PRODUCTION AND TRANSFER OF SUBAERIALLY GENERATED ROCK DEBRIS AND RESULTING LANDFORMS ON SOUTH GEORGIA: AN INTRODUCTORY PERSPECTIVE

JOHN E. GORDON

Nature Conservancy Council, Northminster House, Peterborough, PE1 1UA

and

RICHARD V. BIRNIE

Macaulay Institute for Soil Research, Craigiebuckler, Aberdeen, AB9 2QJ

ABSTRACT. During the Holocene, bedrock disintegration has been highly active, producing a copious supply of debris that is a primary source of the considerable volume of rock waste material in geomorphological transport on South Georgia. A qualitative review of landforms and deposits associated with bedrock weathering, talus, rock glaciers and supraglacial morainic till leads to the development of a preliminary investigative framework for more detailed studies. A key aspect of this framework is a debris transport model which stresses the continuum and co-existence of landforms in space and time.

INTRODUCTION

South Georgia (lat. 54–55° S; long. 36–38°W) is a mountainous and heavily glacierized island in the sub-Antarctic (Fig. 1). A combination of climatic environment, steep rock walls and friable lithologies means that rock weathering, rockfall-generated sediments, talus, talus-derived landforms and supraglacial morainic till make a significant contribution to the geomorphology of the island. This paper presents a qualitative review of subaerial debris production and transfer, the resulting landform and sediment associations, and develops a model of an integrated system of features including talus, rock glaciers, ice-cored moraines and debris-covered glaciers. The aim is first to record the contribution of subaerially generated debris to the geomorphology of South Georgia, and second to provide an investigative framework for interpreting contemporary form–process–material relationships that might also provide a basis for reconstructing landscape evolution and environmental change from the evidence recorded in an interrelated set of Holocene landforms and sediments.

ENVIRONMENTAL VARIABLES

Geology

The geology of South Georgia has been reviewed by Tanner (1982). The island occurs on the Scotia Ridge on a small block of continental crust that became detached from South America probably in the Tertiary. Four major stratotectonic units that formed part of an island arc–back arc system have been recognized on the main island itself. Much of the latter comprises intensely deformed volcaniclastic turbidite sediments of Mesozoic age (Cumberland Bay and Sandebugten Formations). The Cumberland Bay Formation is thrust over the more quartzose sediments of the Sandebugten Formation. In the southern part of the island the Larsen Harbour

Br. Antarct. Surv. Bull. No. 72, 1986, pp. 25–46

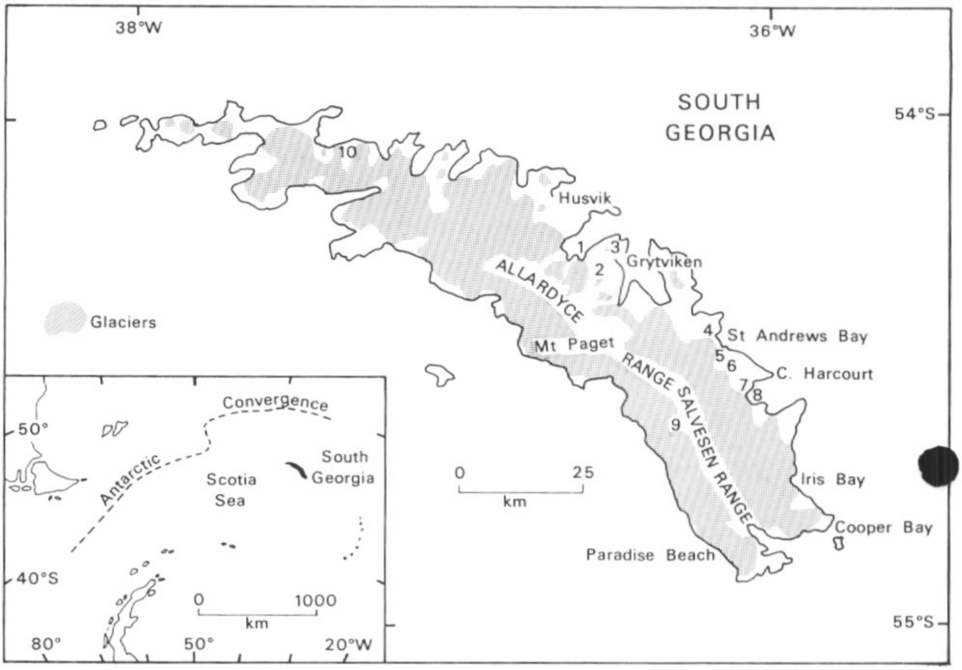

Fig. 1. Location maps. (1) Lyell Glacier; (2) Glacier Col; (3) Hodges Glacier; (4) Heaney Glacier; (5) Cook Glacier; (6) Nachtigal Glacier; (7) Little Moltke Harbour; (8) Ross Glacier; (9) Spenceley Glacier; (10) Grace Glacier.

Formation is an ophiolite sequence of submarine lavas and sheeted dykes emplaced into metasedimentary continental crust. The adjacent Drygalski Fjord Complex comprises acid and basic intrusions and deformed metasedimentary country rocks. In the extreme south-east, a sequence of metamorphosed sediments (Cooper Bay Formation) is separated from the igneous complex by a narrow belt of mylonites. The highly deformed nature of the main lithologies on the island renders them particularly susceptible to weathering and erosion. In broad outlines of plan and profile shape, the forms of mountain ridges and valley walls are determined by structural controls of bedding and jointing. These controls influence the features and foci of ro[illegible] weathering, namely forms and shapes of mountain ridges and peaks, distributions of buttresses and couloirs, zones of high and low debris production and locations of couloirs feeding talus.

Climate

South Georgia lies south of the Antarctic Convergence (Fig. 1) and is exposed to a persistent stream of depressions moving east across the Scotia Sea throughout the year. Although orographic effects associated with the mountains produce wide spatial variations in weather conditions (Richards and Tickell, 1968), the climate of the island can be summarized briefly as cold, wet, windy and cloudy. At the meteorological station at King Edward Point for the period 1951–1980, average annual temperature was +2.0°C; average summer temperature (December, January, February), +4.8°C; and average winter temperature (June, July, August), −1.2°C (from Headland, 1984).

Temperatures show considerable within-month variability throughout the year; for example, for the same period the average maximum and minimum January temperatures were +22.3°C and −4.8°C respectively, while the corresponding figures for July were +14.4°C and −14.2°C. Föhn winds are a feature of the north-east side of the island, producing dramatic fluctuations in temperature when they occur (Richards and Tickell, 1968). Smith (1960*a*) reported seasonal freezing of the regolith to a depth of more than 0.5 m for a period of approximately 26 weeks. However, there is no extensive permafrost on South Georgia (Thom, 1981). Precipitation occurs throughout the year, and the average annual total for the period 1951–1980 at King Edward Point was 1601.5 mm. Snow falls throughout the year but in summer rarely lies for more than few days at the coast.

The mountains and exposed south-west coast of the island are colder, wetter, cloudier and windier than the north-east coast, but there are no systematic records for these areas. Observations over a period of seven days in February 1982 at an altitude of 1292 m on Spenceley Glacier in the centre of Salvesen Range showed air temperatures at or just above zero during persistent cyclonic conditions but diurnal fluctuations between at least +11°C and −11°C occurred during brief clear periods. Since the 1940s there has been a trend in climate towards slightly warmer and wetter conditions on the island (British Antarctic Survey, 1980; Headland, 1984).

