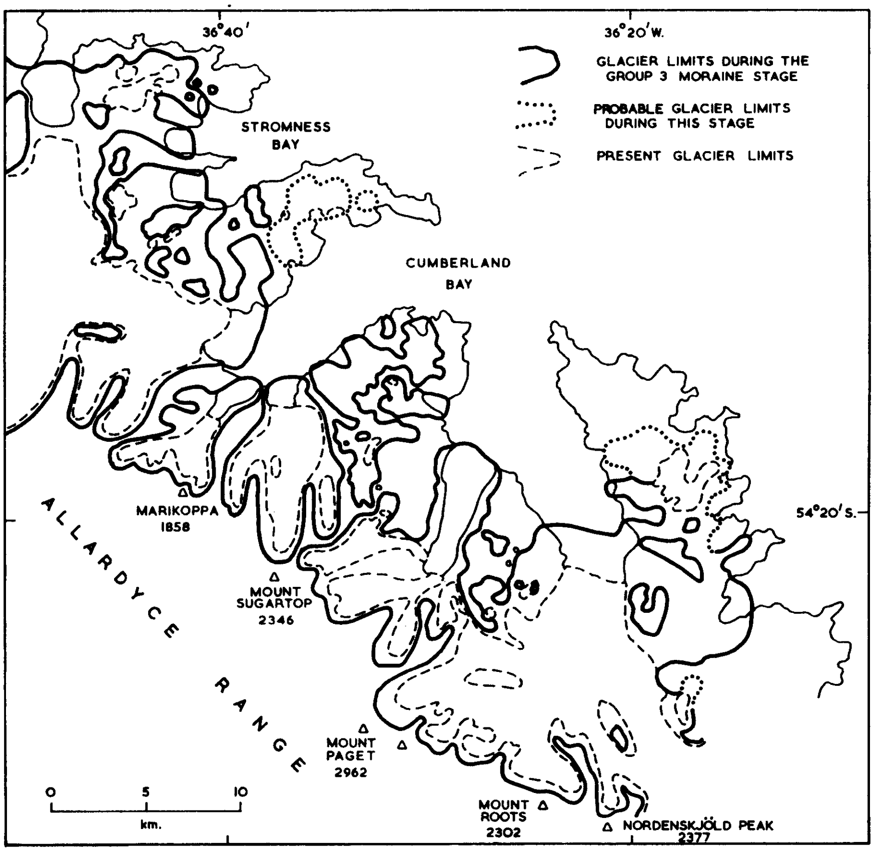

FIGURE 5
Reconstructed glaciers for the stage 2 glaciation in the Stromness Bay–Cumberland Bay area.

by accumulation centres between Glacier Col and the cluster of cirques in the mountains west of Gull Lake.

The remarkable group of moraines located in the upper part of the valley containing Hamberg Lakes was mentioned by Smith (1960), who considered that the three terminal ridges represent the three phases of the Würm glaciation identified in the southern Andes. The three large terminal moraines curve away from laterals on the valley sides and cross the largest of Hamberg Lakes as continuous narrow ridges except for one short gap in each ridge (Plate IIa). Varying from 0·5 to 10 m. in height, they are slightly sinuous and noticeably lower where they cross the lake. The moraine system is most complex on the east side of the valley, where short segments link the three main ridges and where several parallel subsidiary ridges are found. The latter are probably too low to show above the lake surface. Like the moraines in King Edward Cove, the ridges have asymmetric cross-profiles. Proximal slopes of 7° and distal slopes of 25° (on land) and 50° (in water) are typical. The corresponding lateral moraines are best preserved on the west side of the valley where at least eight are grouped together on the hillside. The uppermost moraine is at an altitude of about 170 m. The fact that the terminal moraines form one inter-connected complex of ridges suggests that they do not relate to three separate phases of the Würm glaciation but that they were formed by irregular recession of the diffluent lobe of Hamberg Glacier during one phase of glaciation. Evidence will be presented later (p. 14) in support of the theory that this phase of glaciation was considerably younger than the recognized Würm stages of both the Southern and Northern Hemispheres.

Moraine Fjord contains what is probably the most impressive and complete sequence of lateral and terminal moraines of the third group that can be seen anywhere in South Georgia. These moraines clearly mark the former extent and retreat stages of a large valley glacier composed of the confluent Hamberg and Harker Glaciers, and adjacent glaciers. On the eastern side of the fjord, a continuous system of lateral moraines extends from Harker Glacier to Dartmouth Point at the mouth of the fjord, a distance of 6·4 km. The number of lateral moraines at any one place varies from one to nine, but four or five are commonly present (Plate IIb). From an altitude of about 300 m. the uppermost moraine declines down-valley until it merges with the terminal moraine at sea-level. Curving into the mouths of hanging tributary valleys and winding sinuously up and down intervening spurs, most of the lateral moraines normally occur as ridges, but short terrace segments are also found. In some places the ridges are linked by cross branches and form complex topography. Most of the moraines slope down-valley at an angle between 2° and 8°, but a few even climb up-hill for short distances over bedrock spurs. Although most of the lateral ridges are 1–4 m. high, one of the most impressive ridges rises over 35 m. in the tributary valley immediately north of Harker Glacier (Plate IIc). At this locality all of the lateral debris has been deposited as one massive ridge rather than as several separate ridges. Boulders up to 3 m. in size are strewn all over the ridge which has ponded up a shallow lake in the valley. At least ten old lake shorelines surround the lake up to *c.* 8 m. above its surface, suggesting that a considerable ice-dammed lake was formerly present.

The great barrier of boulders across the mouth of Moraine Fjord represents the continuation of the terminal-moraine complex. It probably rests on a bedrock bar enclosing the seaward end of the rock basin in Moraine Fjord. The boulder barrier leads directly into a fully developed terminal-moraine system on the west side of the fjord. The moraine ridges are evidently superficial forms, up to 10 m. high, and rest on till which is at least 30 m. thick. An analysis of the surface debris suggests that, although small percentages of angular and rounded stones are present, ice-worn stones predominate. Rounded stones are abundant on the fourth ridge, particularly on the bare proximal slope. The majority of the stones are smooth and rounded like present beach cobbles, and many of them are also well striated. This indicates that the glacier advanced over previous beach deposits and agrees with similar evidence from the cliff exposure east of Dartmouth Point.

Associated with the terminal moraine is the extensive plain called Hestesletten. The plain declines away from the moraine with a slope of 4° but within a short distance the slope becomes 2° and is maintained at that angle to the distal edge of the plain. The plain is approximately 3 km. wide and from 0·5 to 1·6 km. long. Braided systems of dry channels 0·5–1 m. deep furrow the surface in many places and they can be traced continuously from gullies in the moraine to their termini at the outer limit of the plain. Pavements of water-worn gravel are exposed where vegetation is absent. The stones are commonly 1·2 to 10 cm. in size but boulders up to 0·6 m. are also present. A river-bank section exposes 1 m. of crudely bedded and sorted sand and gravel. Hestesletten is clearly a pro-glacial outwash plain which formed while the Moraine Fjord glacier stood at the terminal-moraine complex. A similar but smaller outwash plain borders the terminal moraine east of Dartmouth Point where cliff sections expose 3 m. of the outwash sands and gravels; this deposit may be much thicker.

From the position of the lateral moraines in Moraine Fjord, it can be inferred that the glacier surface was at least 300 m. above present sea-level in the upper part of the fjord. Since the floor of the fjord is over 190 m. below sea-level, the glacier probably had a maximum thickness of about 450 m.

d. *Group 4.* A fourth group of morainic deposits is present in a few places outside the limits of the third group. These deposits occur mainly as ground moraine and do not form conspicuous ridges. Most of the fine debris appears to have been washed out of the surface layer of the deposit, leaving it very stony and loose. Up to 2 m. of the till are exposed in gullies. The till is frequently mixed with the frost-shattered debris from bedrock knolls, and substantial amounts of the till appear to have been moved by solifluction. Above the upper limit of vegetation, many of the surface stones have been frost-heaved onto their edges and stone stripes are common. At lower altitudes a dense cover of vegetation has colonized the till.

The till is located on the two peninsulas between Cumberland East Bay and the valley containing Hamberg Lakes. In view of its position in relation to the other groups of moraines, this till is probably the oldest glacial deposit in the Stromness Bay–Cumberland Bay area. Since the till occurs up to 360 m. a.s.l. on two coastal peninsulas, it was probably deposited during a period of extensive glacierization when most of South Georgia was buried beneath an ice cap which extended a continuous front some distance beyond the present coastline.

3. *Raised beaches*

Although there are many references in the literature on South Georgia to wave-cut rock platforms above sea-level, there are no detailed accounts of raised beach deposits.

The author mapped and studied raised beach deposits at seven localities: Stromness, Husvik, Cumberland West Bay (near Carlita Bay and at Sphagnum Valley), King Edward Point, the bay south of Sandebugten on the Barff Peninsula, and Hound Bay. At each place small sections expose the deposits. Smooth flat-shaped stones varying in size from less than 1 mm. to cobbles over 30 cm. are crudely bedded with coarse sand; most of the stones are lying flat. The morphometry of the stones is quite different from that of stones in till, fluvio-glacial outwash and other stream deposits, but it is very similar to that of stones on the present beaches. The dominant characteristics of these stones are their flatness and degree of smoothing. The raised beach at King Edward Point is mainly shingle with only a small amount of interstitial sand and grit; it is thus very loosely compacted. On the other hand, the beach at Hound Bay varies in composition from crudely bedded sand containing sporadic pebbles to layers consisting mainly of coarsely bedded shingle.

