BRITISH ANTARCTIC SURVEY

SCIENTIFIC REPORTS

No. 73

THE GEOLOGY OF SOUTH GEORGIA:

III. PRINCE OLAV HARBOUR AND STROMNESS BAY AREAS

By

M. J. SKIDMORE, M.Sc.

British Antarctic Survey

and

Department of Geology, University of Birmingham

LONDON: PUBLISHED BY THE BRITISH ANTARCTIC SURVEY: 1972

NATURAL ENVIRONMENT RESEARCH COUNCIL

THE GEOLOGY OF SOUTH GEORGIA:

III. PRINCE OLAV HARBOUR AND STROMNESS BAY AREAS

By

M. J. SKIDMORE, M.Sc.

British Antarctic Survey

and

Department of Geology, University of Birmingham

(Manuscript received 31st October, 1971)

ABSTRACT

THE geomorphology, largely the result of the main Antarctic glaciation 3·5 m. yr. ago, is described. From recent work on other sub-Antarctic islands, the Falkland Islands and Tierra del Fuego, where a more complete record has been established by Auer, tentative post-glacial base-level correlations are suggested. The stratigraphy of South Georgia and structure of the Sandebugten and Cumberland Bay Series is partly comparable to other sequences in the Scotia arc and on Navarino Island (Tierra del Fuego), although no direct correlation of the largely unfossiliferous Cumberland Bay Series can be made.

The sediments of the Cumberland Bay Series are moderately inclined with an axial-plane dip between 40° and 60° to the south-west; asymmetrical, concentric and similar folds with a slight inversion of the shorter limb. They are intensely cleaved along a north–south strike, possibly the result of the break-up of a pre-Eocene landmass.

The characteristics of the turbidite sedimentation of the Cumberland Bay Series closely resemble those of an epicontinental flysch-like lithofacies. They are characterized by deformation of secondary structures, possibly due to earthquake shocks, indicating thixotropic conditions after partial consolidation. Texturally, the greywackes are immature and they are almost entirely composed of terrigenous material from clay grade to coarse sand. From the petrology of the greywackes, a possible scheme of modal and textural classification has been proposed. The term "tuffaceous" given by earlier workers to the greywackes of South Georgia has been revised to "volcanic", because of the wholly epiclastic andesitic volcanic constituents and the lack of pyroclastic debris.

The petrography of the authigenic minerals is discussed and it is concluded that the alteration through low-grade burial metamorphism to the quartz-prehnite field of the prehnite-pumpellyite metagreywacke facies is complete and indicates that the Cumberland Bay Series has possibly been buried to about 10 km. depth under a geothermal gradient of between 40° and 50° C/km. The albitization and chloritization of both the detrital and volcanic andesine feldspar clasts is described and illustrated from which prehnitization is considered to be largely dependent on available calcium.

Petrological differences from those of other contemporaneous circum-Pacific sedimentary sequences suggest that the provenance of the Cumberland Bay Series was more continental and the succession was deposited in a separate eugeosynclinal area, possibly east of a postulated Tierra del Fuego–Antarctic Peninsula link. A contemporaneous intrusion of a probable intermediate phase of the Andean Intrusive Suite occurs in the south-east of the island. From the distribution of islands and geophysical evidence of submarine plateaux of continental origin which form the Scotia arc, it is concluded that South Georgia once formed part of a pre-Eocene landmass which has been subject to (?) Gondwana fragmentation and drift due possibly to some differential east–west plate tectonism.

CONTENTS

I. INTRODUCTION

1. *Location*

South Georgia lies about 1,600 km. east of Cape Horn between lat. 54° and 55° S., and long. 36° and 38° W. Its relationship to other landmasses in the South Atlantic Ocean is shown in Fig. 1.

Two separate localities on the north-east coast of South Georgia have been examined. A survey of the Stromness Bay area from Cumberland West Bay to Fortuna Bay was completed (Figs. 2 and 3) and the results compared with a smaller but similarly situated area about 30 km. to the west at Prince Olav Harbour, Possession Bay (Figs. 4 and 5).

2. *Previous work*

A. F. Trendall visited the island in 1951–52 and again in 1953–54 as a member of the South Georgia Survey (led by V. D. Carse), the primary object of which was topographical survey.

Trendall's (1953) first report contained a chronological account of all previous investigations, and described the structure and sedimentary features from which he concluded that the sedimentary rocks of South Georgia were divisible into two groups. He proposed the name "Sandebugten Series" for the older, strongly folded, well-cleaved grits and shales of greywacke facies cropping out between Cumberland East Bay and Royal Bay; these could possibly be correlated with other parts of the Scotia arc, thereby suggesting a Palaeozoic age. "Cumberland Bay Series" was retained for the younger, possibly Aptian, sediments comprising predominantly tuffs of greywacke facies. He suggested a tectonic contact between the two series, although the Cumberland Bay Series may have originally lain unconformably on the Sandebugten Series.

Trendall considered that the igneous complex in the south-eastern extremity of South Georgia was possibly divisible into two groups: a sequence of occasionally pillow-form spilitic lavas interbedded with the tuffs in the upper part of the Cumberland Bay Series and a foliated late plutonic granodiorite intrusion associated with the metasomatic recrystallization and alteration found throughout the sediments and lavas.