Ocean currents transport icebergs and very occasionally pack ice from the Weddell Sea. Normally the edge of the Antarctic pack ice in winter lies to the south of South Georgia (Heap, 1964), and open water exists around the island, apart from a few sheltered bays. Exceptionally, as in 1980, the edge of the pack may lie well to the north of the island (Headland, 1984), Calving glaciers on the island provide a local source of small icebergs, bergy bits and brash ice.

In the context of the present study, climate is an important influence on rock weathering, the distribution of snow and ice and spatial variations in glacier type and regime.

Glaciers and topography

The dominant topographic feature of the island is an axial mountain chain rising to 2960 m and comprising the Salvesen and Allardyce Ranges. Below the major summits, subsidiary ridges and spurs show general summit accordances at levels of 1700–2000 m, 600–650 m and 20–75 m, representing the remnants of intensely dissected planation surfaces (Clapperton, 1971). Such has been the intensity of dissection that, apart from raised shore platforms of restricted extent, there are few plateau fragments of significance on the island; South Georgia is a classic example at sea-level of the alpine-type of glacierized landscape recognized by Sugden and John (1976). Glaciers cover some 58% of South Georgia but their distribution is markedly asymmetric, reflecting regional climatic controls and a firn line which rises from *c.* 300 m a.s.l. on the south-west coast to *c.* 450 m on the north-east side of the island (Smith, 1960*b*). Apart from a coastal fringe there is little extensive ice-free ground on the south-west side of the island and most glaciers extend down to sea-level. On the north-east side, the coastline is more indented and large tidewater glaciers with sources in the high mountains occupy the major valleys. However, the intervening peninsulas support only relatively small cirque glaciers in the precipitation shadow of the Allardyce and Salvesen Ranges. Coastal landforms, including shore platforms and beaches, reflect the interaction of glacial, fluvioglacial, periglacial and marine processes (Hansom, 1979).

Current knowledge of the glacial history of South Georgia was reviewed by

Clapperton and others (1978). During the Late Wisconsin an ice cap extended offshore, probably covering all the lower ground and all the lower mountains (T_4 stage). By about 10,000 BP the glaciers had retreated to near the mouths of the fjords (T_3 stage), and since then there have been two minor Neoglacial re-advances during the 17th–19th centuries (T_2 stage) and *c*. A.D. 1930 (T_1 stage). Therefore present interfluves and valley slopes have been largely ice-free for about 10,000 years. Indeed, Barrow (1983) has recorded vegetation development and peat formation from about 10,000 BP onwards on low ground in the north-east of the island.

Cirque and small valley glaciers have been progressively receding since around 1930. In the mid-1970s some of the larger valley glaciers were at their most advanced positions since the Neoglacial maximum of the 17th–19th centuries but they too have noticeably receded in the last few years (Gordon and Hansom, in press).

BEDROCK WEATHERING

Field observations

Subaerial rock breakdown has been highly active on South Georgia during the last *c*. 10,000 years. The effects and products of this weathering are most apparent on the mountains below *c*. 700 m because first, these are not perpetually covered in ice and snow and second, the weathered debris frequently accumulates *in situ* and is less commonly incorporated into glaciers above their equilibrium lines. Several specific examples from different rock types illustrate salient features and forms of rock weathering on South Georgia.

The first example is from the Cumberland Bay Formation east of Lyell Glacier at an altitude of *c*. 300 m (Fig. 2). Breakdown is proceeding in a horizontal dimension

Fig. 2. Weathering of Cumberland Bay Formation (greywackes) near Lyell Glacier. The ice axe is 0.65 m long (27 November 1975).

both along major bedding planes to produce blocks *c.* 0.5 m thick and also along internal foliation planes to produce highly angular, platy fragments a few millimetres to a few centimetres thick. The profile form of the rock face reflects the relative strengths of individual beds, producing series of steps and ledges and undercut notches capped by relatively more resistant and often quartz-rich beds. At one point a coarse-grained inclusion in more fine-grained slate had almost totally weathered out by granular disintegration, emphasizing the effects of differential weathering and the importance of lithological controls.

In a vertical plane a series of master joints *c.* 1.5 m apart provides significant lines of weakness, while at various angles to them there is dense network of irregularly spaced fractures. These differ in orientation and spacing between individual beds, so that the exposed faces of the beds are rarely parallel to one another. Generally, it is these fractures and the bedding cleavage that control the size of weathered debris produced. Locally, where there has been mass failure of the bedrock, jointing is relatively more important in controlling block sizes.

Two examples from the Cooper Bay area at altitudes of 300–500 m demonstrate [illegible]ical weathering features in the rocks of the igneous complex and the Cooper Bay Formation. In the gabbro southwest of Cooper Bay, two major sets of vertical joints control the broad outlines of mountain profile forms (Fig. 3). At a smaller scale, a combination of exfoliation cracks and irregular fractures severely disrupt the bedrock. The forms range from flakes 1 cm thick to slabs 0.6 m thick. Open cracks are ubiquitous. On the mountain ridges, gendarmes are riven by exfoliation sheets and other fractures. At a smaller scale still, superficial granular distintegration is disaggregating rock crystals, and felspars in particular have selectively weathered out, forming coarse, pitted surfaces on the bedrock.

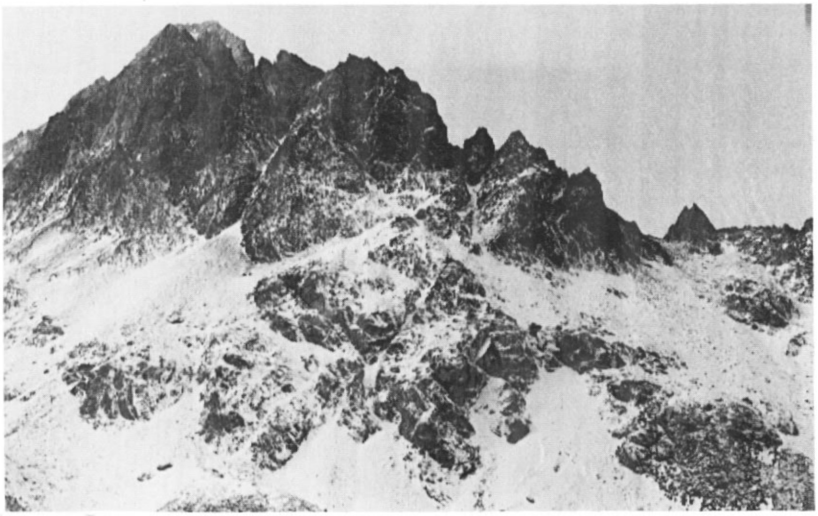

Fig. 3. Gabbro mountain near Cooper Bay showing the role of two intersecting joint systems in forming diamond-shaped buttresses and triangular pinnacles. The height of the rock face is *c.* 200 m (15 April 1976).

In the Cooper Bay metasediments and mylonites, rock breakdown is associated with steeply dipping bedding and cleavage planes, with some granular disintegration of

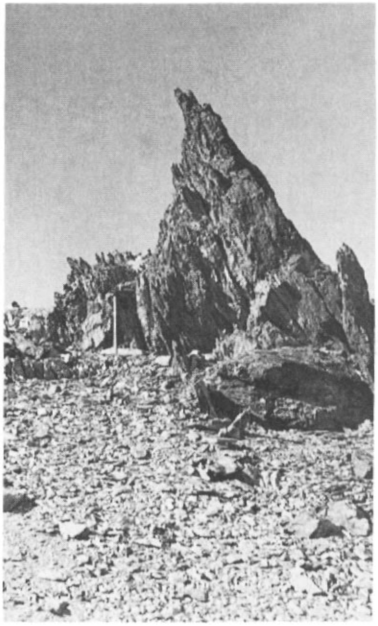

Fig. 4. Tor in steeply dipping mylonite south-west of Cooper Bay. The litter comprises angular, platy debris reflecting the bedrock cleavage. The ice axe is 0.65 m long (8 April 1976).

coarser beds. Locally more resistant beds have produced small tor-like forms (Fig. 4). Again open joints and cracks are widespeard.

