PHYSIOGRAPHY OF THE NORTH-EAST COAST OF SOUTH GEORGIA

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ABSTRACT. The physiography of the north-east coast of South Georgia is described and the major landforms are related to an ice-cap glaciation and one major phase of subsequent glacierization. Observations on the positions of glaciers during the last 100 years are compared with the results from current field work. Details of raised beaches, wave-cut platforms and patterned ground are presented and the implications of their distribution are discussed.

THIS paper describes the physiography of the north-east coastal area of South Georgia; it is based on observations made during the course of geological survey work in the summer seasons of 1970–71 and 1971–72. South Georgia is an island of considerable relief lying to the south of the Antarctic Convergence and in the path of the prevailing westerly winds. The dimensions of the island are approximately 160 km. by 5–30 km. with the central mountain ridge trending north-west to south-east and rising to almost 3,000 m. The deeply embayed north-east coast between Barff Point (lat. 54°14′ S., long. 36°24′ W.) and Gold Harbour (lat. 54°37′ S., long. 35°56′ W.) (Fig. 1) is on the lee side of these mountains and therefore enjoys milder conditions than the rest of the island, but even so the mean annual temperature is only just above freezing point, and the annual precipitation is well in excess of 1,000 mm. Of greater erosional significance, however, are the short periods of extremely high rainfall. For example, between 00.01 and 18.00 hr. on 4 April 1972, 194 mm. of rain were recorded at the British Antarctic Survey station at King Edward Point, the final total for the 24 hr. period being 215 mm. During this deluge the track from King Edward Point to the Grytviken whaling station was cut by torrent gullies and extensive solifluction lobes, and the natural drainage pattern of the surrounding area was considerably altered.

Geologically, the area discussed here consists of a thick sequence of flysch-type sandstones which have been intensely deformed and overfolded. The larger topographical features of the island tend to follow the structural grain, a phenomenon remarked on by the earliest investigators (e.g. Andersson, 1907), and more local features such as valley orientation are frequently structurally controlled, especially by faults and the joint systems.

The permanent ice cover for the whole of South Georgia has been estimated as 58 per cent (Smith, 1960), whereas for the north-east coastal area this figure must be less than 10 per cent. This comprises the Szielasko Ice Cap in the centre of Barff Peninsula, and several cirque and valley glaciers which form natural boundaries to the area (Fig. 1).

COASTAL DEVELOPMENT

The coastal foreland

The most striking feature along the north-east coast of South Georgia is a series of well-defined platforms ranging from sea-level up to 150 m. a.s.l. On the headlands between the more southerly bays, extensive areas of foreland are preserved at various heights from 20 to 150 m. a.s.l. (Fig. 2) and there has been considerable speculation on the origin of this prominent landform. Gregory (1915) referred to ". . . raised rock platforms . . . a wide plain of marine denudation", whereas Holtedahl (1929) favoured the action of ice, in the form of a piedmont glacier, as the major erosive agent. The surface of the South Georgia foreland certainly shows considerable evidence of the passage of ice. The platform forming the surface of the Cape Vakop promontory is extensively roughened into knob-and-tarn topography and large areas are covered by till, so that it is very difficult to deduce the earliest stages in the development of the foreland. The variation in height of 20–150 m. a.s.l. would certainly not be incompatible with a marine origin, especially if more than one level had been originally involved, and platforms up to 120 m. a.s.l. have been reported in the South Shetland Islands (John and Sugden, 1971). However, these platforms of marine abrasion are backed by relict sea cliffs with a sharp break of slope, whereas the higher parts of the South Georgia foreland steepen into the mountain front in a smooth concave slope. As such, the situation is more reminiscent of

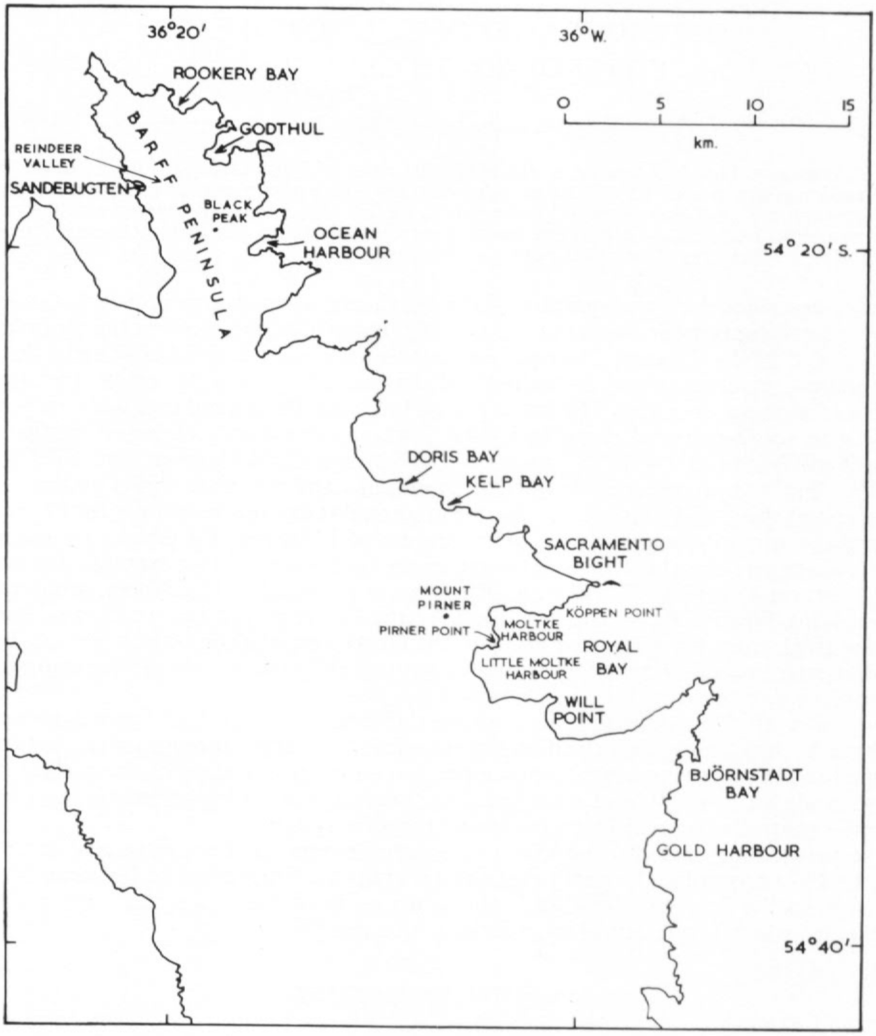

Fig. 1. Sketch map of the north-east coast of South Georgia which is discussed in this paper.

subaerial slope retreat or pediplanation as described by King (1962) in his standard cycle of denudation.

Generally, the height of the foreland above sea-level decreases towards the north and the east, an effect which is even more pronounced if the flat-topped, offshore rocky islets are regarded as relict foreland. There are also some more abrupt slope changes within the foreland, but these are low-angle breaks similar to knick points in a mature landscape, as shown on the promontories between Johannsen Loch and Ocean Harbour, and Ocean Harbour and Penguin Bay (Fig. 2). In the latter case there are signs of a higher "step" above the widely observed 50 m. foreland level rising to 100 m. at the mountain foot. In the Royal Bay area, a relict foreland is preserved on the promontories to the north and south of the bay. Cape Harcourt and Harcourt Island to the north show a remarkably smooth profile, sloping gently inland from 30 to 80 m. a.s.l. over a distance of about 2·5 km. The surface of the foreland here shows occasional glacial striae, it is extensively ice-smoothed, and the till cover is locally sorted into

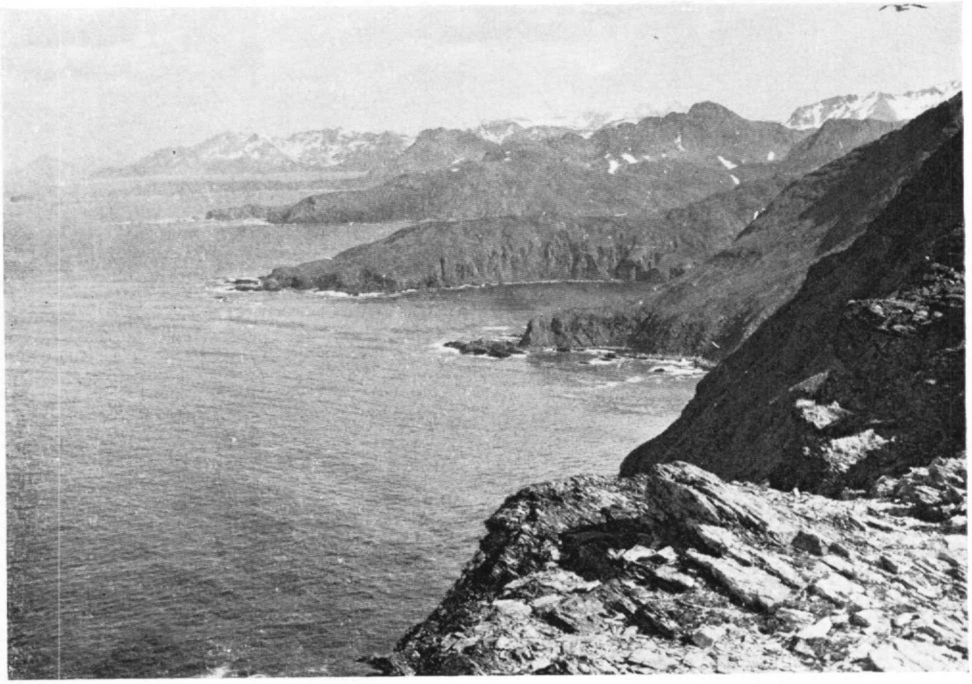

Fig. 2. The north-east coast of South Georgia looking south-east from Cape George towards Cape Charlotte. The coastal foreland is well preserved on the headlands, and the mountains in the background show an accordance of summits at 600–650 m. a.s.l.

stripes. Along the coastline of the Cape Harcourt promontory, sea cliffs truncate the foreland and the development of offshore wave-cut rock platforms is extensive.