Most of the beaches are flat-topped terraces set some distance back from the present shoreline (Plate IId). All of the beaches are covered with a layer of peat and they appear to be remnants of more extensive formations. The beaches at King Edward Point and Sphagnum Valley were accurately heighted with a Wild T2 theodolite. The results indicate former beaches at three different altitudes (Fig. 6). The beach shingle at King Edward Point is 7·4 m. above mean sea-level (determined from the adjacent tide gauge).

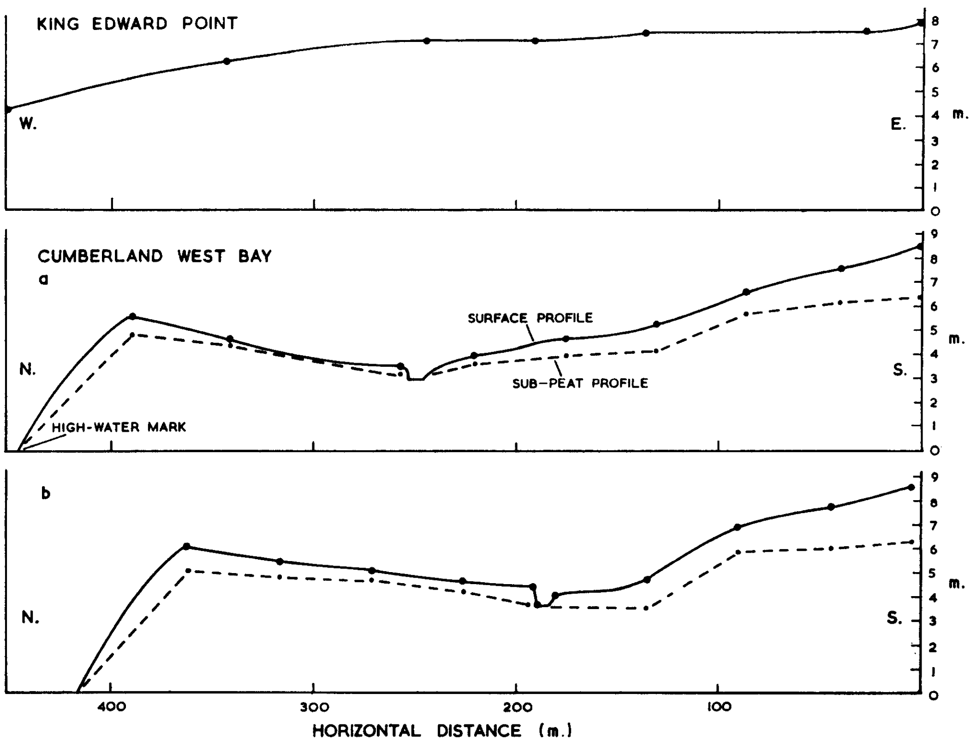

FIGURE 6

Levelled profiles on raised beaches at King Edward Point and Cumberland West Bay (a and b).

The profile was made along the centre of the raised beach to avoid scree lobes at the back edge and alterations caused by sea action and the construction of Shackleton House at the front edge. The sloping part of the profile is on a degraded part of the beach where streams and the sea have probably modified the original feature. Together with a thick peat cover, these prevent the identification of any lower beach levels which may be present.

A profile was made across the beach at Sphagnum Valley from the front edge to the relict cliff at the back. Simultaneously, the overlying peat was probed with graduated rods so that the depth of the buried beach surface could be accurately determined. The results indicate the presence of two separate surfaces, at 4·6 and 6·2 m. above high-water mark. Raised beaches at the other sites were not heighted by instrument but they were estimated in relation to high-water mark. Their surfaces all appear to be at 3·5–4 m. a.s.l. It is therefore possible that raised beaches occur at four different altitudes, i.e. 7·4, 6·2, 4·6 and 3·5–4 m. a.s.l. Because the levelling datum used at Sphagnum Valley was the high-water mark indicated by the line of beach debris, whereas the datum at King Edward Point was mean sea-level according to the tide guage, the 1·2 m. difference in the beach heights may well be due to the probable discrepancy between these two datum levels. The 7·4 m. raised beach at King Edward Point and the one apparently at 6·2 m. in Cumberland West Bay may therefore represent the same former sea-level (which was probably closer to 7·4 than 6·2 m., since the tide gauge is the more accurate datum). Similarly, because height estimations are nearly always inaccurate, the beaches estimated at 3·5–4 m. may well be at the 4·6 m. level and therefore correlate with the lower beach at Sphagnum Valley.

Until all of the beaches have been accurately levelled from the same datum, the precise number of raised beach levels cannot be confidently stated. Neither can it be determined from the available evidence whether or not isostatic depression was uneven on South Georgia, resulting in the warping of correlative beaches. Because raised beach deposits in South Georgia probably relate principally to local glacio-isostasy, there seems little point in attempting to correlate them with raised beach levels reported from the Falkland Islands (Adie, 1953), the South Orkney Islands and the South Shetland Islands (Adie, 1964*b*; John and Sugden, 1971) and elsewhere in Antarctica.

The raised beaches must post-date the maximum position of the glaciers represented by the group 3 moraines since the beaches occur inside the terminal moraines; the beaches are all located outside the terminal moraines of group 2. On an island the size of South Georgia, it seems reasonable to expect that an increase in glacierization of the magnitude indicated by the group 3 moraines would cause isostatic depression. Before the land recovered isostatically, the sea appears to have transgressed onto the coastal areas as they became ice-free and deposited beaches at more than one level. Most of the beaches are located where abundant supplies of debris were transported into the sea by melt streams. A fruitless search was made for organic remains in the beaches, and therefore they can only be dated relative to the group 3 moraines.

The base of a relict cliff cut into these raised beaches is at the back of a low raised beach lying behind the contemporary storm ridges. The surface of the low raised beach is approximately 2·5 m. above high-water mark. A thin layer of peat and tussock grass normally covers the beach gravels which occur as narrow strips of land along many parts of the shoreline around Stromness and Cumberland Bays. The presence of many whale carcasses and planks of wood on the surface of the low raised beach suggests that the latter is not more than 200 yr. old. It can perhaps be tentatively suggested that the low raised beach is related to the slight isostatic recovery of South Georgia following the glacier recession from the advance which led to the deposition of the group 2 moraines. It is probably part of a continuous prograding shingle deposit which is currently accumulating as the land slowly rises in response to contemporary glacier retreat. This theory can only be substantiated with accurate and continuous tide-guage records over a number of years.

4. *Conclusions from the deposits*

The detailed mapping of glacial deposits in the Stromness Bay–Cumberland Bay area has enabled four separate stages of glaciation to be identified. These stages will be referred to as 1, 2, 3 and 4, stage 1 being the oldest. It has not been possible to date stages 1 and 2 absolutely and only tentative correlations can be made with known glacial stages elsewhere in the Southern Hemisphere. A peat bed lying behind the terminal moraines of stage 2 in Sphagnum Valley gave a ^{14}C date of 6,000±500 yr. at a depth of 1–1·13 m. (Fergusson and Libbey, 1964; personal communication from S. W. Greene); the stage 2 re-advance must therefore be older. A re-advance of the glaciers in southern Chile was similar in extent to that in South Georgia and occurred later than 6,850±200 yr. B.P. but before 4,000 yr. B.P. (Heusser, 1960). Mercer (1968, 1970) dated basal peat on similar moraines in Patagonia at 4,300 and 4,000 yr. B.P. During the previous glacial stage in southern Chile the ice had pushed westward into the Pacific Ocean, indicating a phase of extensive glacierization like that of stage 1 in South Georgia. The moraines of stage 2 may also correlate with those in southern Victoria Land and McMurdo Sound, Antarctica, which date from 6,000+ yr. B.P. (Bull and others, 1962; Péwé, 1962; Calkin, 1964).

Smith (1960) concluded that South Georgian glaciers have recently been in their most advanced positions for several thousand years. He tentatively dated the culmination of one advance at 1875. From meteorological and photographic records for the Cumberland Bay area, Smith found that climatic deterioration beginning in 1924 caused large sea-calving glaciers to re-advance to maximum positions between 1926 and 1929; a cirque glacier with a land terminus halted its advance between 1928 and 1936. The two glacial advances dated by Smith are undoubtedly represented by the moraines of stages 3 and 4. The presence of peat and whale bones in stage 3 moraines is consistent with Smith's tentative date of 1875, for it is considered that the whale bones probably derive from carcasses that were strewn over South Georgian beaches during the whaling activities of the eighteenth and nineteenth centuries. However, the re-advance may have culminated during the eighteenth century rather than in 1875. It would then correlate with the Little Ice Age of the Northern Hemisphere and the "third Neoglacial re-advance" of Patagonia which Mercer (1970) dated at between A.D. 1750 and 1800. The retreat of a glacier lobe from its maximum stage 4 position south-west of Husvik was, in 1968, marked by 38 parallel terminal moraines. If these are annual features, they suggest a continuous retreat of the glacier since 1930. The absence of a substantial glacier re-advance between stages 2 and 3 is in agreement with the stages identified by Heusser in southern Chile, where San Rafael glacier began advancing less than 500 yr. ago and started to recede from its terminal moraine in 1882. However, the glaciers in Patagonia have behaved differently and differentially. Mercer dated re-advances of Uppsala Glacier at *c.* 2,000 yr. B.P., A.D. 1600 and during the early nineteenth century; smaller adjacent glaciers reached maximum positions around A.D. 350, A.D. 1150, the late seventeenth century and the late eighteenth century. All of the glaciers in the Stromness Bay–Cumberland Bay area responded more or less simultaneously to the climatic changes indicated by glacial stages 2, 3 and 4, but there might be variations from this pattern on the opposite side of the island. The glacial stages so far identified on South Georgia thus seem to correlate much more closely with these on the western side of the southern Andes than with those in Patagonia.