Particle-size analysis shows relatively little consistent variation among the different rock types in the composition of the fine-grained material produced by rock weathering. Silt- and clay-sized particles in thirteen samples from the main rock types comprise between 3 and 40% of the fraction smaller than 2 μm.

The traditional view of chemical weathering of bedrock in cold environments is that it is relatively ineffective. Some recent studies have supported this view (Kelly and Zumberge, 1961), but there is a growing body of evidence to suggest that it may be understated (for example Reynolds, 1971; Derbyshire, 1972; Boyer, 1975; Claridge and Campbell, 1984). On South Georgia superficial chemical weathering is everywhere evident in the form of surface oxidation on all rock types. Clay minerals analysis [illegible] fine detritus collected from rock crevices (Table I) suggests no significant chemical alteration of the bedrock, which is borne out by the absence of features such as saprolite or corestones. The clay fractions of the detritus in the samples examined are dominated by chlorite regardless of rock type. The smectite and laumontite present in some of the samples are probably associated with hydrothermal activity and do not seem to be associated with weathering processes (M. J. Wilson, personal communication).

In view of the maritime environment, salt weathering might be an additive factor in rock breakdown (cf. Williams and Robinson, 1981; Fahey, 1985), although McGreevy (1982) has cautioned that under certain environmental conditions the presence of salts can inhibit frost weathering. One sample of fines analysed did show sodium saturation, but any pronounced effects such as taffoni or other salt weathering forms (Selby, 1971, 1972) have not been recorded.

Table I. Mineralogy of $< 2\mu m$ fraction from X-ray diffraction.

Sample	*Rock type*	*Smectite*	*Chlorite*	*Illite*	*Hornblende*	*Laumontite*	*Quartz*	*Felspar*	*Serpentine*
L1	Cumberland Bay Formation	—	+++	+	—	—	tr	tr	—
L2	Cumberland Bay Formation	—	+++	+	—	—	+	tr	—
CB7	Cooper Bay metasediments	—	+++	+	—	—	—	—	—
CB11	Mylonite	—	+++	—	—	tr	—	—	—
HB1	Gabbro	—	+++	—	+	tr	—	—	—
HB3	Gabbro	—	+	—	+	+++	—	—	—
HB6	Dolerite	+++(Na)	++	—	+	—	—	—	++
HB11	Dolerite	—	++	—	+	—	—	—	++
HB12	Gabbro	—	+++	—	+	tr	—	—	—

+++ Dominant (> 50%); ++ abundant (25–50%); + subordinate (5–25%); tr, trace; Na, sodium saturated.

Controls on bedrock weathering

The relative efficacy of different processes and mechanisms postulated to explain rock weathering and the generation of rock debris in contemporary cold environments is far from clear (Ives, 1973; White, 1976*a*; Thorn, 1979; Washburn, 1979; McGreevy, 1981; Walder and Hallet, 1985). Mechanical weathering by frost-assisted processes is usually held to to be more significant than chemical weathering, and laboratory experiments have suggested some key constraints and problems concerning rock structure, material properties, porosity, degree of saturation, number and type of freeze–thaw cycles and rate and intensity of freezing (cf. Washburn, 1979; McGreevy, 1981; Lautridou and Ozouf, 1982). Although the extent to which laboratory conditions replicate field environments is essentially untested, these simulations suggest that local site factors will be highly significant in determining the productivity of frost-assisted weathering within the periglacial environment and its very existence at the altitudinal and latitudinal limits of the latter.

The extent to which direct freeze-thaw action is the primary process in rock disintegration may also be overstated; for example White (1976*a*), while ackn[illegible]ledging that freezing is adequate to produce some granular disintegration, questioned its competence to disrupt solid rock except possibly under very specific circumstances of greater than 50% water saturation and rapid freezing. Instead, he postulated that hydration may be the critical process, as elaborated by Dunn and Hudec (1966) and Hudec (1973) for carbonate- and clay-rich rocks. Washburn (1979), although not denying a role for hydration shattering, considered the question of whether it could produce angular detritus from sound rock was still open, and he retained the traditional view with its emphasis on frost wedging. His caution appears to be supported by the subsequent laboratory work of Fahey (1983).

Bedrock stress conditions comprise a fundamental set of variables that merit greater consideration. They determine not only the strength of the rock, but also the location and condition of the basic lines of weakness exploited by weathering. The extent to which pressure release, for example, also facilitates the operation of weathering processes by inducing fatigue in pre-existing lines of weakness (bedding planes, foliation, joints) or by creating exfoliation features, is also unquantified. Undoubtedly, the stress conditions within the bedrock must be an additive factor to the environmental conditions under which rocks break down (cf. McGreevy and Whalley, 1982; Whalley, 1984).

There have been no detailed studies of rock weathering on South Georgia. The few temperature measurements reported provide only a minimum of guidance on possible frost weathering conditions. Observations by Smith (1960*a*) at an altitude of 120 m a.s.l. revealed that the temperature of the ground surface layers to a depth of between 1 and 2 m was at or below 0°C between mid-May and the end of November. For much of this time the ground surface was blanketed by snow. Similar patterns have been confirmed by Heilbronn and Walton (1984). Recent studies (Hall, 1980; Walder and Hallet, 1985), which question the importance of temperature oscillations about 0°C, will therefore have a bearing on rock breakdown on South Georgia.

On the accessible mountains below *c*. 700 m, the association of ubiquitous open joints and fissures in the bedrock with abundant rock detritus and talus indicates highly active bedrock disintegration during the Holocene. The extent to which this is the product of frost-assisted processes or the interaction of the latter and bedrock stress conditions requires further investigation at sites at different altitudes and in different parts of the island to isolate the key variables or key combinations of possible variables. Compared with mechanical disintegration, chemical weathering as reflected in clay mineral products appears to be relatively ineffective, although this may be a function of the short duration of rock exposure.

DEBRIS TRANSFER AND RESULTING LANDFORMS

Talus and talus-related forms

Rockfall talus is widespread on South Georgia, particularly on the mountain slopes of the eastern forelands and the few ice-free peninsulas on the south-west coast. Most talus is associated with couloirs, although sheet forms also occur. Some typical examples are illustrated in Fig. 5. Block sizes in talus are typically less than 1–2 m