To the south of Royal Bay, the tendency for the foreland surface to rise to the south and west is continued, the foreland area at the north-east end of the Cape Charlotte promontory having a base level of approximately 150 m. a.s.l., above which an isolated monadnock-like hill rises to 250 m. The slope to the sea on both sides of the promontory is very steep with the foreland to the south-east impressively truncated by 100 m. sea cliffs. Farther south a poorly defined 150 m. terrace level also descends steeply to the sea in most places.

The lower parts of the foreland are complicated by the existence of definite low-level coastal cirques and marine terraces up to 50 m. a.s.l. backed by steep sea cliffs. Adie (1964) recorded wave-cut rock platforms around the coast of South Georgia at heights of 2·0, 4·8, 6·1–7·0 and 20–50 m. a.s.l. and observations from the Barff Peninsula and Royal Bay areas confirm a series of platforms backed by steep relict sea cliffs up to 50 m. a.s.l.

Raised marine features

Barff Peninsula. Either eustatic changes or isostatic re-adjustment has resulted in the development of raised beaches and wave-cut platforms. The former are most extensively developed in the larger more sheltered bays, and on the west coast of Barff Peninsula several localities show a series of three or more beaches. Two fairly extensive areas showing a succession of raised beaches were mapped in detail at Sandebugten (Fig. 3) and at the bay 1·5 km. farther south (Fig. 4). Raised beach observations on Barff Peninsula are summarized in Table I, and, when shown quantitatively in Fig. 5a they fall into two groups, at 2–3·5 and 5·5–7·5 m. a.s.l. The higher group may perhaps be subdivided into a lower set at 5·5–6·0 m. and a higher set at 6·5–7·5 m. These figures agree well with the results of Brook reported by Skidmore (1972) for Stromness Bay (Fig. 5b) and those of Clapperton (1971), who considered that the raised

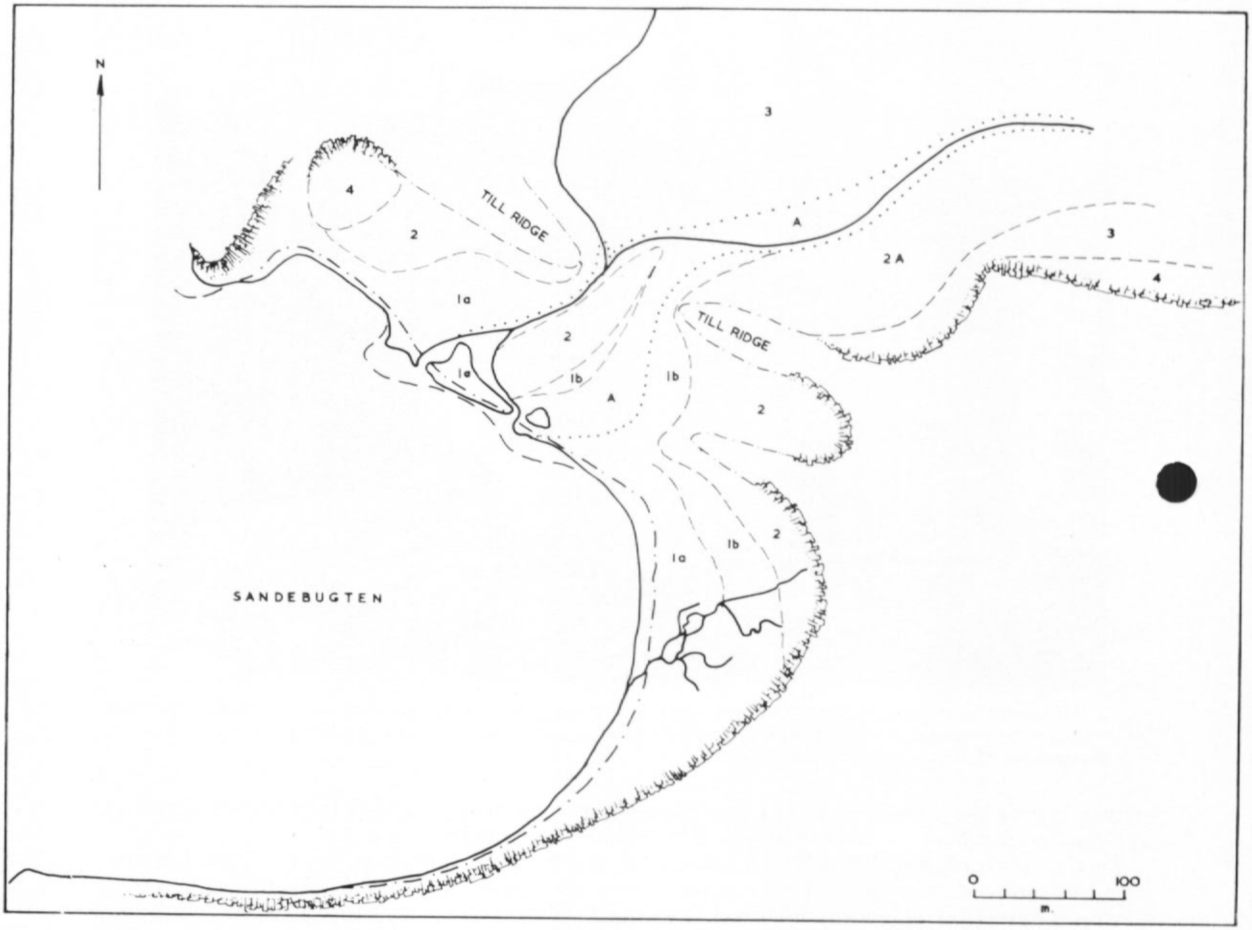

Fig. 3. Sketch map of Sandebugten, showing the distribution of raised beaches.
Raised beach terraces:

1a. 2·0 m. a.s.l. } grading into each other.
1b. 2·5 m. a.s.l. }
2. 5·0–6·0 m. a.s.l.
3. 6·5 m. a.s.l.
4. 9 m. a.s.l.
2A. An alluvial terrace of corresponding height to the raised beach.
A. Alluvial material.

beaches of the Stromness Bay–Cumberland Bay area fall into two main groups at 2–5 and 3·5–7·4 m. a.s.l.

Typically, the raised beaches are built up of fine-bedded shingle with a peat development of 5–50 cm. on top. A low cliff cut into superficial deposits 3 km. south of Sandebugten illustrates this (Fig. 6) and also shows that the raised beach material rests directly on till. However, some of the higher beaches, such as the 5 and 9 m. levels at Sandebugten, consist only of a thin layer of peat overlying till and therefore they must represent either an original surface of abrasion rather than deposition or an area where subsequent re-working has removed the finer beach material. The sea cliff cut into till also provides the key to the main difference observed in the composition of the contemporary beaches on the north and south coastlines of western Barff Peninsula. In the south, large angular boulders derived directly from the till are characteristic