VI. MORAINE-FORMING PROCESSES

THE moraines currently forming at the glacier snouts in the Stromness Bay–Cumberland Bay area appear to have resulted from several processes. Some ridges may be forming entirely by one process and others by a combination of processes. These are as follows:

i. At the snouts of glaciers terminating on land, such as parts of Lyell, Harker, Neumayer and Nordenskjöld Glaciers, the following processes seem to contribute significantly to the construction of moraines. During the ablation season supraglacial debris continually slides over the steep edges of the glaciers and in most places forms ridges. Simultaneously, englacial detritus constantly melts out of the ice cliff at the glacier snouts and is added to the moraines. The supraglacial debris consists mostly of rusty brown, angular scree fragments, while the englacial material is grey in colour and consists of saturated stony clay.

ii. In some of the morainic zones, terminal ridges are linked by short cross branches usually aligned at right-angles. The latter type of ridge predominates amongst the group 1 moraines at Harker Glacier and it is also common round one of the glacier lobes south-west of Husvik. At these places the glaciers are furrowed by longitudinal crevasses, which reach the ground and widen towards the glacier snouts. Supraglacial debris tumbles into the crevasses and mixes with englacial till melting out from dirt bands along the crevasse walls. This type of crevasse filling creates ridges approximately at right-angles to the terminal moraines.

iii. Medial moraines composed principally of scree and avalanche debris are prominent on König, Neumayer and Lyell Glaciers. Some of these moraines are now ice-cored and form prominent ridges up to 5–7 m. above the surrounding ice. The ice-cored medial moraines indicate overall thinning of the glaciers and they probably started to form during the recession from stage 3. It is possible that these moraines will be left as ridges on the ice-free ground as the glaciers continue to retreat.

None of the processes so far described are adequate to account for the small terminal ridges which are typical in the first group of moraines adjacent to the glacier snouts near Stromness and Husvik, and at Hodges Glacier and Glacier Col.

South-west of Husvik, 13 small ridges are parallel to the glacier snout on ground sloping gently away from the ice front. None of these ridges is more than 0·5 m. high but an exposure beside the adjacent melt stream shows 4 m. of till. The ridges are therefore relatively minor surface features. Although the till was saturated and of a muddy consistency immediately in front of the glacier (March 1968), the ground became quite firm within 4–5 m. In 1968 there was no obvious sign of a ridge being fashioned out of this saturated material. In the valley west of Stromness, 15 small ridges similar to those near Husvik are spaced 1–15 m. apart and are parallel to part of the glacier snout. A segment of the glacier, 3–5 m. broad and 20 m. long, had become detached along a shear plane near the ice edge and a ridge of till 0·3–0·35 m. high was present on the ice surface (Plate IIIa). Similar features occur at Glacier Col where dirt-filled shear planes curve across the glacier near its snout. The small parallel ridges of grey stony till thus appear to be closely linked with cirque and col glaciers and with high-angle shear planes intersecting the ice surface near the snouts. The development of these shear planes may be partly related to the local topography, for all three glaciers terminate on sloping ground. The glacier west of Stromness and that in Glacier Col have recently receded down gentle reverse slopes; the ground fronting the glacier south-west of Husvik slopes gently away from the ice front. The debris bands on the glaciers at Glacier Col and west of Stromness stand up as dykes dipping steeply up-glacier. They closely resemble features at the margins of Sørbreen, Spitsbergen (Boulton, 1967). Boulton considered that the debris bands probably originated either as material which was subglacial debris frozen on to the base of the glacier by a mechanism similar to that suggested by Weertman (1961) and brought to the surface as the flow lines turn upwards at the frontal margin, or as material which was subglacial debris brought to the surface along shear planes, a mechanism suggested for similar bands in the Thule area, Greenland (Bishop, 1957). The debris bands on the glaciers at Glacier Col and west of Stromness appear to be associated with shear planes and formed supraglacial ridges as the glacier surfaces thinned by ablation. The majority of the small ridges in front of the glaciers have probably originated in this manner, forming superficial features on the ground moraine (Fig. 7). The presence of saturated till in front of the glaciers south-west of Husvik and west of Stromness, however, raises the question of whether some of the ridges have originated as ice-squeezed phenomena. It is possible that the weight of detached segments of the glacier snouts is sufficient to squeeze thin wedges of saturated till up through the fissure between the active and passive ice, so that the till appears on the glacier surface as a narrow dyke of debris. Segments of the glacier snouts at Glacier Col and west of Stromness had certainly become detached along weaknesses created by thinning at prominent shear planes. Price (1969) tentatively suggested that some of the moraine ridges at Breidamerkurjökull, Iceland, may have been formed by squeezing of saturated till.

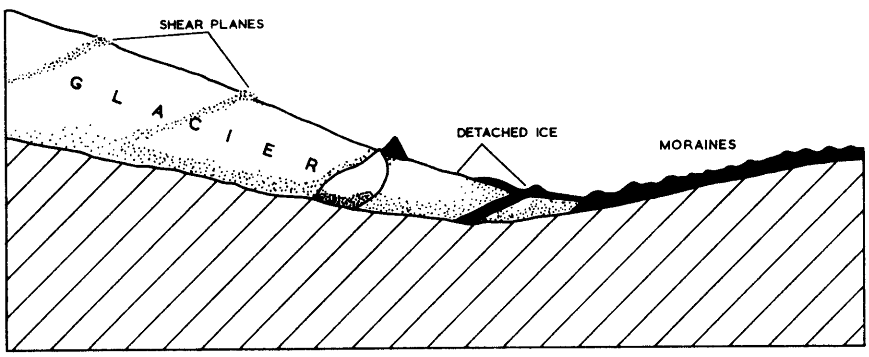

FIGURE 7
Diagram illustrating the development of moraines at Glacier Col in 1968.

Analyses of the till fabric in two of the terminal ridges (one lying 2 m. in front of the ice at Glacier Col and one situated 50 m. from the snout of Hodges Glacier) show that the stones have a preferred orientation almost at right-angles to the alignment of the ridges (Fig. 3). This alignment could have been induced either by movement of the debris up shear planes or during the flowage of the till as it became squeezed into the fissures. If the first alternative was the dominant mechansim, the majority of stones should dip up-glacier; this is the situation at the site analysed at Glacier Col. If the second alternative was the dominant mechanism, it would theoretically be possible for stones to dip up-glacier on the proximal side of a ridge and down-glacier on the distal side of a ridge; this situation occurs at the site analysed at Hodges Glacier. It therefore seems likely that both mechanisms operate at some of the glaciers in South Georgia, but further measurements are necessary to fully investigate the conditions under which each mechanism is dominant.

VII. GLACIER-DAMMED LAKES

THREE glacier-dammed lakes occur in association with Neumayer and Lyell Glaciers, both of which terminate in Cumberland West Bay. All three lakes are bordered by high shorelines which indicate former levels of the lakes.

1. *Neumayer Glacier lakes*

Two lakes are ponded in small tributary valleys by the northern margin of Neumayer Glacier 5·5 km. and 650 m. from the snout. Gulbrandsen Lake, the uppermost one, is the larger of the two and in March 1968 it measured approximately 1,000 m. by 700 m.; the surface was about 200 m. a.s.l. (Plate IVa). Four small streams from adjacent ice-free ground flow steeply into Gulbrandsen Lake, whose hidden outlet must drain through an englacial or subglacial tunnel. The glacier margin calves into the lake as icebergs up to 6 m. in size. A remarkable series of abandoned shorelines has been cut into the scree and till mantling the steep slopes surrounding the lake. At least 30 shorelines are present, extending at irregular height intervals to about 50 m. above the lake surface. Some are narrow benches only 0·6 m. wide, particularly on steep slopes, but on gentler slopes they are 3–4 m. wide. The treads are generally composed of very fine gravel, whereas the intervening risers consist of coarser debris. This suggests that the fine material has been washed out of the hillslopes and deposited as beaches. All of the shorelines continue into the gullies cut in bedrock by the four streams. The shorelines clearly represent higher stands of the lake and seem to be closely related to old moraines of a marginal lobe of Neumayer Glacier which formerly penetrated farther into the tributary valley. There are two sets of moraines. The older and outer deposits relate to the stage 3 glaciation discussed earlier (p. 9); the inner moraines mark recessional stages of the glacier from its maximum position in the late 1920s. The upper three shorelines terminate at the stage 3 moraines with which they are probably contemporaneous. Shorelines immediately beneath the upper three are cut across the stage 3 moraines but they terminate against the stage 4 moraines. At increasingly lower levels, successive shorelines in descending order cut across successive moraines so that it appears as though the lake level fell in harmony with the shrinking glacier.