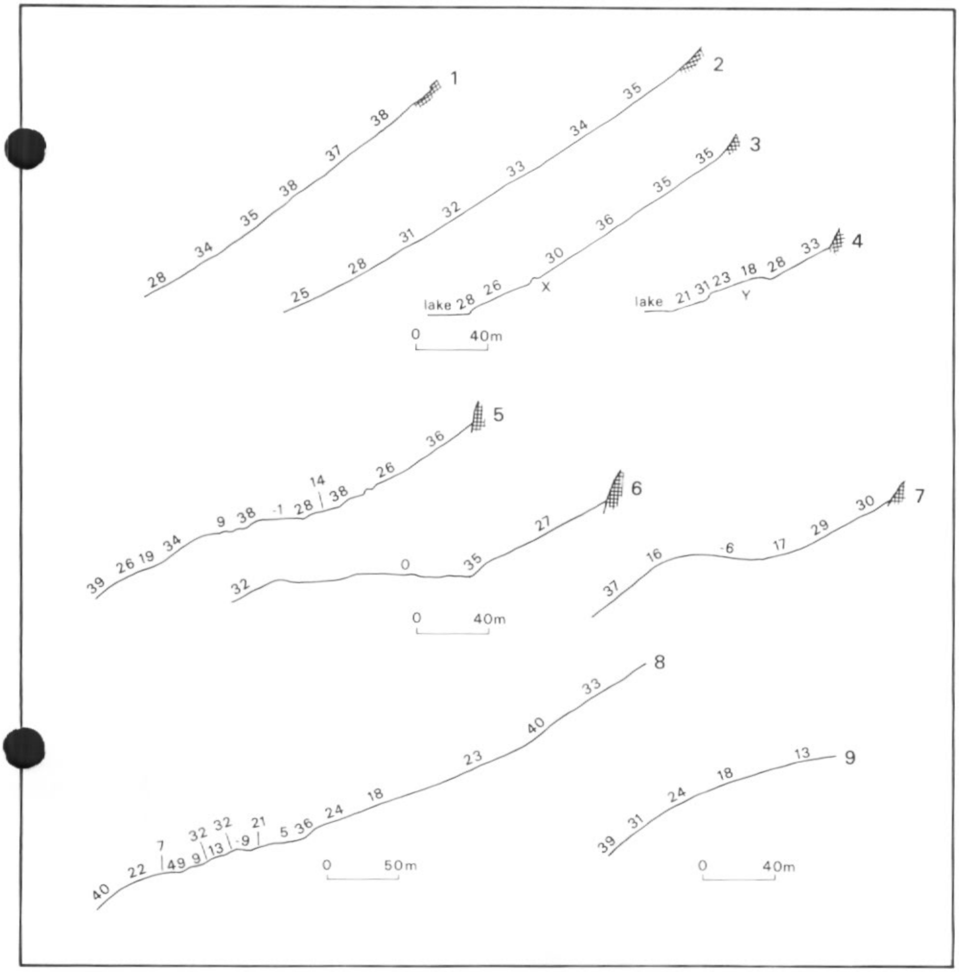

Fig. 5. Comparative surveyed profiles of talus and rock glaciers. (1) Unvegetated talus at Brown Mountain, near Grytviken; (2) vegetated talus at Brown Mountain, near Grytviken; (3 and 4) talus at Skua Lake, near Cooper Bay; the feature at X and Y is a partially buried ridge, possibly a fossil pro-talus rampart; (5, 6 and 7) lobate rock glacier at the base of a talus slope near Cooper Bay; the profiles are across the north, centre and south of the feature, respectively; (8) rock glacier, Little Moltke Habour (see Fig. 11); (9) ice-cored moraine and lobate rock glacier near Cooper Bay (see Fig. 10). The numbers above the profiles are slope angles.

unless associated with large rockfalls. In glacier basins with exposed rock walls, rockfall and talus are important sources of supraglacial debris supply. In accumulation areas rockfall and avalanche debris is incorporated directly into glaciers; in ablation areas the input is more commonly through talus. An important observation with a bearing on Holocene glacier reconstructions is that the up-valley limits of talus typically coincide with glacier equilibrium lines (Birnie, 1978).

Modified talus forms include talus lobes, where the toe of the talus has deformed by mass movement to form a series of lobes. Such forms have been recorded on Cape Harcourt peninsula and near Cooper Bay. A second variant is the talus terrace (Liestøl, 1961) or lobate rock glacier (White, 1981). These arcuate accumulations of debris extend out into the valley floor from the base of the talus and are known to occur near Cooper Bay and on the east flank of a 567 m-high hill south of Nachtigal Glacier. Representative profiles of the former feature show a crenulate surface form in its northern part and a depression at the base of the talus towards its southern edge (Fig. 5).

Several pro-talus ramparts have been identified on South Georgia, notably in the Cooper Bay area (Birnie, 1978; Birnie and Thom, 1982). Their formation requires [illegible] only a suitable debris source but also favourable snowbank surface conditions. The latter point was emphasized by experiments at Cooper Bay in April 1976 which revealed that most debris did not travel to the base of snowbanks but became embedded in the snow surface (Birnie, 1978).

Patterned ground and gelifluction features

Patterned ground and gelifluction features occur widely on South Georgia (Clapperton, 1971; Clayton, 1977; Clapperton and Sugden, 1980; Thom, 1981) and represent the slow mass transfer of weathered debris. The few process studies conducted suggest that current activity is restricted to relatively small-scale forms developed in a shallow (*c.* 0.12 m deep) surface layer of the regolith and that short-term variability is associated with local snow-lie patterns (Smith, 1960*a*; Walton and Heilbronn, 1983; Heilbronn and Walton, 1984). The maximum annual downslope movement on a 20° till slope was 0.06 m (Walton and Heilbronn, 1983). Most of the larger features appear to be relict and absent from deposits of T_1 and T_2 age (Clapperton, 1971; Clapperton and Sugden, 1980; Thom, 1981).

Glacier-related features

A striking facet of South Georgia glaciers is the variation in cover of supraglacial morainic till (Birnie, 1978). This is illustrated with reference to specific examples using the sediment and landform associations defined by Boulton and Paul (1976) and Boulton and Eyles (1979).

1. *Glaciers with low concentrations of supraglacial morainic till*

At one end of the spectrum of debris-covered glaciers are those with low or negligible amounts of supraglacial morainic till. This is typical, first of most glaciers on the south-west coast of the island; second, of a number of large calving glaciers on the north-east coast, for example Hertz and Twitcher Glaciers at Iris Bay and much of Ross Glacier, all of which have only narrow bands of medial moraine; and third, of some small east coast glaciers, for example Hodges Glacier and Glacier Col. In the first case the controlling variables appear to be primarily a lack of exposed bedrock cliff source areas and secondarily a persistence of englacial transport to the glacier termini, many of which are calving; in the second case, primarily a persistence of englacial transport to the glacier termini; and in the third case, primarily a lack of suitable cliff sources.

Where glaciers of this type terminate on land, they demonstrate features typical of the subglacial–proglacial landform and sediment association (Boulton and Paul, 1976), formed during the period of recent ice margin recession. Lodgement till spreads are common, sometimes with fluted till surfaces and with small recessional, possibly annual, moraines typically less than 1 m high. Extended sequences of such moraines occur notably near Husvik and Paradise Beach. In the latter case at least 30 ridges occurred between the icefront in 1982 and the moraine marking the T_2 stage. In the foreland of Heaney Glacier, lodgement till deposited during the T_1 and T_2 stages overlies older, weathered gravels and is on average 0.5 m thick. Regelation stacking of debris within the ice was not evident in the walls of a meltwater tunnel underneath Heaney Glacier, and this seems to be typical of the South Georgia glaciers investigated. In only a few cases, for example Grace and Cook Glaciers, are thick sequences of subglacial debris apparent. However, where land-terminating icefronts [illegible]e been stationary in the past, end-moraine systems have developed through the accumulation of subglacially derived till at the glacier termini (Clapperton, 1971; Clapperton and Sugden, 1980).