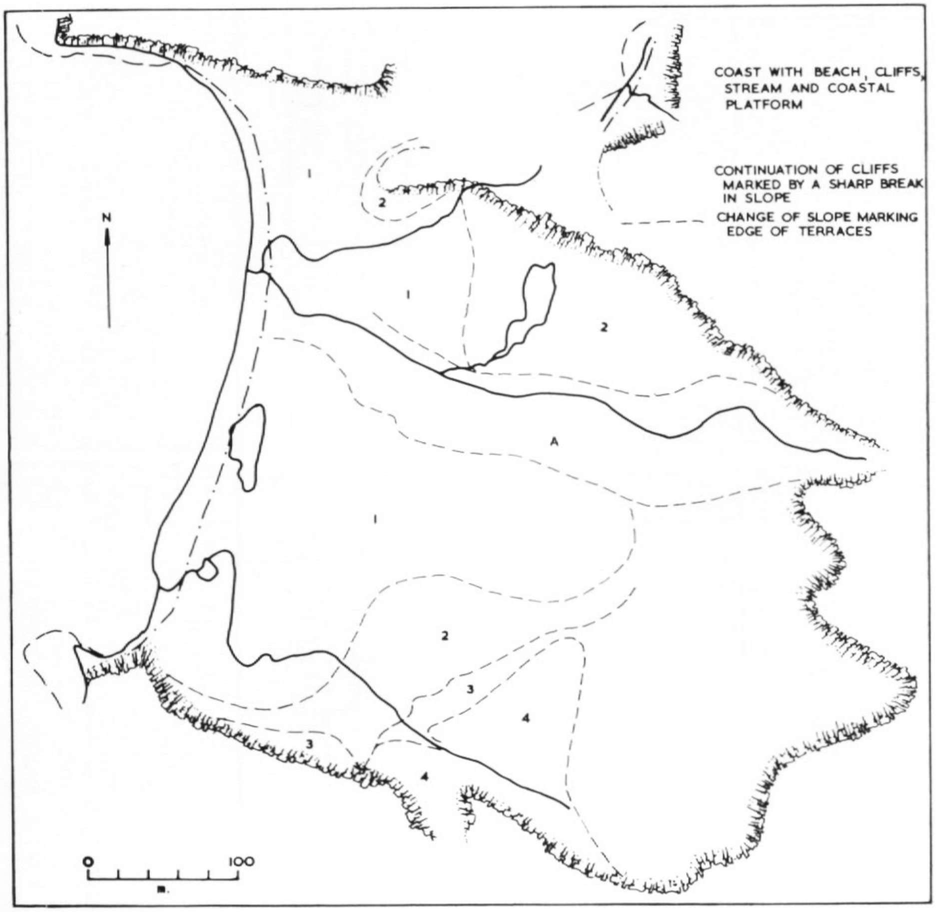

Fig. 4. Sketch map of the bay approximately 2 km. south of Sandebugten, showing the distribution of raised beaches.

Raised beach terraces:
1. 2·0 m. a.s.l.
2. 3·0–3·5 m. a.s.l.
3. 4·0 m. a.s.l.
4. 5·5 m. a.s.l.
A. Alluvial material.

of the very coarse, unsorted beach material, whereas a typical northern beach consists of much finer, well-rounded and sorted pebbles. There is also a close similarity between the material of the present and the raised beaches in the north, but in the south the coarser contemporary beach material contrasts strongly with the fine shingle of the raised beaches, which may have been derived directly from the outwash sands and gravels.

A consideration of the beach material suggests that pre-raised beach till extends for about 4 km. to the north of the present snout of Nordenskjöld Glacier. This is in agreement with the maximum re-advance of Nordenskjöld Glacier suggested by recessional moraines on the western (Dartmouth Point) side of Cumberland East Bay (Clapperton, 1971).

A raised wave-cut platform at 20–25 m. a.s.l. is developed around the more exposed headlands on the east coast of Barff Peninsula (Fig. 7), and a lower wave-cut platform, from sea-level to 2 m. a.s.l., has a wide distribution both on the east coast of the peninsula and within Cumberland Bay.

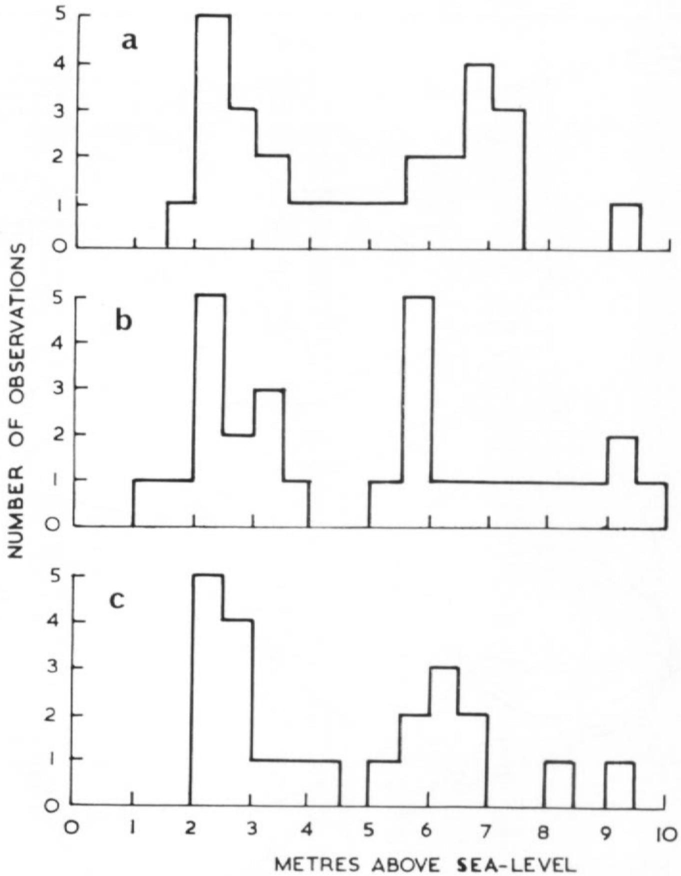

Fig. 5. A quantitative summary of raised beach data.
a. 27 raised beaches on Barff Peninsula.
b. 28 raised beaches in Stromness Bay.
c. 22 raised beaches in the Royal Bay area.

Royal Bay area. The majority of the bays in the Royal Bay area show raised beach development, a low beach at 2–3·5 m. a.s.l. being very widespread, whilst beaches up to 9 m. a.s.l. were observed in the larger bays. The localities and heights of beaches examined are summarized in Table I, and the information in a quantitative form (Fig. 5c) shows that the elevations of the raised beaches of the Royal Bay area agree well with those recorded in Stromness Bay and on Barff Peninsula, and they fall into two main groups: 2–3·5 and 5·5–7 m. a.s.l. From all three areas there is the suggestion of a higher beach level at 9 m. a.s.l. Generally, the material forming the raised beaches is very similar to that of the contemporary beaches. Associated with the lower raised beach, 2 km. west of Will Point, is a large sea cave. This has been eroded along a fault line and beach material covers the floor of the cave which runs into the cliff for at least 40 m., narrowing and bifurcating inwards. The mouth of the cave is now approximately 2·5 m. a.s.l.

Terrace levels behind the beach at Moltke Harbour and in the lower part of Whale Valley (Fig. 8) have been extensively modified by stream action and channelling, and, of the terrace levels recorded behind the beach, only the lowest (at 2–2·5 m.) and parts of the 4 m. level are covered by beach deposits. The remainder of the 4 m. level is covered by sub-angular to rounded cobbles and coarse pebbles derived directly from till and showing close similarities to

TABLE I. SUMMARY OF RAISED BEACH OBSERVATIONS

	Height above sea-level (m.)									
	S.L.	1	2	3	4	5	6	7	8	9
3 km. south of Sandebugten			2	3			6·5			
2 km. south of Sandebugten			2	3–3·5	4	5·5				
Sandebugten			2, 2·5			5–6	6·5			9
1 km. north of Sandebugten			2·5				6–7			
North Barff Peninsula		1·5–2					6			
2 km. north-west of Rookery Bay			2–2·5		4·5–5			7		
North-west Godthul			2·5							
Ocean Harbour			2·5–3				6–7			
Doris Bay			2–2·5				6–7			
Kelp Bay						5				
Sacramento Bight			2·5–3							
North Royal Bay			2–3	3			6·5–7			
Moltke Harbour			2–2·5		4	5·5				
Little Moltke Harbour			2·5–3·5							
Will Point			2·5–3				6–6·5		8	
South Royal Bay			2–3							
Björnstadt Bay			2	3·5–4·5			6–7			
Gold Harbour			2·5–3			5·5	6·5			9

the contemporary beaches in the south-east corner of Cumberland East Bay. The 4 m. raised beach is generally free from peat, is only sparsely covered by vegetation and in times of spate is probably flooded by stream water flowing into Moltke Harbour. Above these raised beaches there is a widespread terrace area at approximately 5·5 m. a.s.l. which consists of up to 30 cm. of peat directly overlying till. Higher terraces, from 7 to 10 m. a.s.l., follow the same pattern with up to 50 cm. of peat overlying till; they probably represent erosion surfaces in the original till-choked valley. Marine action could have been responsible for the formation of these terraces, but higher up the valley and occupying a more lateral position terraces at 20 and 30 m. a.s.l. are more likely to be correlated with stream terraces formed during a period of higher base level. On these terraces peat also directly overlies till, the greatest depth of peat measured being 54 cm. on the highest terrace.