The smaller lake is surrounded mainly by scree slopes and rocky cliffs which were too steep to preserve the nineteenth century moraines. The younger series of moraines is also poorly developed and for the most part overlies stagnant ice at the glacier margin. The lake measured approximately 700 m. by 400 m. in March 1968 and its surface was about 50 m. a.s.l. Ten shorelines are cut across the large screes up to a height of 15 m. above the lake surface but, because of frequent rock outcrops, they are much less continuous than those at Gulbrandsen Lake.

2. *Lyell Glacier lake*

Approximately 7 km. from the sea, a small lake is ponded in a short tributary valley by the margin of Lyell Glacier (Plate IIIb). The snout of a large cirque glacier in a tributary valley presently calves into the southern edge of the lake, which measures approximately 450 m. by 325 m. with its surface at about 250 m. a.s.l. The outlet stream flows through a gorge breaching a large lobate terminal moraine deposited by Lyell Glacier during the late nineteenth century and drains englacially or subglacially through the glacier. The moraine rises 25 m. above the lake. A former outlet of the lake has breached the stage 3 moraine about 40 m. east of the present outlet, where the old route is now marked by an abandoned channel hanging almost 5 m. above the lake surface. A large mass of the moraine has thus been isolated by the two gorges. Former levels of the lake are indicated by up to 14 shorelines which have been fashioned out of the moraine and scree slopes surrounding the lake to a height of 15 m. above its surface. The widest beach is 5 m. and the height interval between beaches is 0·5–3 m.

It is possible that Gulbrandsen Lake empties periodically. Icebergs have been seen stranded on dry land extending to the glacier margin (personal communication from D. J. Coleman). The other two lakes may also drain completely on occasions. If the ice tunnel carrying the outlet stream from any one lake collapses or becomes blocked following draining of the lake, a new outlet for the re-forming lake could control a different level of outflow and leave the former level marked by an abandoned shoreline. During glacier retreat any new outlet is likely to form at a lower level, but with an advancing glacier the new outlet might form at a higher level. The latter situation may have occurred at Lyell Glacier but as yet there is no evidence to substantiate this theory.

VIII. PERIGLACIAL LANDFORMS

PERIGLACIAL processes currently operate on ice-free ground in parts of the Stromness Bay–Cumberland Bay area. The cold moist weather of sub-Antarctic depressions and the close proximity of heavily glacierized terrain provide conditions for intense frost shattering, for seasonal frost heaving of superficial deposits and for the down-slope movement of material. The periglacial processes are facilitated by the widespread occurrence of fissile bedrock which splits readily into slabs and platy fragments. Thus most rock faces have aprons of scree; piles of shattered debris surround disintegrating bedrock knolls and rock falls are common (e.g. a large one occurred in Bore Valley during March 1968). Because the glacial till normally contains a high percentage of fines, the surface layer is frequently arranged into stripes on sloping ground. A small area of little stone polygons occurs on flat ground adjacent to such stripes in Junction Valley and in Sphagnum Valley. Particularly good stripes are active on till of stage 2 age in Sphagnum Valley where they are present on an 8° slope facing north-west at an altitude of 175 m. (Plate IIIc). These stripes are up to 30 m. long and consist of pebble stripes 10·2 cm. wide and stripes of fines 7·5–12·5 cm. wide; the stones vary in size from 0·6 to 20 cm. Sorted stone stripes and nets are also present north of Gulbrandsen Lake. The unstable moving stones of the active periglacial landforms are generally free of lichens and are rusty brown and light grey in colour.

Contrasting with the contemporary periglacial landforms are features which have been overgrown with lichens and which have an overall light grey colour. They are forms in which the stones are stable and appear to be relict features that formed previously in a more severe climatic environment. The relict forms include stone stripes, stone polygons, non-sorted stripes and non-sorted circles, in addition to amorphous shattered debris. Confined entirely to deposits older than those of stage 3, the relict forms are mostly larger than the contemporary ones.

Relict stone stripes are common on patches of moraine free of vegetation on Zenker Ridge. At one locality on the highest moraine ridge, two stone stripes up to 1·5 m. wide extend down-slope for 20 m. (Plate IIId). Many of the adjacent stones are shattered and arranged on edge. Similar stripes are found on stage 2 terminal moraines at Hamberg Lakes and in Mercer and Harpon Bays. They also occur in conjunction with large stone polygons on level and gently sloping ground at about 175 m. a.s.l. east of Sphagnum Valley, where a small bedrock basin has become infilled with till and shattered bedrock fragments to form a small area of level ground. A net of stone polygons with a 1–2 m. mesh has developed (Plate Va). The larger stones forming the polygons are up to 0·6 m. in size. All of the stones are on edge and are coloured grey by lichens. Where the ground begins to slope gently, the polygons become elongated and grade into stripes. Of particular interest at this site are the small contemporary polygons actively forming inside the large relict ones (Plate Vb). The contemporary nets consist of eight to nine polygons with a 15–23 cm. mesh. The active stones are pink in colour, contrasting with those which are grey and stable, and are seldom larger than 9 cm. in diameter. On some adjacent till-covered knolls, stone stripes lead down-slope to large lobes of boulders from which the fines have probably been washed by rain water and snow melt. Current movement seems to be adding stones to some of the lobes.

Non-sorted stripes, similar to those described as "stripe hummocks" by Lundqvist (1962), are prominently developed in three places. They occur on gently undulating ground on the west side of Cumberland East Bay, 300–500 m. down-valley from Nordenskjöld Glacier. Situated on low ground beneath the cliff, the stripes are up to 2 m. broad and are covered with dense vegetation. A small area of similar stripes occurs on the proximal slope of the outer terminal moraine on the south side of King Edward Cove, but perhaps the most impressive group of stripe hummocks in South Georgia is that in Cumberland West Bay. Lying on very gently sloping ground, a few hundred metres from Neumayer Glacier (Plate IVb), the parallel stripes are 200 m. long and from 1 to 2 m. broad. The crests of the stripes rise no more than 0·75 m. above the intervening troughs.

A large expanse of non-sorted circles has developed on the distal part of the Hestesletten outwash plain. The average mesh size is 1 m. and the pits lie 30–38 cm. below the enclosing rims. Most of the circles are completely covered by vegetation but the centres of a few are quite bare (Plate Vc). The vegetation consists mainly of moss, grass and *Acaena*. Pits were dug in three places to examine the structure of the circles. The circle rims are largely composed of fine silt with peat, moss and grass growing on top (Fig. 8). The debris rims stand over 15 cm. higher than the enclosed pits, most of which contain sand and gravel. The presence of non-sorted circles on the distal parts of the outwash plain is probably related to a greater concentration of fine loamy material there. Circle nets are certainly absent from the coarse gravels at the proximal end of the plain. The genesis of non-sorted circles has been discussed by Washburn (1956) and Lundqvist (1962).

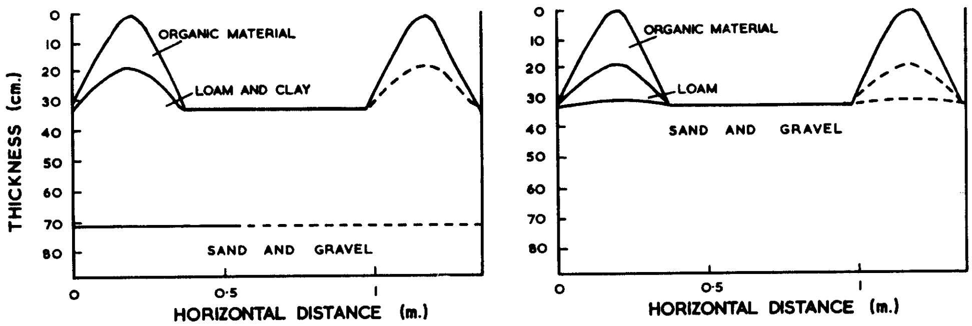

FIGURE 8
The composition of non-sorted circles on Hestesletten.

Another type of periglacial landform common in the Stromness Bay–Cumberland Bay area is found particularly on shattered bedrock debris outside the limits of the stage 2 deposits, but it is also present at a few places inside these limits. The platy angular fragments have been arranged on edge and are frequently orientated down-slope (Plate Vd). They do not form proper stripes but wind down dry gullies and depressions as streams of parallel stones, very like small versions of the stone runs of the Falkland Islands. The stones are also on edge on flat ground, where they form a smooth surface which may be termed a boulder pavement. Neither Washburn nor Lundqvist have described this type of periglacial landform which is fully developed in Bore Valley, on the peninsula between Moraine Fjord and Cumberland East Bay, in Echo Pass and in many other similar environments. Since the relict periglacial landforms occur principally in deposits older than those of stage 3, severe climatic conditions must have prevailed either during the retreat of the glaciers from stage 2 moraines or during the stage 3 re-advance. Contemporary periglacial processes are comparatively slight and operate most intensively on higher ground. They are probably similar in nature to those active on Signy Island (Chambers, 1966*a*, *b*, 1967) but long-term measurements and observations will be necessary to define precisely the operative processes.

IX. GENERAL CONCLUSIONS

THE Stromness Bay–Cumberland Bay area is one of the largest expanses of ice-free land in South Georgia and it offers considerable scope for the study of glacial, periglacial and marine processes of landform development. The detailed geomorphological mapping of the area has provided not only a fairly complete landform inventory, which may be useful for other scientific work, but has also contributed to an understanding of the island's glacial history. Remnants of the pre-glacial topography suggest that a stepped landscape of narrow erosion surfaces at altitudes of 50–75, 600–650 and 1,700–2,000 m. was surmounted by residual summits up to 2,900 m. a.s.l. Pre-glacial river dissection and slope retreat had probably created many steep slopes before the first glaciers formed. The excessively steep gradients and relatively weak rocks of the area enabled valley glaciers and ultimately ice caps to erode deeply into the landscape. Enormous quantities of rock have been removed from the land and from glacially eroded basins below sea-level. Such erosion was effective as much as 12 km. beyond the east coast and to a depth of 270 m. below sea-level. While much of the eroded debris must have been deposited well beyond the present coastline during the glacial maxima, the deposits of the four most recent stages are present on the land.