2. *Glaciers with high concentrations of supraglacial morainic till*

Cook Glacier. Depending on the location of debris inputs relative to glacier geometry and equilibrium line (Birnie, 1978; Boulton, 1978; Boulton and Eyles, 1979; Small and others, 1979), subaerially generated debris is transported supraglacially, englacially or as a combination of both on its route to the glacier snout. This is illustrated by glaciers at St Andrew's Bay. A supraglacial medial moraine of the ice-stream interaction type (Eyles and Rogerson, 1978), generated at the junction of Cook and the innominate central glacier, persists as a supraglacial feature downglacier. In the central part of the innominate glacier several medial moraines emerge at the ice surface some distance below the equilibrium line. Whether or not englacial debris emerges on the ice surface in this way will depend on depth of transport and whether or not the ablation surface intersects the debris septa. This is strikingly illustrated by recent changes at Cook Glacier. In 1975 the glacier terminated in a 30 m-high ice cliff grounded at high water mark. Supraglacial morainic till was associated with discrete bands of medial moraine. Since 1975 the ice terminus has ablated considerably, and in 1981 had the form of a 15 m-high ice ramp sloping at 25–35°. During this period a cover of supraglacial morainic till has enveloped most of the glacier surface in its [illegible]er parts. It may be inferred that significantly more debris flowpaths now intersect the ice surface. The sediments deposited at the icefront comprise interbedded beach, supraglacial morainic till and flow till deposits (Gordon and Hansom, in press).

At the eastern margin of Cook Glacier away from the coastal edge, supraglacial morainic till occurs as a discontinuous veneer over fluted moraine and annual moraines (facies A 1 of Boulton and Eyles, 1979), while in a zone between Cook and Heaney Glaciers a relatively thicker cover of debris associated with a supraglacial medial moraine has produced a hummocky landscape of facies A2-type deposits (Boulton and Eyles, 1979).

Lyell Glacier. The western ice stream of Lyell Glacier has a sea-calving front, up-ice from which is a discontinuous cover of supraglacial morainic till. In the central and upper reaches, an extensive cover of debris relates to a major rock avalanche in 1975 (Gordon and others, 1978). The eastern part of Lyell Glacier is land-based and almost

Fig. 6. Lyell Glacier, showing the widespread cover of supraglacial morainic till and the formation of dump moraines along the land-based terminus. The supraglacial debris in the upper reaches of the western (right) ice stream relates to a large rock avalanche and debris slide in 1976 (30 January 1982).

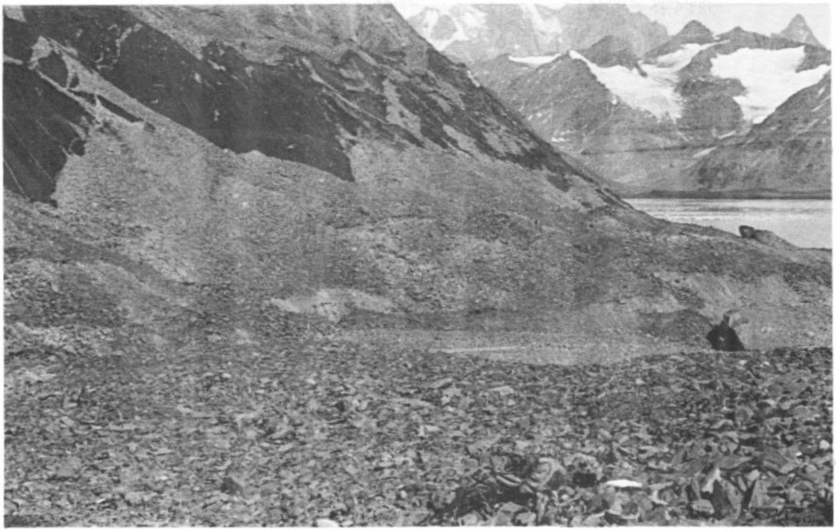

Fig. 7. Dump moraine of supraglacial morainic till at the margin of Lyell Glacier. Scale is given by rucksack in foreground (30 January 1982).

its entire surface is debris-covered (Fig. 6). This part of the glacier is close to its most advanced Neoglacial position. Along much of its edge there is a dump ridge of supraglacial morainic till which has slumped and slid down the steep icefront (facies A 2 of Boulton and Eyles, 1979) (Fig. 7). Towards the calving bay some recession of the icefront has occurred in the last few years, producing ice-cored moraine ridges and mounds.

Ross Glacier. Supraglacial morainic till outcrops on the surface of Ross Glacier near to its eastern, land-based margin. Since about 1975 the glacier has receded approximately 60 m from its most forward position since a Neoglacial advance during the 17th–19th centuries. Landforms produced in the deglaciated area vary according to the relative thickness of supraglacial morainic till on the ice surface and the degree of crevassing. Near to the edge of the calving bay the ice margin is cut by longitudinal crevasses into which supraglacial morainic till is selectively concentrated by washing and slumping. The resulting landforms and sediments (Fig. 8) are essentially those [illegible] the subglacial-proglacial association, but with a veneer of supraglacial morainic till concentrated into longitudinal bands and dump mounds (facies A 1 of Boulton and Eyles, 1979). Away from the calving edge where debris is thicker and crevassing less regular, mounds and ridges of ice-cored debris predominate (facies A 2 of Boulton and Eyles, 1979).

Nachtigal Glacier. Nachtigal Glacier is dominated on its west flank by 400 m-high cliffs from which several very active couloirs feed rockfall debris on to the glacier margin (Fig. 9). This debris forms a supraglacial lateral moraine which extends beyond the glacier snout as terrace along the valley side. In the central and eastern parts of the icefront the thickness of supraglacial morainic till diminishes. Near the lateral moraine a continuous layer of debris rests on subglacial till. However, as the debris cover thins, differential melting produces a more irregular ice surface, and supraglacial morainic till is irregularly deposited as dump features at the bottom of ice gullies or

Fig. 8. The margin of Ross Glacier. A veneer of supraglacial morainic till rests on a lodgement till plain, with a prominent transverse moraine ridge in the foreground. Where the supraglacial morainic till is concentrated in crevasses (top right), it is deposited as dump mounds and longitudinal bands running at right angles to the ice edge (centre) (8 March 1982).

as discontinuous ridges where the ice edge is more regular (facies A 1 of Boulton and Eyles, 1979).

Glaciers near Cooper Bay. A series of small icefields occur on the south-west-facing slopes of the ridge running north-west from Ferguson Peak. In one case rockfall debris from the exposed bedrock headwall has accumulated on the ice surface, which was entirely free of old snow and firn in early March 1976. From an intermittent scatter of debris, supraglacial morainic till thickens downslope to form a prominent ice-cored moraine (Figs. 5 and 10). The lower end of this moraine has deformed into a lobate rock-glacier type of feature. A similar type of ice-cored moraine occurs in an adjacent south-east-facing cirque. The present level of ice in this latter cirque extends almost to the top of the enclosing headwalls, so that the debris inputs in the moraine probably represent a period of diminished ice volume in the past.

3. *Synthesis*

Birnie (1978) identified three main regional zones of supraglacial debris production and concentration related to topography and glacier characteristics. On the south-west side of Allardyce Range the steep, heavily glacierized basins have relatively little exposed bedrock and relatively high throughputs of ice to calving icefronts, so that surface debris concentrations are low. On the north-east side of Allardyce Range large cirques with extensively exposed rockwalls provide higher debris inputs to inferred slower-moving glaciers, and surface debris concentrations attain their highest levels. North-west of Allardyce Range, where topographic relief is lower, debris inputs and glacier surface concentrations are intermediate between those of the other two areas.