South of Royal Bay, good raised beaches have been formed to the south-east of Will Point, in the northern lobe of Björnstadt Bay and, more extensively, in Gold Harbour where at least three different levels can be distinguished. There is the common low raised beach at about 3 m. a.s.l. and a rather degraded level in the 5–7 m. range which may represent the remains of several beaches. These must pre-date the recent glacial advance, since in the south of the bay close to the glacier an outwash stream section exposes fresh till overlying peat and well-bedded pebbles approximately 80 m. in advance of the ice front. The peat layer is about 6·5 m. a.s.l. Isolated remnants of a 9 m. a.s.l. surface are present towards the north-west corner of the bay.

Further evidence of previous higher base levels is indicated by the elevated rock platforms

Fig. 6. A section through a raised beach 3 km. south of Sandebugten, showing beach shingle overlying till.

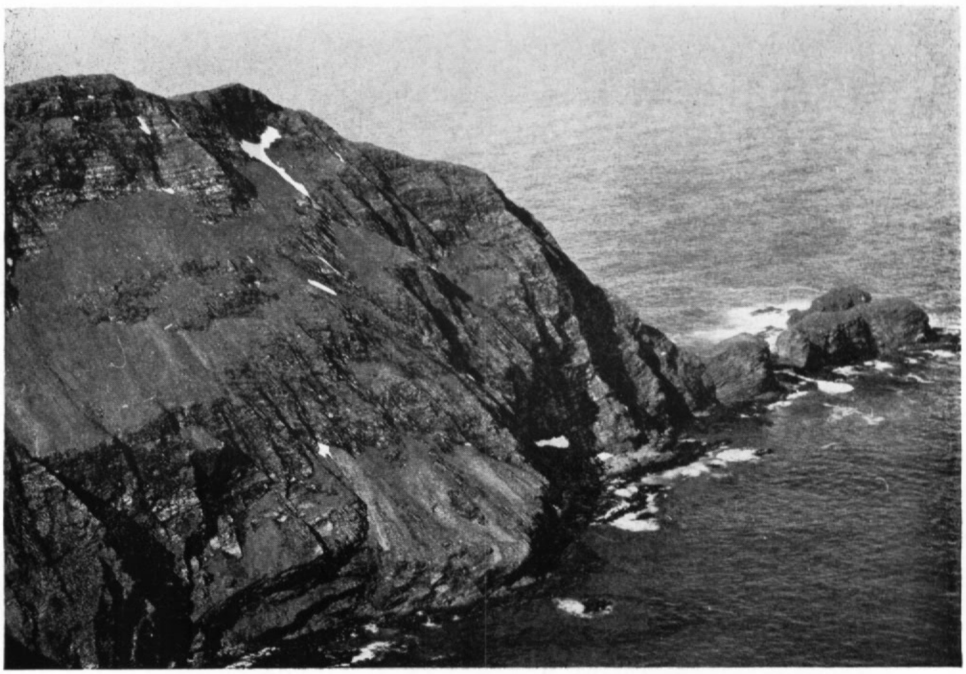

Fig. 7. Wave-cut platforms around Cape George at sea-level and at 25 m. a.s.l.

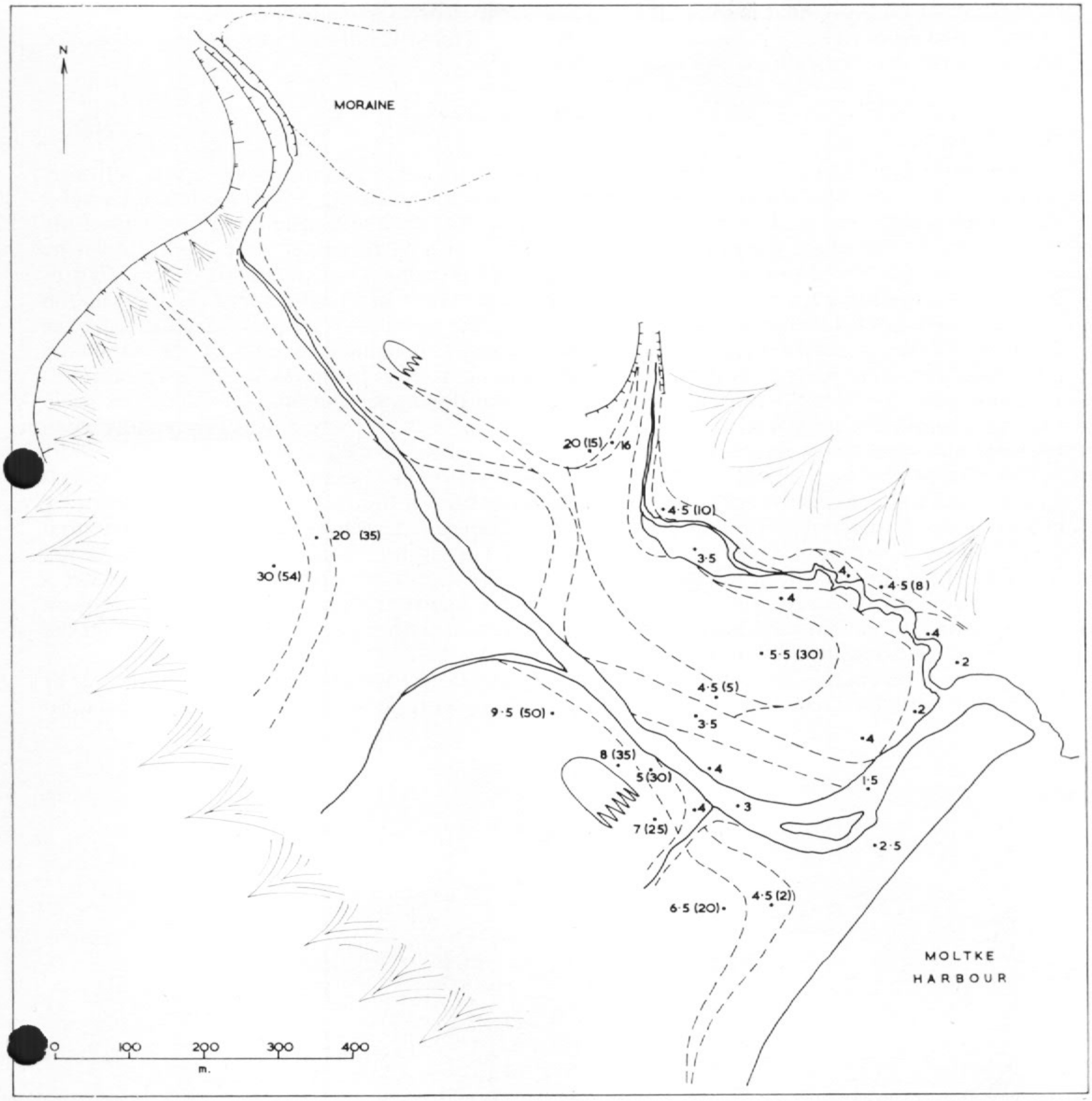

Fig. 8. Sketch map of Whale Valley and Moltke Harbour, showing the distribution of raised beaches and terraces (based on field sketches and levelling by R. B. Crews). The break of slope marking the edge of a terrace is shown as a dashed line. Spot heights are in metres. Figures in brackets are peat thicknesses in centimetres.

around the coast of Royal Bay. They are best developed along the north side of the bay, east of Moltke Harbour, where the highest level recorded is 50 m. a.s.l.; it is backed by a steep cliff and originally it was probably quite an extensive feature since remnants of it can be followed for 1·5 km. along the coast towards Köppen Point. Below this, small platform areas occur at 35–40 m. a.s.l. with the next major development at about 25 m. a.s.l. This is the most widely developed of the higher group of platforms and it is the highest wave-cut platform observed on the south coast of Royal Bay and elsewhere on the north-east coast of South Georgia. Closer to sea-level, wave-cut platforms have been recognized at 6–7, 3·5 and 1·5–2 m. a.s.l., but height estimation or measurement is difficult for the lower platforms since mean sea-level could only be estimated from the debris line at high-water mark. This was only very irregularly developed on the more rocky coastlines.

Glacial Landforms

Barff Peninsula

The north-east coast of Barff Peninsula is characterized by large cirques at various altitudes up to 250 m. a.s.l. The lowest cirques are now drowned, indicating a lower relative sea-level when they were formed. This situation is best illustrated by the cirque complex at Godthul (Holtedahl, 1929), where the intersection of two faults has exercised tectonic control over the distribution of three of the five secondary cirques cut into the walls of the main bay. Two or more phases of cirque formation are also evident at Rookery Bay to the north of Godthul and at Johannsen Loch farther south. At Rookery Bay the secondary cirques have cut into the headwall of the original cirque, the latest and highest still being occupied by ice, following essentially the same pattern as the Godthul development. This contrasts with the situation at Johannsen Loch where the more recent cirque has cut down into the floor of the earlier basin leaving a semi-circular glacial bench. The headwalls of both of these cirques have since been rounded and lowered by eastward overflow from the Szielasko Ice Cap.