The mapping of these deposits has shown that the three youngest stages are consistently present in most of the valleys between Fortuna Bay and Hound Bay. The oldest till, apparently deposited during an ice-cap stage, occurs only on two of the peninsulas. It has not been possible to date absolutely any of the glacial stages but they can be dated relative to each other, and tentatively correlated with dated stages in southern Chile and Patagonia. The oldest (ice-cap) stage almost certainly occurred at least 10,000 yr. ago, possibly in harmony with a glacial advance of that age in the vicinity of McMurdo Sound (Nichols, 1960; Bull and others, 1962; Calkin, 1964). The limits of this stage do not occur on land in the Stromness Bay–Cumberland Bay area. Following a period of retreat, the ice re-advanced as expanded valley glaciers, more or less confined to the valleys in which their remnants are presently located. The presence of peat 5,500–6,500 yr. old inside the moraines of this stage, and correlation with south Chile, suggests that the re-advance had culminated by approximately 5,500 yr. B.P. Systems of multiple moraines record recessional phases of this glaciation, and the raised beach shingle approximately 3·5–7·4 m. a.s.l. was deposited at this time. The extent to which South Georgia had become ice-free when the glaciers had completed their retreat is not known but climatic conditions suitable for peat growth certainly commenced and have endured to the present day. The glaciers did not re-advance to any great extent for over 5,000 yr. until the nineteenth century. The stage 3 glaciation involved a relatively small expansion of the ice fields, the large valley glaciers advancing much less than the smaller cirque and col glaciers. Multiple moraine systems again indicate the complex oscillations of the glacier margins. Historical studies by Smith (1960) have suggested that this stage reached its maximum development around 1875, similar to the late nineteenth century stages of glaciers in South America. Alternatively, the stage 3 glaciation may correlate with the Little Ice Age period of A.D. 1750–1800. Retreat was followed by a small re-advance beginning in the 1920s, from which all of the glaciers in the Stromness Bay–Cumberland Bay area are now receding. In front of some cirque glaciers, moraines which are possibly annual features indicate the nature of contemporary retreat. A low raised beach at an altitude of 2·5 m. probably relates to the slight isostatic depression caused by stages 3 and 4; the present beach may be a prograding continuation of this feature.

The scope for further geomorphological research in other ice-free areas is considerable. Much has still to be discovered from studies of the raised beaches, particularly with accurate levelling. A comparative assessment of glacial stages on the western side of the island, as well as to the north-west and south-east, would also be of great value. Longer-term studies would be profitable at the snouts of cirque glaciers, where annual moraines may be forming, and on areas of contemporary periglacial activity.

X. ACKNOWLEDGEMENTS

THE author gratefully thanks Sir Vivian Fuchs for allowing him to work under the auspices of the British Antarctic Survey during the 1967–68 field season in South Georgia. The invaluable help, advice and encouragement of Dr. R. J. Adie at all stages of the work is also acknowledged with sincere thanks. Travelling expenses between the United Kingdom and South America were generously provided by the Carnegie Trust for the Universities of Scotland and the Trans-Antarctic Association. Professor K. Walton kindly arranged leave of absence from the University of Aberdeen for the author and gave much encouragement.

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APPENDIX

PRODUCTION OF THE GEOMORPHOLOGICAL MAP

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1. *Initial requirement for the map*

It was decided that any published geomorphological map should first of all provide the complete picture of the area on one sheet and, secondly, provide for clear visual relationships between the separate groups of symbols and also between the symbols and the base map.

2. *Preliminary considerations*

Initial investigations indicated the necessity for a coloured map in order that the above requirements could be met, but the number of colours, the format and the method of production were to be controlled by two factors: the experience and facilities of the Department of Geography, University of Aberdeen; the availability of finance. Quotations were obtained from five map-printing organizations for a four-colour map of specified format (later modified to five colours) and including a certain number of photomechanical operations. This provided a working basis and after costing the materials and equipment required prior to map reproduction an application was made to the Carnegie Trust for the Universities of Scotland for a grant to defray the cost of the map. A generous grant from the Carnegie Trust supplemented by finance from the British Antarctic Survey enabled the original plan to go ahead. Most production work was to be carried out in the Department of Geography, University of Aberdeen, but the final processing and printing was to be given to A. W. Gatrell & Co. Ltd.

3. *Base map and geomorphology field manuscript*

There are no detailed large-scale maps of South Georgia. The only published map available in 1968 was the D.O.S. 1 : 200,000 sheet of the Falkland Islands Dependencies (South Georgia, Sheet 610), the first edition of which appeared in 1958. Because this map is highly generalized, with a 500 ft. contour interval, it was extremely unsuitable as a base for detailed geomorphological mapping. The most suitable map was an unpublished one compiled by A. G. Bomford in December 1959 at a scale of 1 : 50,000. This map, incorporating more recent data than the D.O.S. 1 : 200,000 sheet, existed only in manuscript form, but it contained a considerable amount of plan detail and contours at 200 ft. intervals. As will be shown, however, its accuracy and reliability varied in quality. For the present project this map was enlarged to 1 : 25,000 for field mapping.

Production of the final map at the 1 : 25,000 scale would have been costly both in time and money. It was therefore decided to reduce the completed field map to 1 : 50,000, and thus back to the scale of the base map with its known reliability.

Since so much of the interpretation of the map depends upon the reliability of the base, it is important to include some of the information recorded by A. G. Bomford during his compilation of the topographical map. The reliability diagram (Fig. 9) provides separate information for the coastline and interior.

Coastline. Three grades of reliability are indicated:

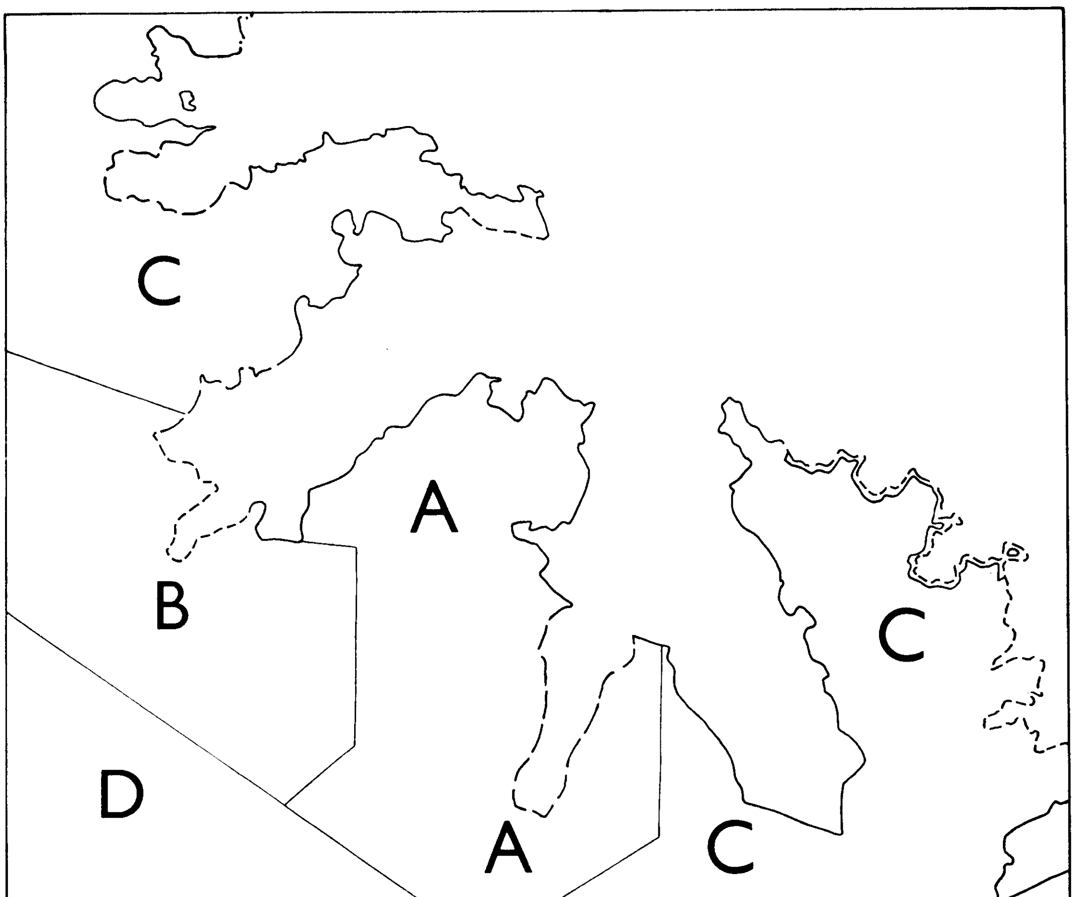


FIGURE 9
Reliability diagram.

i. Solid line. Detail here was derived from vertical air photographs, at a nominal scale of 1 : 14,400, which were taken from a helicopter from H.M.S. *Protector* in November 1957. Control came from the triangulation made by M. J. Stumbles in 1957–58.

ii. Broken line. Detail was again taken from air photographs but without triangulation control. Position was controlled from panoramic photographs taken by V. D. Carse in 1956–57.

iii. Dotted line. Detail and location were derived from panoramic photographs alone. Minor details may have been omitted and the probable error in position may occasionally exceed 200 yd. This was partly improved from a radial-line plot carried out by Bomford in July 1960 (indicated by the parallel continuous line in Fig. 9) but, although local detail is improved, the overall control is still weak through the absence of a trigonometrical framework.