On the north-east side of Allardyce Range, where supraglacial debris concentrations are highest, the resulting landforms at and beyond the land-terminating glacier

Fig. 9. Nachtigal Glacier showing the appearance (left) of supraglacial medial moraines with input sources above the glacier equilibrium line and supraglacial lateral moraines (right) directly associated with talus and rockfall couloirs (13 January 1982).

Fig. 10. Ice-cored moraine merging into a lobate rock glacier near Cooper Bay. Glacier ice underlies the debris and snow in the centre left (15 March 1976).

margins principally comprise facies A of Boulton and Eyles (1979) superimposed upon the subglacial–proglacial landform and sediment association. In comparative terms, the sediment volume and landforming potential of the supraglacial debris are less important than the subglacially derived material that forms the core of till plains and the major end-moraine systems of the T_1, T_2 and T_3 stages. Nevertheless, supraglacial morainic till is a strikingly distinctive depositional formation.

Rock glaciers

Two examples of tongue-shaped rock glaciers have been described by Birnie and Thom (1982). One, at Cooper Bay, was inferred to be a fossil glacier-cored feature; the other, at Binary Peaks on Cape Harcourt peninsula, an interstitial ice feature. Further observations at Binary Peaks in 1982 revealed an unfrozen superficial layer, 2 m thick, of boulders. At the bottom of this layer at the limit of excavation, relatively finer frozen debris was encountered in interstices. The outermost ridge complex consists of relatively finer material than the main bulk of bouldery rock-glacier debris [illegible]utting it up-valley. Possibly these lower deposits represent the moraines of a former glacier that occupied the site but which subsequently became congested with debris, forming a rock glacier.

Fig. 11. Rock glacier near Little Moltke Harbour. Massive ice was exposed in the true right margin of the feature, and slumping of the steep front edge (up to 48°) suggests that it too is ice-cored. The central part of the rock glacier comprises debris from a large rock avalanche. The long profile of the feature is illustrated in Fig. 6 (8 March 1982).

A third tongue-shaped rock glacier occurs at Little Moltke Harbour (Figs. 5 and 11). Massive ice was observed in the west flank of the feature, which has the form of a lateral ice-cored moraine. This rock glacier has been largely formed by a rock avalanche on to the surface of a former glacier.

DISCUSSION

A debris transport model for South Georgia

An investigative framework for South Georgia linking subaerial debris production and resulting landforms is represented schematically in Fig. 12. It attempts to outline a debris transport model encompassing the coarse debris system (Caine, 1974; Barsch and Caine, 1984). Geomorphological processes or combinations of processes can be viewed as producing a series of landform and sediment facies (cf. Madole, 1972). The model provides for a continuum and co-existence of these facies in space and time, reflecting prevailing climatic conditions and their controls on debris production and transfer media. As production rates change or the media change in type or in conditi[illegible] there will be corresponding changes in landform and facies development. By adopting the wider perspective of a debris transport system, the components of which may not only have merged but also varied in their contributions as geomorphological agents through time, this approach seeks to stress the coherence of the geomorphological environment. It incorporates both short-term adjustments under dynamic equilibrium and evolutionary sequences associated with longer-term shifts in controlling variables such as climatic change.

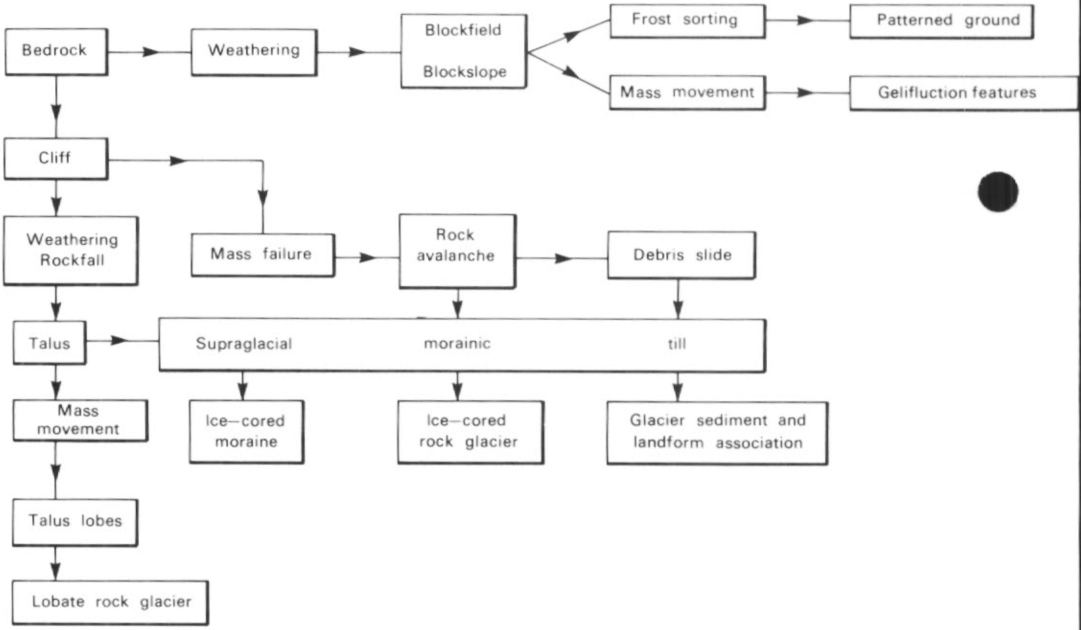

Fig. 12. A debris transport model for subaerially generated rock debris.

This framework does not seek to view individual landforms as unique or special features in mountain geomorphology but focuses on the integration of glacier, rock glacier, talus and weathering subsystems. For example, rock glaciers have stimulated considerable debate concerning their definition, origins, mode of flow and relationships to features such as debris-covered glaciers, ice-cored moraines and pro-talus ramparts. The arguments are well known and the extensive literature has been reviewed, for example, by Whalley (1974) and White (1976*b*). A fundamental problem is that rock glaciers have been identified mostly on the basis of their morphology. The latter, however, can be a function of several different processes. Several authors have therefore proposed that rock glaciers be considered as part of a wider debris transport system involving a continuum of both landforms and dynamic behaviour (Potter, 1972; Johnson, 1974, 1983; Whalley, 1976, 1979, 1983). This approach has the merit of integrating a range of environmental controls on rock-glacier development, including both climatic and debris-supply factors. Given the tendency for rock glaciers to be characteristic of more continental than maritime climates (Østrem, 1974; Corte, 1976), the role of debris supply is likely to be a critical factor in the formation of the South Georgia landforms, as in other maritime areas (Whalley, 1974; Eyles, 1978).

Facies and environmental change

Horizontal distribution and vertical succession in landform and sediment facies may provide one approach to reconstructing Holocene environmental variations as outlined by Madole (1972). Such an approach may have considerable potential if it draws on the integrated evidence of a system of landforms and sediments, rather than on individual features such as moraines or rock glaciers alone, where any patterns may be complicated by problems of definition and variations in such factors as duration of debris storage, rates of transfer, thresholds and response times. Therefore, until detailed studies are available on contemporary debris systems and spatial variations in landform and sediment facies, Holocene reconstructions will remain incomplete or localized.

The importance of the spatial dimension may be illustrated with reference to the variations in contemporary glacier landform and sediment associations. The majority of South Georgia glaciers studied are currently receding, and many of the smaller ones have been doing so for several decades. The contribution of subaerially generated rock debris and supraglacial morainic till to the contemporary landform and sediment associations is illustrated schematically in Table II. These vary not only according to

Table II. Contribution of supraglacial morainic till to sediment and landform associations of South Georgia glaciers.