The pattern of glacial erosion on the north-eastern side of the peninsula is in contrast to that seen on the western side, where valley glaciers have been dominant, cirque formation being limited to small hanging hollows above glacially overdeepened valleys (Fig. 9). This preferential development of cirques on the north-east of Barff Peninsula perhaps parallels the situation which exists in the Allardyce Range, where the sunnier aspect of north-east faces may create a greater number of freeze-thaw cycles to increase rock shattering and facilitate cirque erosion (Clapperton, 1971). With the prevailing westerly winds, a greater accumulation of snow on the lee slopes would accentuate this effect.

An ice cap, reaching its maximum extent at least 10,000 yr. ago and effective to a distance of 12 km. offshore, has been suggested by Clapperton (1971) to account for the major glaciation

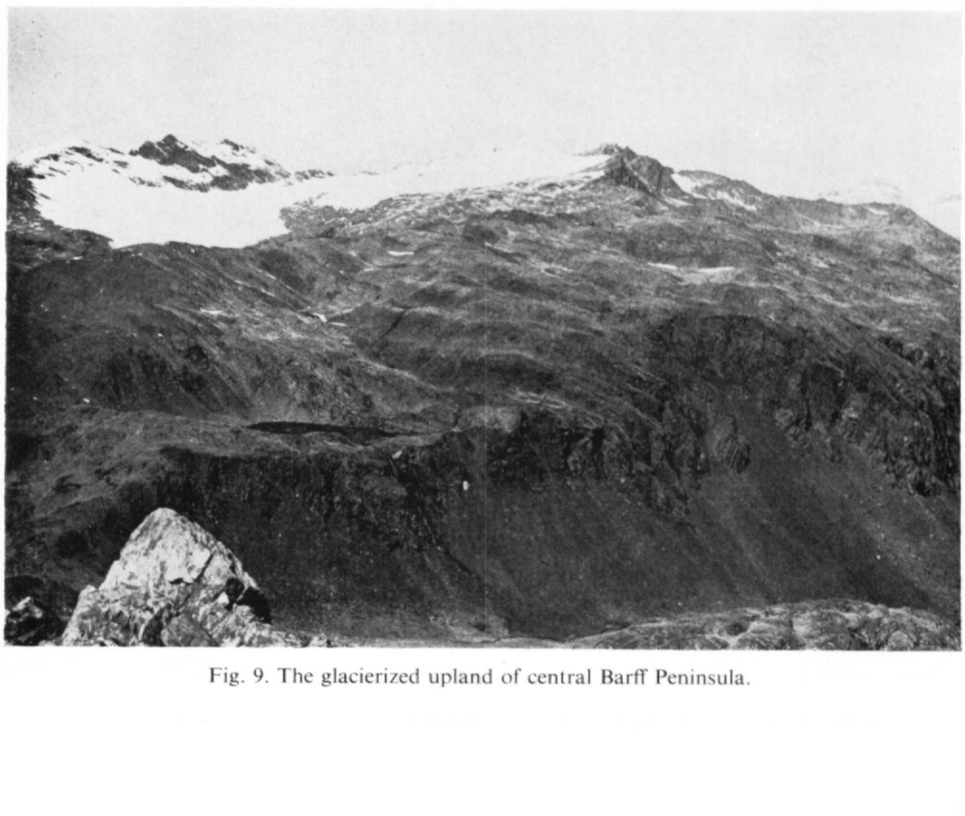

Fig. 9. The glacierized upland of central Barff Peninsula.

of South Georgia. Cumberland East Bay, in common with the other major bays of the north-east coast, may have originated as a pre-glacial valley overdeepened during the major glaciation, and the preservation of part of the foreland platform to the north of Sandebugten shows that Cumberland East Bay at least has been largely unmodified by post-ice-cap glacierization. During this ice-cap stage, the earliest glaciation for which evidence was seen, an enlarged Szielasko Ice Cap, flowing north and north-west to merge with the main body of ice, was responsible for the smoothing and moulding into knob-and-tarn topography of the upland area of northern Barff Peninsula (Fig. 9). Ice movement followed the structural grain along the length of Barff Peninsula, and a valley following the fault zone which trends north-west from peak 2056 was probably overdeepened at this time. During this stage the pyramidal peaks of the north-eastern part of the peninsula formed a barrier between the north-west-flowing glacier in Cumberland East Bay and the north-east-flowing ice from the coastal cirques at Rookery Bay and Godthul.

With the eventual decay of the South Georgia ice cap, the Szielasko Ice Cap became isolated from the main body of ice. Melt-water erosion grew in importance and it was perhaps then that considerable erosion took place along the fault zone trending south-west from peak 2056, and the east–west valley south of Black Peak. A re-advance of the larger glaciers in the Cumberland Bay area has been dated by Clapperton (1971) at approximately 5,500 yr. ago, and expansion of the Szielasko Ice Cap was probably contemporaneous with this. Ice advance was mainly channelled into the valleys previously eroded by melt water and, in particular, the valleys south-west from peak 2056 and south of Black Peak show signs of considerable overdeepening (Fig. 9). To the south-east of the ice cap there was overflow of ice into Johannsen Loch and Ocean Harbour which may originally have been a coastal cirque, whilst secondary cirques developed at Godthul and Rookery Bay. An impressive feature of the valley south of Black Peak is its abrupt trough end. The origin of such features has been related to the up-valley retreat of knick points formed by water erosion after a period of uplift (Embleton and King, 1968) but in this case the configuration of the eastern trough end, with a central peak and no canyons of adjustment, suggests that the origin involves the up-valley migration and merging of glacial steps initiated by ice plucking on the lee sides of pre-glacial features (Gjessing, 1966). It may also be of significance that at this point ice flowing south from the Szielasko Ice Cap merged with ice flowing north from the Allardyce Range to coalesce and flow to the west. In this situation a greater degree of turbulence and a considerable increase in ice depth might have been expected, which would certainly increase the erosive power of the glacier.

To the north of the peninsula a small ice bay formed at the head of the valley north-west from peak 2056 but this did not grow to any great extent. As a result of this lengthy static occupation of the head of the valley, a sizeable terminal moraine barrier was built up and this is now breached by a stream (Fig. 10). The maximum northward extent of the Szielasko Ice Cap during this phase of re-advance probably merged with ice occupying a large cirque south of peak 2056. From here a very active glacier flowed south-west to reach Cumberland East Bay 1 km. north-west of Sandebugten. A lateral moraine ridge has been deposited on the coast, but the main valley is free from any sign of recessional moraines except for a barrier along the rock threshold to the cirque which has dammed a large lake system. This suggests rapid retreat of the valley glacier followed by slow wasting of the residual cirque glacier, and this may have been caused by the deepening of Reindeer Valley thus cutting off the northward flow of ice from the Szielasko Ice Cap. Reindeer Valley was probably initiated by subglacial streams but the westward movement of ice along the valley, which is evident from *roche moutonnées* and extensive striated surfaces, has excavated a large basin closed down-valley by a rock threshold. The basin is now largely filled by outwash deposits but the large lake occupying the western end shelves very steeply and its original depth may have been quite considerable. At the peak of this phase of glacial activity a large ice fall must have existed above Sandebugten, although there is the possibility of some overflow of ice to the north-west, and till ridges at Sandebugten may mark the extent of the ice-talus mound at the foot of the ice fall. This advance via Reindeer Valley and Sandebugten was probably a local effect, reaching a climax after the overall maximum position of glaciers in the Cumberland Bay area had been attained.

The present state of the Szielasko Ice Cap is one of decay and retreat. It has now split into two lobes which are only connected in the extreme south, the smaller eastern lobe occupying a

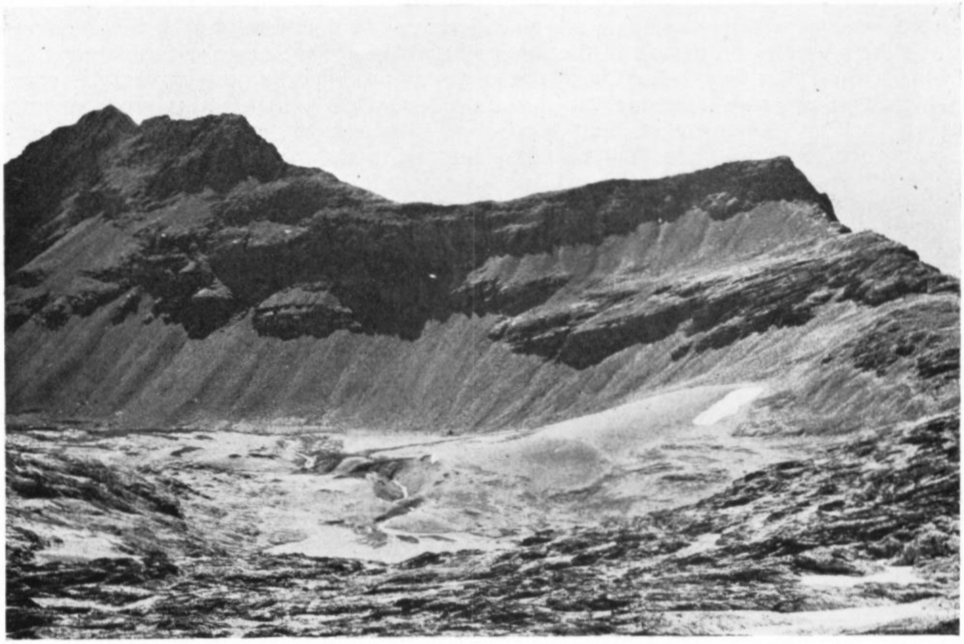

Fig. 10. A moraine-dammed valley in the north-west of Barff Peninsula.