Interior. The interior is subdivided into four reliability zones:

A. Plane-table survey by J. Smith in 1957–58, based on the South Georgia Survey triangulation, made in 1951–52.

B. Here the detail was taken from panoramic photographs, taken by V. D. Carse in 1956–57, based on the South Georgia Survey triangulation of 1955–56.

C. Position and detail were taken from panoramic photographs only, triangulation being inadequate or absent.

D. This area has been enlarged from the D.O.S. map of South Georgia at 1 : 200,000 for which this area in turn had been compiled from long-range panoramic photographs, taken in 1953. The area is inadequately surveyed and important features may have been omitted.

Further corrections to coast and topography have been made during the compilation of the present map, by comparison of existing maps with notes and photographs taken by C. M. Clapperton in 1968. It was also noted by Bomford that sufficient soundings existed for the interpolation of submarine contours, and this has been done specifically for the present map, from Admiralty Chart 3589 "Harbours and anchorages in South Georgia". It helps to extend topographical information below sea-level and reinforces the landward evidence, especially in the inlets.

The projection on which Bomford's base map is plotted is similar to the D.O.S. map at 1 : 200,000, i.e. the Lambert Conical Orthomorphic with one standard parallel, the origin being lat. 54°30′ S., long. 37°00′ W. The grid, on which Bomford's base map was constructed (and which appears in the form of edge ticks on the present map), is the arbitrary 5 km. grid drawn for *British Antarctic Survey Scientific Report* No. 45. It is not a U.T.M. grid, but has the same origin (false coordinates 100,000 m. east, 100,000 m. north) as the grid appearing on the D.O.S. map of South Georgia at 1 : 200,000.

The geomorphology manuscript map provided for the compilation was at a scale of 1 : 25,000 and on three sheets of polyester draughting film. Contours and coastline were in black ink, and all other geomorphological symbols were drawn in brown and green.

4. *Compilation of the final manuscript at 1 : 50,000*

First, a photographic copy on polyester base of Bomford's original map was obtained from the Directorate of Overseas Surveys. A precise 5 km. grid was plotted on film for the 1 : 50,000 scale by coordinatograph. This provided a control for all subsequent compilation work, information being transferred on a square by square basis. Materials to be used at the final scale, draughting film, scribe coat, and peel coat were pre-punched on a precision punch register.

The compilation of the final manuscript, base data and geomorphological symbols proved to be the most time-consuming and complex part of the operation. In spite of the provision of photographic reductions of the original manuscript, great care was necessary to reconcile the details of the geomorphology with the partly unreliable base. This would have been unnecessary, of course, had a good photogrammetric base map been available. It was also during this stage that the corrections and improvements were made to the coastline and contours but, since it was realized that the contour lines were inaccurate, the modifications made were mainly with respect to the geomorphological symbolism. It cannot be claimed that the present base map is any more accurate than the original, as no additional instrumental survey measurements were actually carried out in the field.

The symbols used on the field manuscript were partly based on the recommendations of the I.G.U. Sub-Commission on Geomorphological Mapping. As the compilation progressed, however, certain modifications were introduced to provide a less abstract picture of the landscape (since many of these official symbols are only slightly representational) and also to bring out areal features such as till and outwash. The point and line symbols modified were "shoulder of glacially eroded valley", "cirque" and "rock wall". All till areas were represented on the field sheet by distributions of the official symbols. These point symbols, however, were too easily confused with other point symbols on the map and so, although the exact boundaries were not known, it was decided to represent all till with area tints. Similarly, fluvio-glacial deposits, beaches and alluvial fans were represented by an area tint, and this began to introduce to the map a visual structure of easily differentiable zones of till, outwash, bare rock and sea. The final manuscript of the geomorphological symbols was produced initially in pencil to allow for the numerous modifications which were to be necessary. All other manuscript work was done in ink.

Although in principle all manuscripts were completed before draughting took place, the stages were staggered, and it was possible to commence with certain final drawings while other sections of the manuscript were being checked. This was also partly influenced by the fact that only one cartographic draughtsman was responsible for the final production work.

5. *Colour plan*

The original plan was to produce the map in four colours (blue, red, yellow and black) and they were utilized as follows:

Blue. Base map: ice contours, bathymetric contours, snow and glacier boundaries, streams and, in combination with yellow, lakes and the sea.

Geomorphology: all symbols in till and, in combination with red, areas of till.

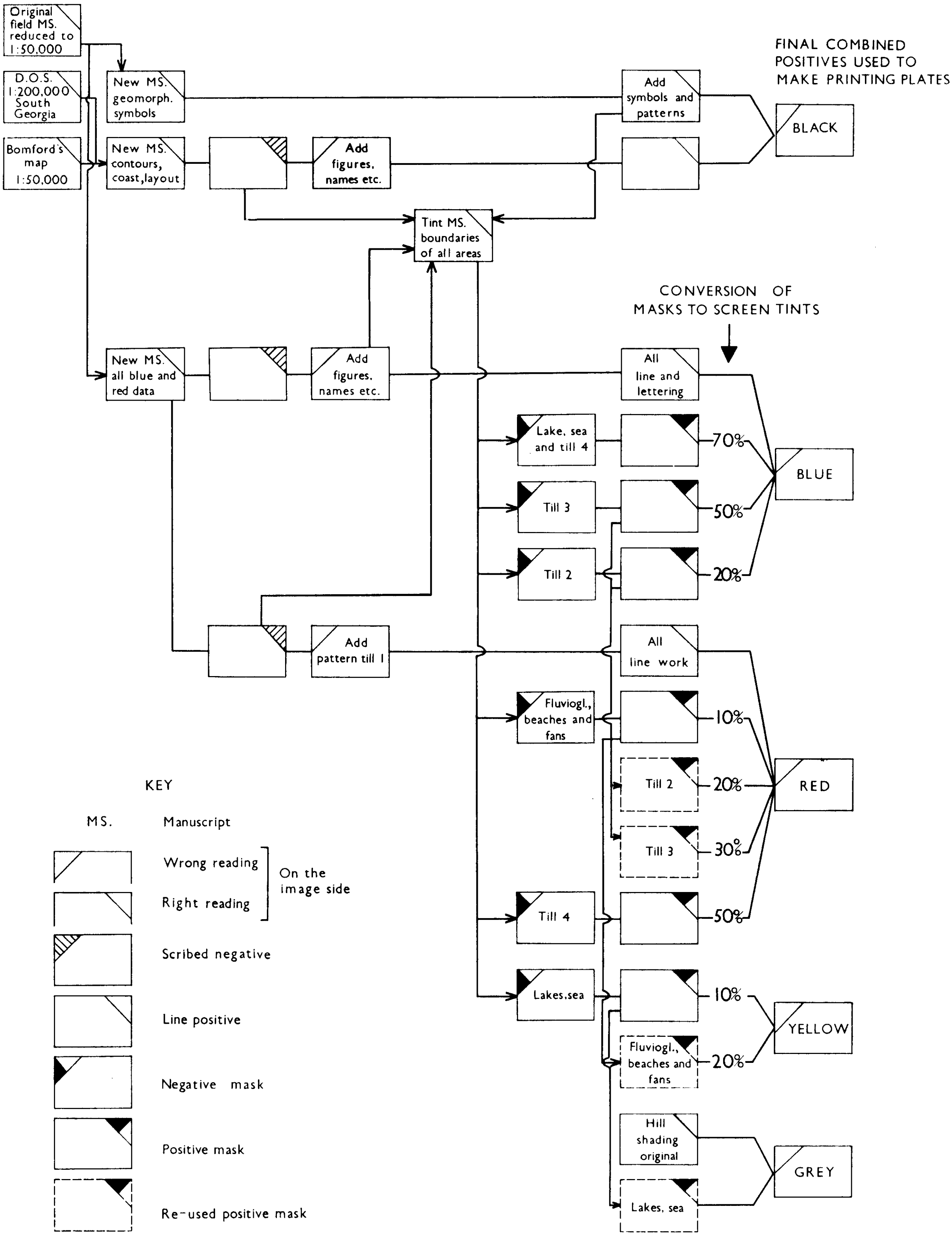


FIGURE 10
Map production flow chart.

Red. Geomorphology: outlines of till zones, and four tints (combined with blue) defining the four age categories of till, all fluvio-glacial, beach and alluvial fan symbols, and, in combination with yellow, a tint covering the full extent of these deposits.

Yellow. Base map: in combination with blue to produce a blue-green sea.
Geomorphology: in combination with red to cover fluvio-glacial deposits, etc.

Black. Base map: contours, coastline, names, frame, title, scale and key information.
Geomorphology: all base rock and rock-cut symbols, shattered rock and scree; also the moraine ridge symbols in the two most recent till groups so that they would stand out against the dark tints planned for this till.