Supraglacial morainic till	*Glacier terminus*	*Sediment and landform association*
Negligible	Advancing	Not applicable
	Retreating	Subglacial – proglacial
	Stationary	Subglacial – proglacial
	Calving	Marine
Thin	Advancing	Not applicable
	Retreating	Subglacial – proglacial with supraglacial morainic till facies A 1
	Stationary	Subglacial – proglacial with supraglacial morainic till facies B
	Calving	Marine
Thick	Advancing	Not applicable
	Retreating	Subglacial – proglacial with supraglacial morainic till facies A 1 and A 2
	Stationary	Subglacial – proglacial with supraglacial morainic till facies B
	Calving	Marine

the state and type of glacier terminus but also to patterns of sediment supply. Where glaciers terminate on land, the subglacial–proglacial association predominates. Superimposed upon it are the landforms and sediments of supraglacial morainic till. Where the latter is thin, it forms a series of small, discontinuous dump moraines in receding glacier forelands. Where it is thicker, for example in the vicinity of supraglacial medial moraines, hummocky, ice-cored topography is formed. At stationary icefronts, continuous dump moraines are produced by debris sliding and slumping down the ice edges. A feature of recent glacier recession and surface lowering has been a tendency for increased concentrations of supraglacial morainic till to appear on glaciers, most noticeably Cook Glacier. Here also the transition from a sea-calving terminus to a land-based one has produced an association of beach and glacier sediments.

CONCLUSION

South Georgia contains a legacy of features reflecting highly active rock weathering and failure during the Holocene. The landforms and sediments provide, qualitative[illegible] at least, a distinctive contribution to the geomorphology of the island in terms of landforms and sediments in transport. Further investigation – notably of process mechanisms and their relative importance, the roles of different controlling variables, process rates and relationships between different landforms – might be usefully considered from the perspective of a debris transport model that links rock weathering, mass movement, talus, rock glaciers and glacier landform and sediment associations. Such a model may also provide an appropriate key to interpreting Holocene landform and sediment patterns and their associated environmental changes.

ACKNOWLEDGEMENTS

We thank Dr R. M. Laws for the opportunity to work under the auspices of the British Antarctic Survey, the late Professor K. Walton for early stimulus and support, and Dr C. M. Clapperton and Dr D. E. Sugden for their enthusiasm and stimulation. J. E. G. gratefully acknowledges support from the Carnegie Trust for the Universities of Scotland, the Trans-Antarctic Association and the Royal Geographical Society; R. V. B., from the Natural Environment Research Council. Many people have assisted us in the field and it is a pleasure to thank Dr Jim Hansom and Dr Gordon Thom for their cheerful company and enthusiastic support, members of the 1981–82 Joint Services Expedition to South Georgia and the captains and crews of RRS *John Bisco*[illegible] RRS *Bransfield* and HMS *Endurance*. Dr M. J. Wilson kindly undertook the clay minerals analysis. We are also grateful to Dr C. M. Clapperton, Dr A. F. Gellatly, Dr D. E. Sugden and Dr W. B. Whalley for comments on the manuscript.

Received 31 January 1986; accepted 23 March 1986

REFERENCES

BARROW, C. J. 1984. Palynological studies in South Georgia. III. Three profiles from near King Edward Cove, Cumberland East Bay. *British Antarctic Survey Bulletin*, No. 58, 43–60.

BARSCH, D. *and* CAINE, N. 1984. The nature of mountain geomorphology. *Mountain Research and Development*, **4**, 287–98.

BIRNIE, R. V. 1978. Rock debris transport and deposition by valley glaciers in South Georgia. Unpublished Ph.D. thesis, University of Aberdeen.

Birnie, R. V. *and* Thom, G. 1982. Preliminary observations on two rock glaciers in South Georgia, Falkland Islands Dependencies. *Journal of Glaciology*, **28**, 377–86.

Boulton, G. S. 1978. Boulder shapes and grain-size distributions of debris as indicators of transport paths through a glacier and till genesis. *Sedimentology*, **25**, 733–99

Boulton, G. S. *and* Eyles, N. 1979. Sedimentation by valley glaciers; a model and genetic classification. (*In* Schlüchter, Ch. *ed. Moraines and varves: origin, genesis, classification. Proc INQUA symposium on genesis and lithology of Quaternary deposits, Zürich* 10–20 *Sept*. 1978. Rotterdam, A. A. Balkema, 11–23.)

Boulton, G. S. *and* Paul, M. A. 1976. The influence of genetic processes on some geotechnical properties of glacial tills. *Quarterly Journal of Engineering Geology*, **9**, 159–94.

Boyer, S. J. 1975. Chemical weathering of rocks on the Lassiter Coast, Antarctic Peninsula, Antarctica. *New Zealand Journal of Geology and Geophysics*, **18**, 623–8.

British Antarctic Survey. 1980. *British Antarctic Survey Annual Report*. Cambridge, British Antarctic Survey, 79 pp.

Caine, N. 1974. The geomorphic processes of the alpine environment. (*In* Ives, J. D. *and* Barry, R. G. *eds. Arctic and alpine environments*. Methuen, London, 721–48.)

Clapperton, C. M. 1971. Geomorphology of the Stromness Bay–Cumberland Bay area, South Georgia. *British Antarctic Survey Scientific Report*, No. 70, 25 pp.

Clapperton, C. M. *and* Sugden, D. E. 1980. Geomorphology of the St. Andrew's Bay–Royal Bay area, South Georgia. *British Antarctic Survey* (Misc.), Sheet 1.

Clapperton, C. M., Sugden, D. E., Birnie, R. V., Hansom, J. D. *and* Thom, G. 1978. Glacier fluctuations in South Georgia and comparison with other island groups in the Scotia Sea. (*In* Van Zinderen Bakker, E. M. *ed. Antarctic glacial history and world palaeoenvironments*. Rotterdam, A. A. Balkema, 95–104.)

Claridge, G. G. C. *and* Campbell, I. B. 1984. Mineral transformation during weathering of dolerite under cold arid conditions in Antarctica. *New Zealand Journal of Geology and Geophysics*, **27**, 537–45.

Clayton, R. A. S. 1977. The geology of north-western South Georgia. I. Physiography. *British Antarctic Survey Bulletin*, No. 46, 85–98.

Corte, A. E. 1976. Rock glaciers. *Biuletyn Peryglacjalny*, **26**, 175–97.

Derbyshire, E. 1972. Tors, rock weathering and climate in southern Victoria Land, Antarctica. *Institute of British Geographers Special Publication*, **4**, 93–105.

Dunn, J. R. *and* Hudec, P. P. 1966. Water, clay and rock soundness. *Ohio Journal of Science*, **66**, 153–68.

Eyles, N. 1978. Rock glaciers in Esjufjöll nunatak area, south-east Iceland. *Jökull*, **28**, 53–6.

Eyles, N. *and* Rogerson, R. J. 1978. A framework for the investigation of medial moraine formation; Austerdalsbreen, Norway, and Berendon Glacier, British Columbia, Canada. *Journal of Glaciology*, **20**, 93–113.

Fahey. B. D. 1983. Frost action and hydration as rock weathering mechanisms on schist: a laboratory study. *Earth Surface Processes and Landforms*, **8**, 535–45.

Fahey, B. D. 1985. Salt weathering as a mechanism of rock breakup in cold climates; an experimental approach. *Zeitschrift für Geomorphologie*, N.F. **29**, 99–111.