high-level shelf north-west of Johannsen Loch into which it wastes by melt and ice falls. The western lobe occupies the central plateau of Barff Peninsula and most of the ice movement and melt is towards Reindeer Valley in the north. There is also minor ablation to the south and west. The low serrated northern snout of the western ice lobe, which is charged with a great deal of englacial and supraglacial debris, lies behind an area of low, sinuous and branching moraine ridges indicating very irregular retreat both in space and time. Some of the moraine mounds appear to have been pushed into position, suggesting temporary local advance which may be a seasonal phenomenon. Subglacial melt streams emerging from beneath the ice have cut gullies over 1·5 m. deep in bedrock and melt water is therefore carried away directly from the snout in rock gorges. There is also a considerable quantity of supraglacial melt-water run-off which, in places, has eroded channels in the ice. There are several large ponds of standing water among the chaotic moraine ridges.

Royal Bay area

The Cape Harcourt promontory and its hinterland, to the north and north-west of Royal Bay, is essentially the glacially incised remains of a high-level plateau. Over the whole area, mountain summits show a remarkable accordance at approximately 650 m. a.s.l. and some of them display a very flat-topped mesa-like form (Fig. 2). Inland from this plateau there is a steep rise to a narrower "step" in the landscape at 800 m. a.s.l. before another steep rise to the peaks of the Allardyce Range. South of Royal Bay, the landscape steps are not so well marked but parts of the 650 m. plateau can be detected with a higher step at about 800 m. a.s.l. at the foot of the Salvesen Range. Thus the stepped landscape of South Georgia (Gregory, 1915; Clapperton, 1971) is well illustrated with the coastal foreland as the lowest step in the series.

The glacial landforms eroded into this 650 m. plateau north of Royal Bay are nearly all the result of valley glacier ice flowing radially towards the sea. This has resulted in a complex pattern of glaciated and hanging valleys with moraines and glacially smoothed topography marking the previous extent and passage of the ice.

To the north-west of this area, the steep rock wall west of the glacier flowing towards Doris Bay must have been eroded by a far larger body of ice than now occupies the valley. A hanging cirque 300 m. above the valley floor perhaps gives some indication of previous ice volumes. Two hanging valleys have also been formed above the eastern side of the main Doris Bay valley; they contain residual permanent snow patches at their heads but beneath them the stages in the retreat of the main valley glacier are marked by a series of three crescentic moraines. A valuable and interesting comparison may be drawn between the present situation and that shown on the map produced by the German International Polar Year Expedition in 1882–83 (Neumayer and Börgen, 1886). At that time, the glacier occupying the Doris Bay valley (called by them "Nachtigal" glacier) had retreated very slightly from a large terminal moraine barrier, located mainly on the western side of the snout. This moraine can be recognized today, and when the relative positions of ice and moraine are compared with the map produced by the Combined Services Expedition of 1964–65 a retreat of 1·5 km. is evident. In fact, in December 1971, the ice front of "Nachtigal" glacier showed a further retreat of approximately 0·5 km. from the position recorded in 1964–65, so over the last 90 yr. this valley glacier has retreated almost 2 km. The crescentic recessional moraines referred to earlier are, however, beyond the position recorded by Neumayer and Börgen, and therefore they indicate a previous glacial episode of more extensive proportions. The 1882 situation recorded by the Germans is in strong agreement with an 1875 glacial maximum suggested by Smith (1960) after comparison with the meteorological and glaciological records for South America.

To the south-east, a similar retreat from the 1882–83 position can be deduced in the valley behind Kelp Bay. Neumayer and Börgen showed the valley occupied by a glacier they referred to as "Forster" glacier; this now exists only as a small patch of permanent ice at the head of the valley with a great deal of fresh moraine in irregular ridges below. Among these ridges a moraine-dammed lake has old shorelines 2 and 3 m. above the present lake level. The lower part of the valley is occupied by a platform at 30–34 m. a.s.l. cut into till, probably by melt water. Comparison with the Neumayer and Börgen map indicates a retreat of at least 1·5 km. over the last 90 yr.

From the cirques on the eastern face of Mount Krokisius there has been considerable ice flow, in part to the north-east but mainly to the south-east along the valley to the south of Brocken. The oldest moraine system observed is immediately to the east of the eastern lake, where a terminal ridge dams the lake and links with a lateral moraine ridge on the south side of the valley. This lateral ridge extends for almost 0·5 km. eastward but beyond the terminal ridge, and therefore it must mark only a stage in the glacier's retreat. A similar though slightly smaller recessional ridge dams the north-western lake. Retreat from these positions had been completed well before 1882 when the Mount Krokisius cirque glacier was in fact smaller than in 1972. This is a rather paradoxical situation considering the continuing retreat of "Nachtigal" and "Forster" glaciers from a possible 1875 maximum.

One of the most complex glacial valleys of this area is centred on Whale Valley, where glacial benching is very pronounced and represents two phases of advance. Whale Valley itself is divided into upper and lower sections by a steep trough end or glacial step about 1·5 km. inland from Moltke Harbour, with the most impressive features on the south-western side of the upper section (Fig. 11) where hanging cirques open out on to the higher bench. To the north-east the features are generally more subdued, but overall the bench level descends from 300 to 150 m. a.s.l. over 3·5 km. to give a broad 150 m. terrace immediately north of Moltke Harbour. The glacierization of the coastal foreland may be contemporary with the formation of this terrace. Above Whale Valley, high-level hanging valleys, one still occupied by a small glacier, are situated to the north of Mount Pirner. The confluence of the ice from this valley system and that from the upper section of Whale Valley would have coincided with the major glacial step and this may have been a factor in its development by providing a greater depth of ice with a more turbulent flow pattern. A series of large crescentic recessional moraines now marks the slow retreat of this glacier from the lip of the step above lower Whale Valley. Further glacierization of Whale Valley cut down into the older glacial valley and lowered the northern side of the step. The maximum extent of this advance is unknown but the *roche moutonnées* at Moltke Harbour were probably formed at this stage, and subsequent retreat has left a large recessional moraine at the narrowest point in the valley where the glacial step had

Fig. 11. The southern glacial bench in upper Whale Valley.

been lowered. The topographical break between the two parts of Whale Valley was thus re-established.

The higher Whale Valley terrace may well be associated with the ice-cap glaciation of South Georgia (Clapperton, 1971) but the subsequent re-advance must have been completed some considerable time before the 1875 maximum suggested by "Nachtigal" and "Forster" glaciers.

The larger of the two glaciers flowing into Royal Bay, Ross Glacier, is also the one which has received the greatest attention over the last century, thus allowing changes in the position of the ice front to be followed in some detail. During the German International Polar Year Expedition a retreat of almost 1·5 km. was recorded between August 1882 and August 1883 (Neumayer and Börgen, 1886) but by April 1902, when the snout was surveyed by Duse of the Swedish Antarctic Expedition (Nordenskjold and Andersson, 1905), re-advance had taken the snout to a position slightly beyond the maximum recorded by the Germans. In 1920 the ice front was back in the maximum German position (Douglas, 1930) but during the following 9 yr. an advance of about 1 km. was indicated by the observations of Holtedahl (1929) before the British South Georgia Expedition of 1954 made ice-front measurements from which Brown (1956) described a retreat of 1·5 km. to a position approaching the minimum German record for 1883. Another phase of re-advance was shown by the 1964–65 Combined Services Expedition's survey of the ice front when it was found to be again in approximately the position determined for 1882. Observations in December 1971 showed little further change in the position of the southern part of the ice front but some retreat in the north. The retreat observed by the German expedition in 1882–83 was probably from an 1875 maximum position, whilst subsequent re-advance, culminating about 1929, may have been associated with a climatic deterioration in 1924 which caused glaciers in the Cumberland Bay area to advance for up to 12 yr. (Smith, 1960). A recent development is the appearance of a shingle beach along the foot of most of the northern half of the ice front (Fig. 12). Soundings in Royal Bay show there is deep water quite close to the ice, and the active calving from the southern half of the snout suggests that it is