At a later stage it was decided that it would be possible to finance the printing of an extra colour, a blue-grey for hill shading. This was designed to help bind together the open framework of contours and give some solidity to the landscape. During the planning of the lay-out it was decided to produce a pictorial key with symbols in typical locations within two idealized map sections of the landscape: a ridge zone, and a glacier and frontal zone. This meant that all colours would also appear in the key, and the compilation manuscripts were adjusted accordingly.

On the basis of the above colour plan, three separate manuscript sheets were compiled:

i. Geomorphological symbols—for black.
ii. Coast, contours, names, frame and all other marginal information—for black.
iii. All symbols appearing in blue and red, including names of glaciers and bathymetric contour values.

An approximate manuscript was prepared for tint areas, but this required precise re-draughting at a later stage when all other final drawing was complete.

6. *Final drawing**

It had been planned that all line work would be scribed at the final production scale, but it proved more convenient to draw the geomorphology plate using Chinese ink on polyester draughting film. For all other line work a diazo image was put down on scribe coat and scribing proceeded as planned (Fig. 10). Contacts were made to positives from these, and symbols and lettering added where appropriate, all lettering being produced on the Barr and Stroud Photonymograph. When all line work had been completed, a precise tint manuscript was prepared and etched into six sheets of peel coat. Open window negatives were then produced by peeling out appropriate areas on these sheets. These were contacted to produce the positive masks which were used to print down screen tints at the final combined positive stage (Fig. 10). The hill-shading was produced as a same-scale drawing in pencil. This later passed through a camera and half-tone negative stage before plate-making.

The commitment of the Department of Geography, University of Aberdeen, ended with the production of final black positive line images for red and blue, six positive masks, and one hill-shaded drawing, ten originals, all designed to fit in perfect register.

After final checking, these positives were sent to A. W. Gatrell & Co. Ltd. to carry out the final stages of processing and the production of the five final combined positives. A five-colour electrostatic proof was produced and examined. After final corrections had been made the map was printed and the project brought to a conclusion.

7. *Acknowledgements*

I should like to thank Mr. C. B. Bremner, who carried out all the draughting work and contributed to the design of the map, and also Mr. C. Wilson and the photographic staff of the Department of Geography, University of Aberdeen, without whose skill and experience the work could not have been brought to a satisfactory completion.

* Owing to certain problems which arose at a late stage in the production of the geomorphological map, changes had to be made to the colour plan. Although the printed map does not comply exactly with the colour plan and flow chart which appear in the above text, the latter do characterize the production procedure.

PLATE I

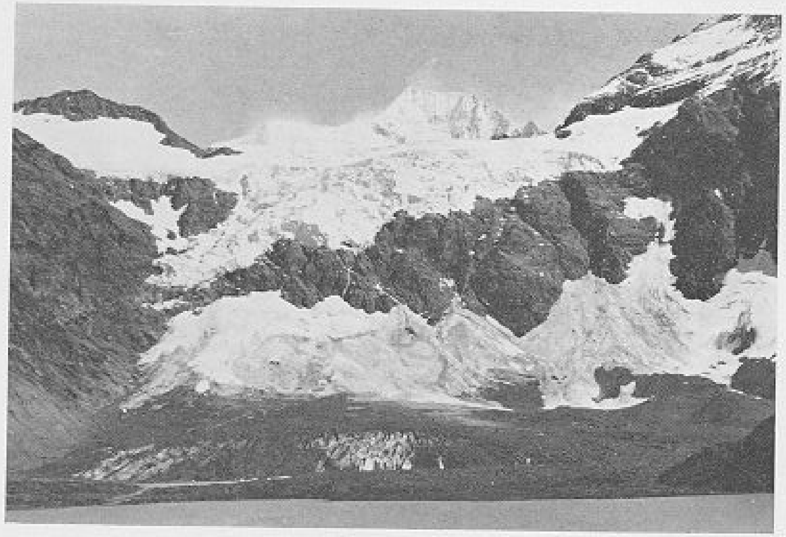
a. Group 1 terminal moraines, some of which may be forming annually, on top of ground moraine south-west of Husvik.

b. Group 1 terminal moraines, some of which may be forming annually, at Glacier Col.

c. Group 1 and group 2 moraines in front of the detached part of the distributary branch of Hamberg Glacier. The locality is the head of the Hamberg Lakes valley; Mount Sugartop (2,310 m.) is in the background.

a

b



c

PLATE I

PLATE II

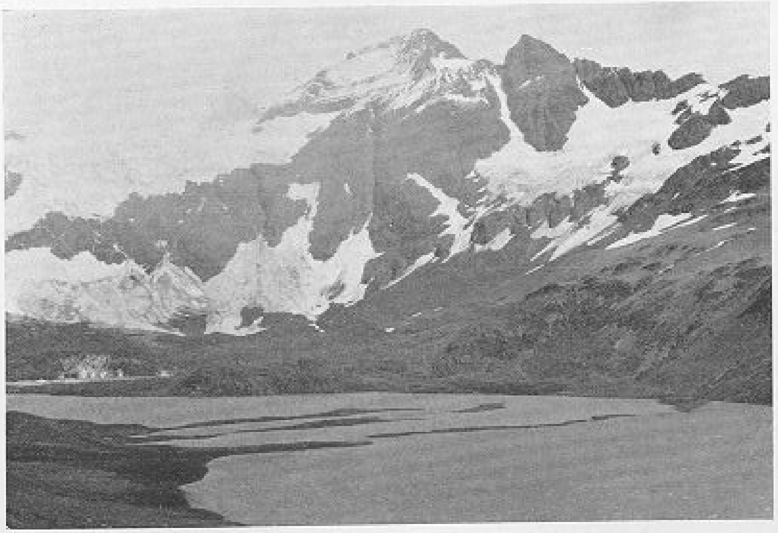
a. Group 3 moraines in the Hamberg Lakes valley.

b. Group 3 lateral moraines on the east side of Moraine Fjord.

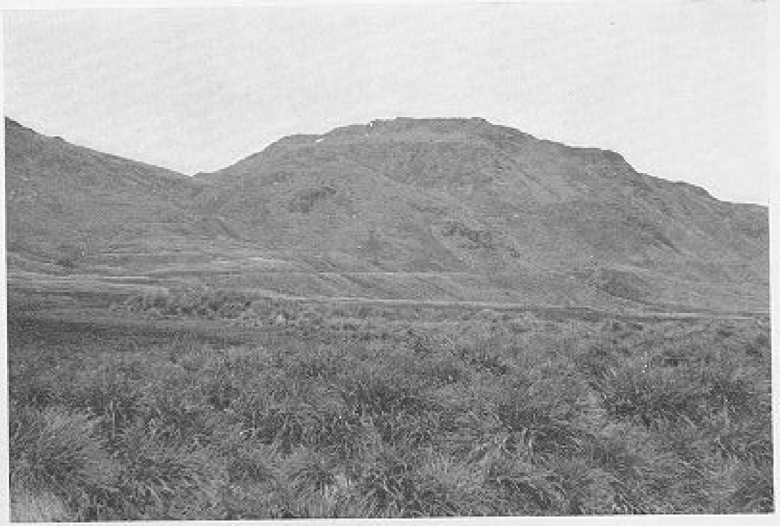
c. Harker Glacier and the large group 3 lateral moraine on the east side of Moraine Fjord.

d. The upper raised beach (7·4 m.), King Edward Cove. It is composed mainly of crudely bedded shingle.

PLATE II



a



b

c

d

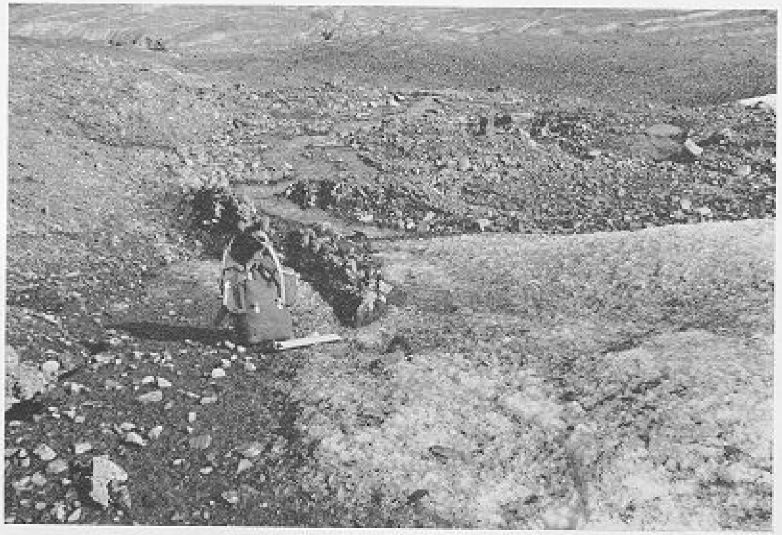
PLATE III

a. A ridge of basal till apparently being squeezed up a shear-plane crevasse at the glacier south-west of Stromness.