Gordon, J. E., Birnie, R. V. *and* Timmis, R. 1978. A major rockfall and debris slide on the Lyell Glacier, South Georgia. *Arctic and Alpine Research*, **10**, 49–60.

Gordon, J. E. *and* Hansom, J. D. In press. Beach forms and changes associated with retreating glacier ice, South Georgia. *Geografiska Annaler*.

Hall, K. J. 1980. Freeze–thaw activity at a nivation site in northern Norway. *Arctic and Alphine Research*, **12**, 183–94.

Hansom, J. 1979. Beach form and process variation in South Georgia, a sub-Antarctic island. Unpublished Ph.D. thesis, University of Aberdeen.

Headland, R. K. 1984. *The island of South Georgia*. Cambridge University Press, 293 pp.

Heap, J. A. 1964. Pack ice. (*In* Priestly, R. E., Adie, R. J. *and* Robin, G. de Q. *eds. Antarctic Research*. London, Butterworths, 308–17.)

Heilbronn, T. D. *and* Walton, D. W. H. 1984. The morphology of some periglacial features on South Georgia and their relationship to local environment. *British Antarctic Survey Bulletin*, No. 64, 21–36.

Hudec, P. P. 1973. Weathering of rocks in arctic and sub-arctic environments. (*In* Aitken, J. D. *and* Glass, D. J. *eds. Proceedings, Symposium on the geology of the Canadian Arctic*. Waterloo, Geological Association of Canada, 313–35.)

Ives, J. D. 1973. Arctic and alpine geomorphology – a review of current outlook and notable gaps in knowledge. (*In* Fahey, B. D. *and* Thompson, R. D. *eds. Research in polar and alpine geomorphology, 3rd Guelph symposium on geomorphology*, 1973. Norwich, Geo Abstracts, 1–10.)

Johnson, P. G. 1974. Mass movement of ablation complexes and their relationship to rock glaciers. *Geografiska Annaler*, **56A**, 93–101.

Johnson, P. G. 1983. Rock glaciers. A case for a change in nomenclature. *Geografiska Annaler*, **65 A**, 27–34.

Kelly, W. C. *and* Zumberge, J. H. 1961. Weathering of a quartz diorite at Marble Point Sound, Antarctica. *Journal of Geology*, **59**, 433–46.

Lautridou, J. P. *and* Ozouf, J. C. 1982. Experimental frost shattering: 15 years of research at the Centre de Géomorphologie du CNRS. *Progress in Physical Geography*, **6**, 215–32.

Liestøl, O. 1961. Talus terraces in arctic regions. *Norsk Polarinstitut Årbok*, 102–5.

McGreevy, J. P. 1981. Some perspectives on frost shattering. *Progress in Physical Geography*, **5**, 56–75.

McGreevy, J. P. 1982. 'Frost and salt' weathering: further experimental results. *Earth Surface Processes and Landforms*, **7**, 475–88.

McGreevy, J. P. *and* Whalley, W. B. 1982. The geomorphic significance of rock temperature variations in cold environments: a discussion. *Arctic and Alpine Research*, **14**, 157–62.

Madole, R. F. 1972. Neoglacial facies in the Colorado Front Range. *Arctic and Alpine Research*, **4**, 119–30.

Østrem, G. 1974. Present alpine ice cover. (*In* Ives, J. D. *and* Barry, R. G. *eds*. *Arctic and alpine environments*. London, Methuen, 225–50.)

Potter, N. Jr. 1972. Ice-cored rock glacier, Galena Creek, northern Absaroka Mountains, Wyoming, *Geological Society of America Bulletin*, **83**, 3025–58.

Reynolds, R. C. 1971. Clay mineral formation in an alpine environment. *Clays and Clay Minerals*, **19**, 361–74.

Richards, P. A. *and* Tickell, W. L. N. 1968. Comparison between the weather at Bird Island and King Edward Point, South Georgia. *British Antarctic Survey Bulletin*, No. 15, 63–9.

Selby, M. J. 1971. Salt weathering of landforms and an Antarctic example. (*In: Proceedings*, 6*th Geograp*[illegible] *Conference*, *Christchurch*, *New Zealand*. Christchurch, N.Z., Geographical Society, 30–5.)

Selby, M. J. 1972. Antarctic tors. *Zeitschrift für Geomorphologie* N.F. Supplement Band, **13**, 73–86.

Small, R. J., Clark, M. J. *and* Cawse, T. J. P. 1979. The formation of medial moraines on alpine glaciers. *Journal of Glaciology*, **22**, 43–52.

Smith, J. 1960*a*. Cryoturbation data from South Georgia. *Biuletyn Peryglacjalny*, **8**, 73–9.

Smith, J. 1960*b*. Glacier problems in South Georgia. *Journal of Glaciology*, **3**, 705–14.

Sugden, D. E. *and* John, B. S. 1976. *Glaciers and landscape*. London, Edward Arnold, 376 pp.

Tanner, P. W. G. 1982. Geologic evolution of South Georgia. (*In* Craddock, C. *ed*. *Antarctic Geoscience*. Madison, University of Wisconsin Press, 167–76.)

Thom, G. 1981. Patterned ground in South Georgia, Antarctica. Unpublished Ph.D. thesis, University of Aberdeen.

Thorn, C. E. 1979. Bedrock freeze–thaw weathering regime in an alpine environment, Colorado Front Range. *Earth Surface Processes and Landforms*, **4**, 211–28.

Walder, J. *and* Hallet, B. 1985. A theoretical model of the fracture of rock during freezing. *Geological Society of America Bulletin*, **96**, 336–46.

Walton, D. W. H. *and* Heilbronn, T. D. 1983. Periglacial activity on the subantarctic island of South Georgia. (*In Proceedings*, 4*th International Conference on Permafrost*, *Fairbanks*, *Alaska*, *July* 1983. Washington, D.C. National Academy Press, 1356–61.)

Washburn, A. L. 1979. *Geocryology*. London, Edward Arnold, 406 pp.

Whalley, W. B. 1974. Rock glaciers and their formation as part of a glacier debris-transport system. *University of Reading*, *Geographical Papers*, No. 24, 60 pp.

Whalley, W. B. 1976. A rock glacier and its relation to the mass balance of corrie glaciers, Strupbreen, Troms, Norway, *Norsk Geografisk Tidsskrift*, **30**, 52–5.

Whalley, W. B. 1979. The relationship of glacier ice and rock glacier at Grubengletscher, Kanton Wallis Switzerland. *Geografiska Annaler*, **61 A**, 49–51.

Whalley, W. B. 1983. Rock glaciers – permafrost features or glacial relics? (*In Proceedings*, 4*th International Conference on Permafrost*, *Fairbanks*, *Alaska*, *July* 1983. Washington, D.C., National Academy Press, 1396–1401.)

Whalley, W. B. 1984. Rockfalls. (*In* Brunsden, D. *and* Prior, D. B. *eds*. *Slope instability*. Chichester, John Wiley and Sons, 217–56.)

White, S. E. 1976*a*. Is frost action really only hydration shattering? A review. *Arctic and Alpine Research*, **8**, 1–6.

White, S. E. 1976*b*. Rock glaciers and block fields, review and new data. *Quaternary Research*, **6**, 77–97.

White, S. E. 1981. Alpine mass movement forms (noncatastrophic): classification, description, and significance. *Arctic and Alpine Research*, **13**, 127–37.

Williams, R. B. G. *and* Robinson, D. A. 1981. Weathering of sandstone by the combined action of frost and salt. *Earth Surface Processes and Landforms*, **6**, 1–9.