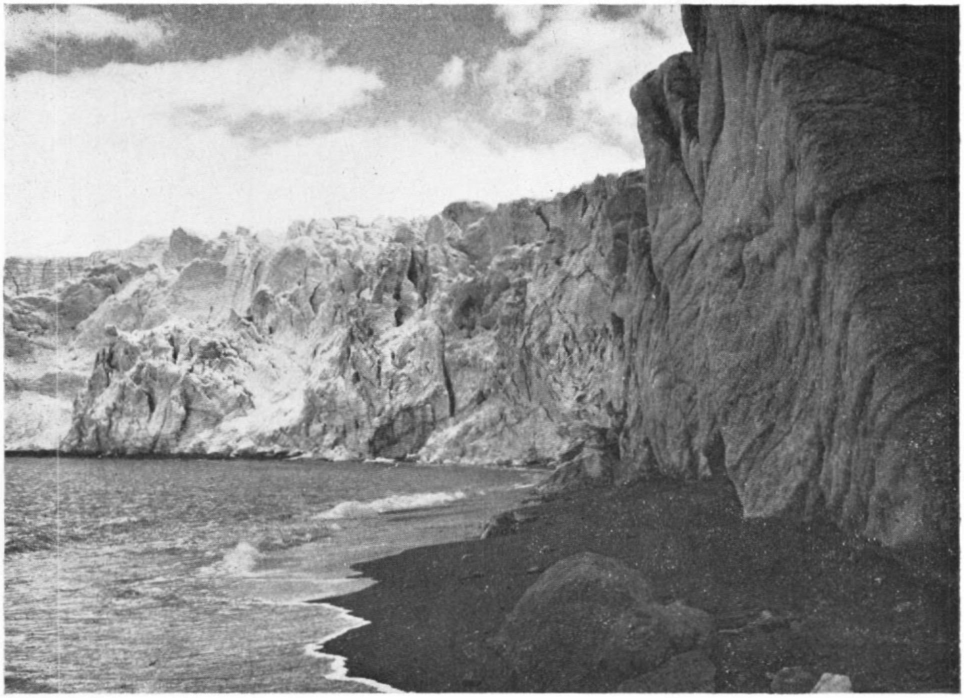

Fig. 12. A recent raised beach along the foot of the ice front of Ross Glacier.

floating. About 0·5 km. inland in Little Moltke Harbour, the northern side of Ross Glacier is fairly shallow and descends steeply over quite rough topography and so this side of the ice front, where the beach has developed, is probably grounded. A much greater depth of ice must therefore form the southern half of the glacier and the composite map of ice-front positions (Fig. 13) shows that the southern half of the snout has been the more active. This may have resulted from the height differences of the sources of ice to the north-west and south-west, the "sudden surge" advances of the southern half of Ross Glacier resulting from a drastic increase in supply through ice falls and avalanching from the steep walls of high-level cirques (Brown, 1956).

To the east of Will Point, a large moraine ridge is situated to the west of Weddell Glacier's recessional bay, and a submerged moraine barrier, marked by surf and patches of kelp, crosses the mouth of the bay to link with a small moraine ridge on the eastern side. Neumayer and Börgen (1886) recorded Weddell Glacier in contact with the large western moraine in 1882–83, so a retreat of 0·5 km. to the present-day position is evident, the submerged moraine barrier marking a temporary halt in the retreat, possibly in about 1929. Weddell Glacier flows north from a snow field at about 700 m. a.s.l. which also feeds the eastward-flowing Bertrab Glacier. The snout of this latter glacier reaches the sea at Gold Harbour where an extensive moraine system shows slight recent retreat of the glacier. Since the glaciers share the same source, some similarity might be expected with the movements of Weddell Glacier, but the large well-developed moraines in Gold Harbour show a maximum retreat of 150 m. with signs of some very recent re-advance locally and on a small scale. One of the oldest moraines of Bertrab Glacier, probably formed during an 1875 advance, has been pushed to overlie peat and raised beach material 6·5 m. a.s.l. The large cirque and valley to the north-west of Gold Harbour which now contain dammed lakes and extensive till deposits was probably free of ice long before the 1875 re-advance. During previous advances, however, a tributary glacier played a part in the development of the glacial step, causing the ice falls of Bertrab Glacier by increas-

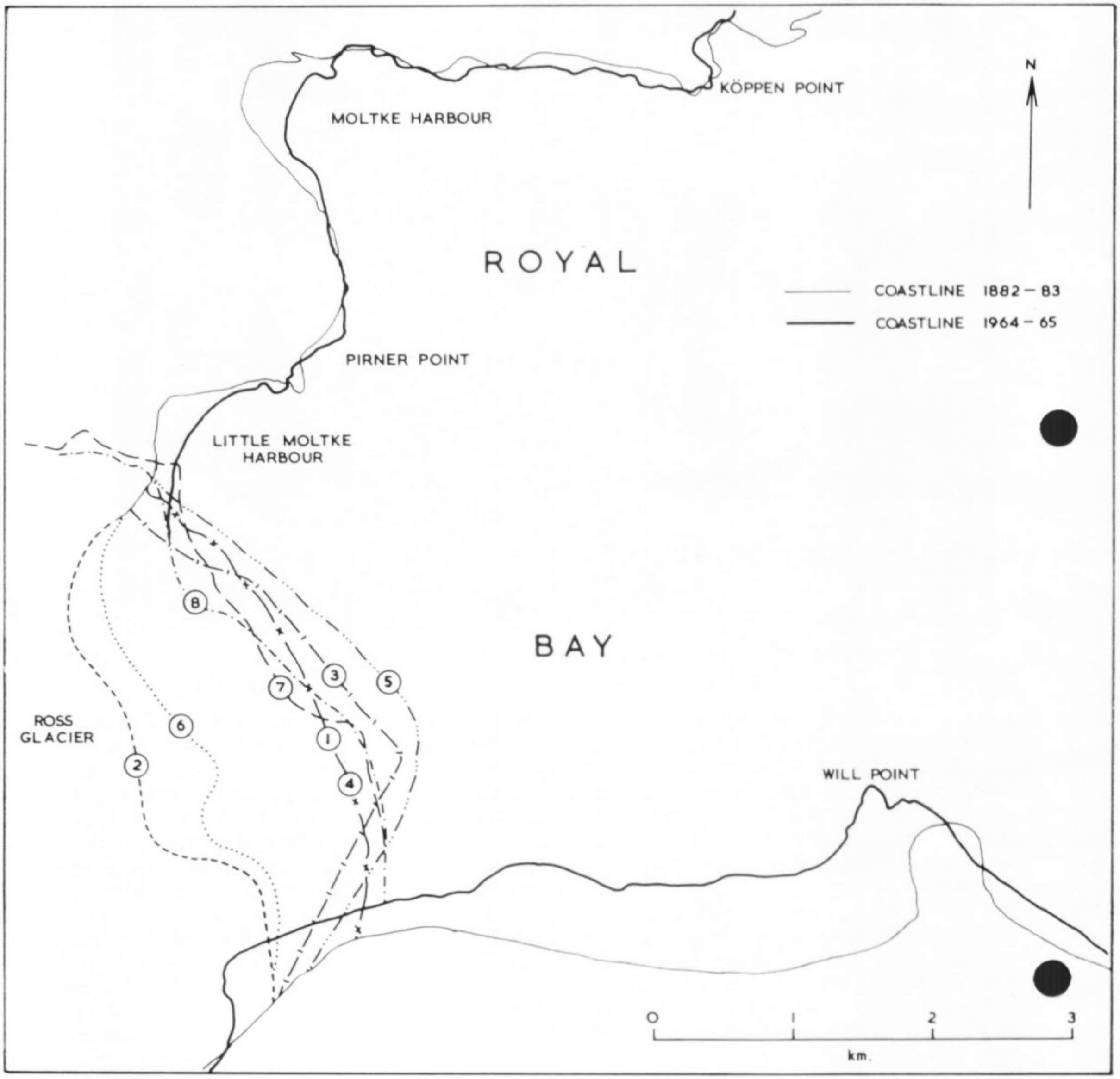

Fig. 13. Sketch map of Royal Bay showing the recorded variation in the position of the snout of Ross Glacier between 1882 and 1972.

1. 1882: Neumayer and Börgen (1886).
2. 1883: Neumayer and Börgen (1886).
3. 1902: Nordenskjöld and Andersson (1905).
4. 1920: Douglas (1930).
5. 1929: Holtedahl (1929).
6. 1955: Brown (1956).
7. 1965: Combined Services Expedition, 1964–65.
8. 1971: Present paper.

The results are compared on the best fit of the coastlines from the 1882–83 and 1964–65 surveys.

ing vertical glacial erosion at the confluence. In fact, nearly all of the trough ends and glacial steps seen in the Barff Peninsula and Royal Bay areas are associated with the merging of glaciers, a coincidence which may be of wider significance.