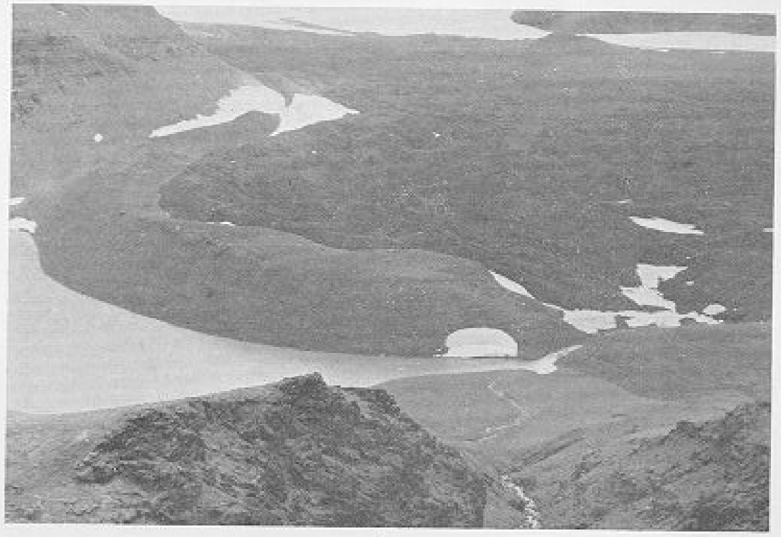
b. Part of the eastern margin of Lyell Glacier covered with superficial debris. The dark colour of group 1 moraine at the glacier margin contrasts with the lighter colour (due to lichens) of the massive group 2 moraine. Former levels of the ice-dammed lake can be seen from the abandoned shorelines on the group 2 moraine.

c. Active stone stripes on a north-west-facing slope east of Sphagnum Valley.

d. Relict stone stripes on group 3 moraine, Zenker Ridge.



a



b

c

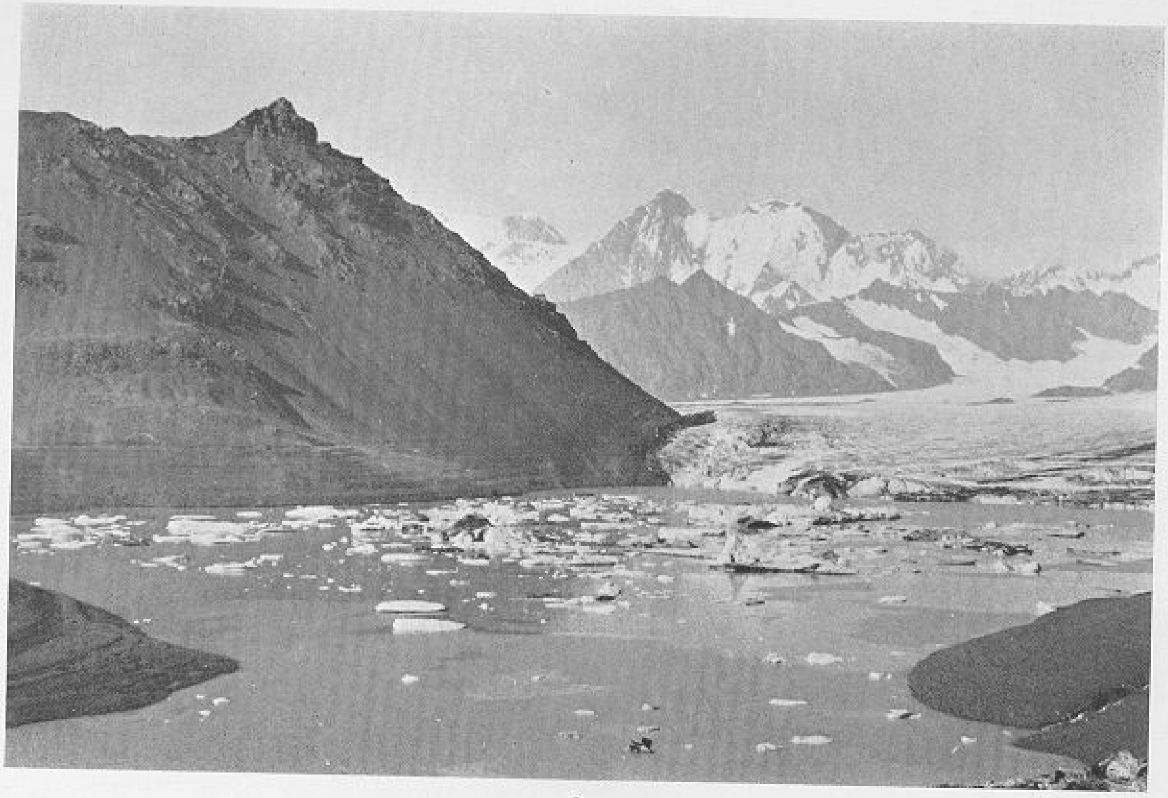
d

PLATE III

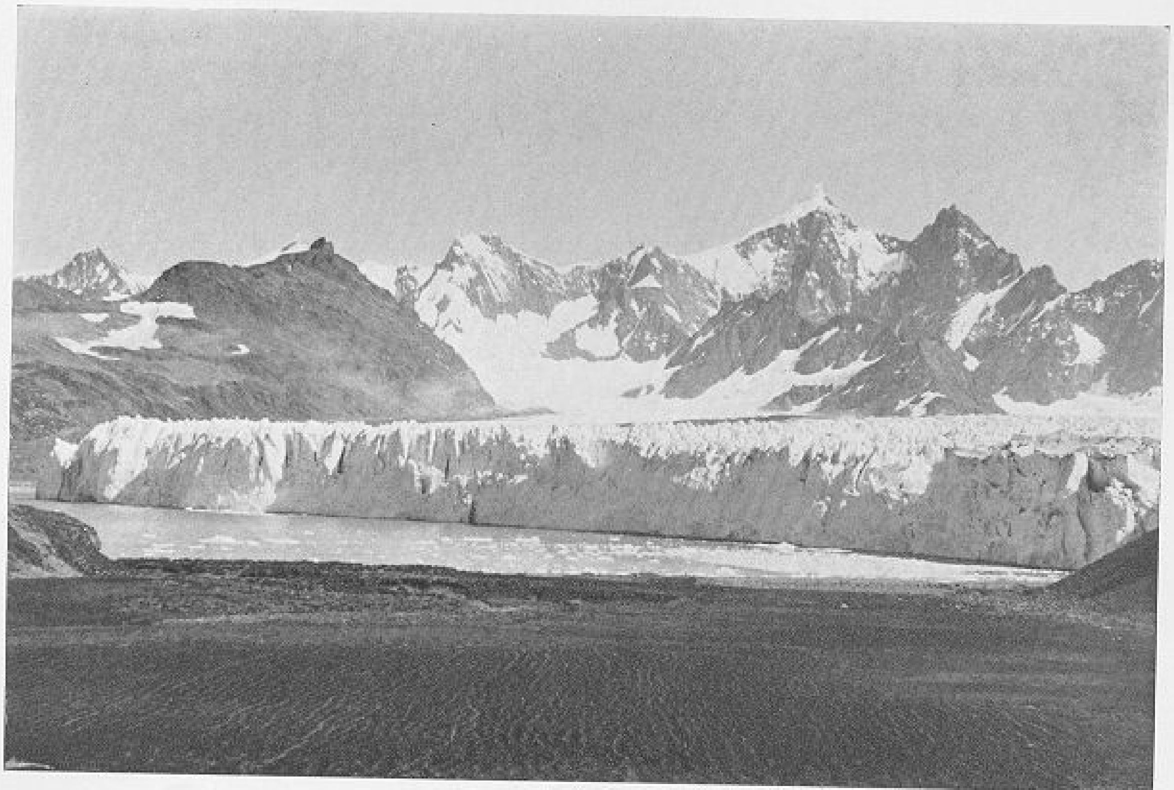
PLATE IV

a. Gulbrandsen Lake and the northern margin of Neumayer Glacier. Relict shorelines mark former levels of the lake. Group 1 and group 2 moraines occur beside the glacier.

b. The highly crevassed snout of Neumayer Glacier in Cumberland West Bay. Non-sorted stripes are in the foreground.



a



b

PLATE V

a. Relict stone polygons with a 1–2 m. mesh, east of Sphagnum Valley.

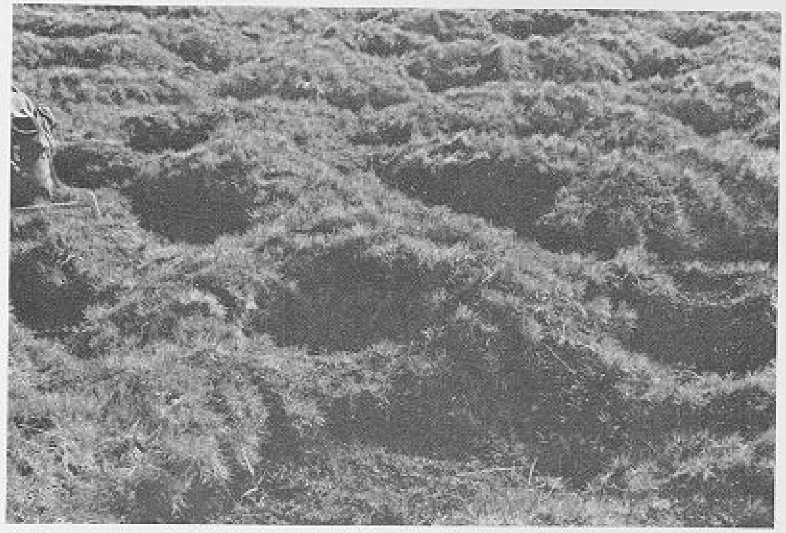
b. Active stone polygons with a 15–23 cm. mesh inside the relict stone polygons, east of Sphagnum Valley.

c. Non-sorted circles, Hestesletten.

d. Plate-shaped stones frost heaved on edge to form stone runs, east side of Moraine Fjord.

a

b



c

d

PLATE V