North of Gold Harbour are two small low-level cirques and the extensive glacial deposits inland from Björnstadt Bay. The lateral moraine terraces at Björnstadt Bay (Fig. 14) originated at the sides of a considerable ice mass flowing eastward from the lowest part of the Cape Charlotte ridge. Some of the cirques on the eastern side of the ridge are still occupied by permanent snow but ice flow from them has not disturbed the lateral ridges in the valley below. The subdued form and mature vegetation cover of these moraine ridges suggest that they are among the oldest glacial features seen in the Royal Bay area, and they may date from the time when the merging of Ross, Weddell and Whale Valley glaciers filled Royal Bay with sufficient ice to allow overspill through the low point of the Cape Charlotte ridge. Later glacierization was limited to cirque formation which was also the case to the north of Björnstadt Bay where a complex of cirques, the higher ones now occupied by lakes, cuts down to sea-level.

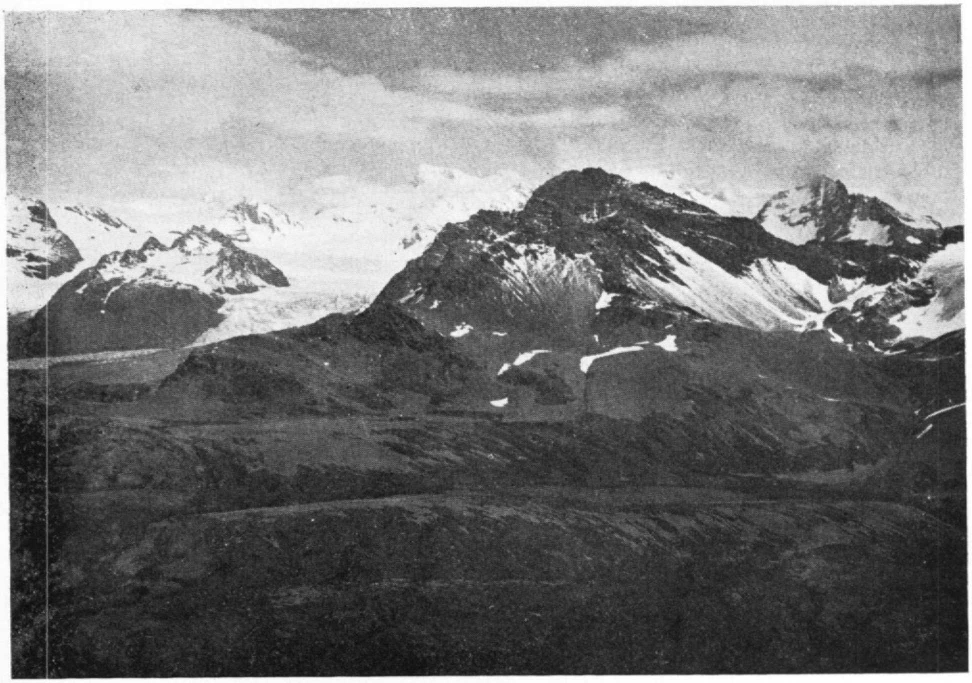

Fig. 14. Lateral moraine terraces west of Björnstadt Bay.

Periglacial weathering

North of Hound Bay, the only examples of patterned ground seen were stripes on some of the moraines and screes. A typical example at the western end of Reindeer Valley occurred on a south-west-facing slope and consisted of 5–10 cm. alternations of pebble-sized debris and fines. The coarse bands were often terminated down-slope by a larger boulder, and a build-up of material disrupted the pattern to give the larger boulders an up-hill "tail". This example was fairly fresh, but elsewhere the stripes were almost completely overgrown and were probably inactive. A series of three concentric circles was observed to the south of Hound Bay at 350 m. a.s.l. on a gentle south-west-facing slope, but only in the Royal Bay area is patterned ground common. Rough polygonal nets, generally less than 1·5 m. mesh diameter, are developed to the north-west of Moltke Harbour and Köppen Point on level ground, or well-sorted stripes occur. Stripes with a less well-sorted form are usual on gentle slopes (Fig. 15) where, despite

Fig. 15. Non-sorted stripes north of Moltke Harbour. (Photograph by R. B. Crews.)

lichen overgrowing the poorly defined coarse bands, down-slope distortion in the broader bands is evident and this suggests fairly recent if not contemporary movement. These are similar to the non-sorted stripes defined by Washburn (1956). Generally, the circular or polygonal forms show a higher degree of sorting than the stripes but as the gradient increases the circles elongate and eventually merge into stripes. As an intermediate stage, the circles "step-down", the coarse mesh acting as terracing between two layers of fines with the step usually 2–3 cm. high. The stripes associated with polygons or nets are generally larger and better sorted than the overgrown variety with the fine band up to 1 m. across. Similar types with a high degree of sorting and fresh appearance are widely distributed, mainly on moraine ridges, from the head of the Kelp Bay valley to Björnstadt Bay and Gold Harbour. Some of the smaller examples are very similar to those described from Barff Peninsula but patterned ground in the Royal Bay area is much more widespread and on a larger scale than is the case to the north-west. Gully stone-runs (Clapperton, 1971) are best developed in the central part of the Cape Charlotte promontory but in the north of Barff Peninsula large areas of the more gently sloping screes are also affected in a similar fashion to give coarse, rather irregular stripes up to 1 m. across. The classification and genesis of patterned ground has been discussed by Washburn (1956), who considered that a polygenetic origin based on the complex operation of frost action and freeze-thaw effects is necessary to explain the variety of forms taken by patterned ground. To the north-west of Moltke Harbour, a pit was dug into an area of sorted polygons on a glacial bench 150 m. a.s.l. but all signs of sorting were lost at a depth of 25 cm., and only very wet homogeneous till was encountered to a depth of 1 m. with no signs of permafrost.

The fissile bedrock allows extensive frost shattering to provide abundant material for scree formation and leads to *felsenmeer* formation on the higher level areas. A high relief and a plentiful flow of melt water has encouraged the cutting of gorges, waterfalls, and in Whale Valley a small natural arch, as streams descend rapidly to sea-level. Honeycomb weathering of the more massive rock units is widespread though not common, and in some cases erosion along joint lines has left small natural arches standing out from exposures. In the centre of the Cape Charlotte promontory the more gentle screes are often cemented to give a "hard-pan" crust up to 1·5 m. thick. Weathered exposures of greywacke in sheltered situations frequently show an overgrowth of calcite flowers.

SUMMARY

Prior to glaciation the mountains of South Georgia were probably surrounded by an extensive lowland plain with well-defined river valleys cutting back into the higher ground. The mountains themselves may have been the dissected remains of plateau areas uplifted during the late Cenozoic structural rejuvenation of the Andes which have risen by 5,000–6,000 m. during the last 30 m. yr. (Dott, 1969). The major glaciation of South Georgia was of ice-cap proportions and must have been active during the climax of the main Antarctic glaciation at least 3·5 m. yr. ago (Mercer, 1969) but several phases of retreat and re-advance may have been completed before the last event on this scale affected South Georgia at least 10,000 yr. ago (Clapperton, 1971). Two Quaternary phases of glaciation, which might be expected to have counterparts in South Georgia, have been reported in the South Shetland Islands (John and Sugden, 1971). The merging of ice from the ice cap and the coastal cirques formed a piedmont glacier which scoured the lowland areas to produce the present surface of the coastal foreland.

The 50 m. wave-cut platform in Royal Bay poses a problem, since it is unlikely to have survived the ice-cap glaciation, yet it represents a sea-level above parts of the coastal foreland which show no signs of drowning. Possibly, these high wave-cut platforms were formed during the closing stages of the ice-cap glaciation when large areas of foreland were still protected by the remnants of the piedmont glacier. The high sea-level at that time would have been caused by an eustatic rise in sea-level as the Antarctic ice sheet wasted, thus outstripping isostatic adjustment of the land masses in response to a decreasing ice load.

During the major post-ice-cap re-advance the maximum position of Nordenskjöld Glacier, 4 km. in front of the present snout, was attained about 5,500 yr. ago (Clapperton, 1971). This was probably contemporaneous with a much more extensive advance in the Royal Bay area where the ice from Ross, Weddell and Whale Valley glaciers merged in Royal Bay to produce a composite snout, which probably stretched from Köppen Point to Cape Charlotte. Sufficient ice may have built up to allow overspill into Björnstadt Bay.

Subsequent to the glacierization of 5,500 yr. ago the formation of the higher raised beaches and the majority of the wave-cut platforms can be linked with continuing isostatic recovery. This process was interrupted in about 1875 by a glacial advance which was again of a far greater extent in the Royal Bay area than in Barff Peninsula and Cumberland Bay. With the resumption of uplift following this episode the lower group of raised beaches were deposited. The recent advance of some glaciers may have been associated with a climatic deterioration in 1924, but the "sudden surge" movements of Ross Glacier are more likely to have been caused by avalanches and ice falls in the high-level cirques feeding the glacier.

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