Trendall's (1959) second report was intended to augment his first one and incorporated an account of the igneous complex. Because the facies of both sedimentary series suggested they were turbidite sequences, and structural evidence from Dartmouth Point suggested contemporaneous deformation, Trendall included both sequences in one series known as the "Cumberland Bay Series". This he subdivided into the older "Sandebugten type" and the younger "Cumberland Bay type", because he believed that only a major palaeogeographical change, although not of orogenic proportions, occurred before the deposition of the younger "Cumberland Bay type".

Both massive and pillow lavas occur together at Undine South Harbour but at Annenkov Island there are only the massive lavas which are interbedded with deep-water sediments. Trendall considered these to have been intruded as sills along the flow planes of previously extruded pillow lavas and were therefore of a subaqueous extrusive origin.

Trendall thought that the intrusion of the south-east igneous complex is paratectonic and that the gabbros were intruded into the more acidic rocks after the main period of folding. The petrography of two sets of post-tectonic dykes is comparable with that of the pre-tectonic lavas of which those trending north-easterly are later than those trending south-easterly, but both suites were noted to intrude only less deformed rocks.

No geological studies were undertaken during the British South Georgia Expedition, 1954, or during the International Geophysical Year, 1957–58. In 1959–60, N. Aitkenhead and P. H. H. Nelson examined the area between Cumberland West Bay and Cape George. They re-introduced Trendall's (1953) original nomenclature because of the sharp and complex contact between the two sedimentary successions, suggesting both an unconformable and thrust-faulted relationship between rocks of the tightly folded "Sandebugten type", which appear to be in the form of an anticlinorium, and the "Cumberland Bay type" asymmetrically overfolded from the west.

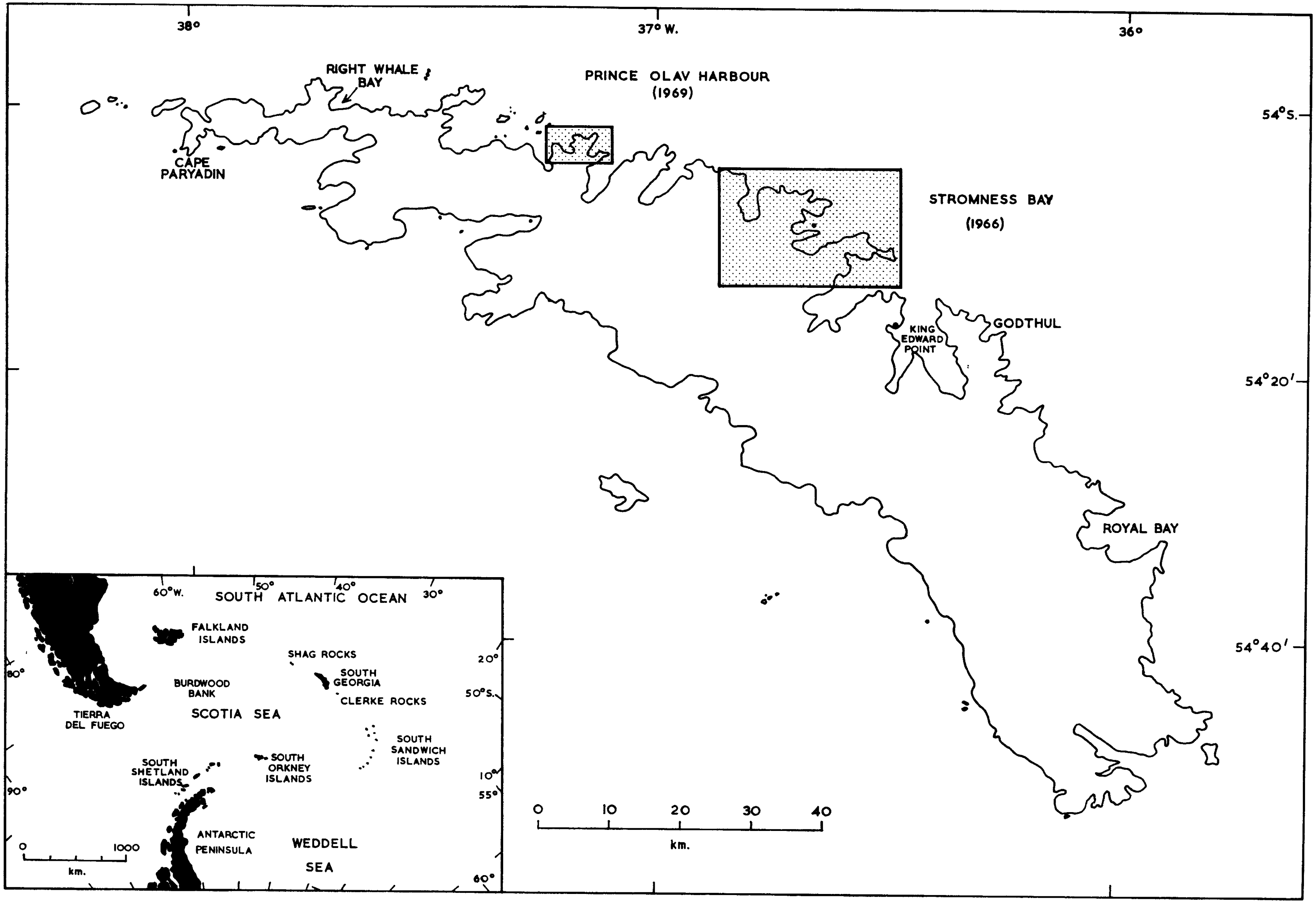


FIGURE 1

Map showing the relationship of South Georgia to other landmasses in the South Atlantic Ocean and the locations of the areas visited in 1966 and 1969.

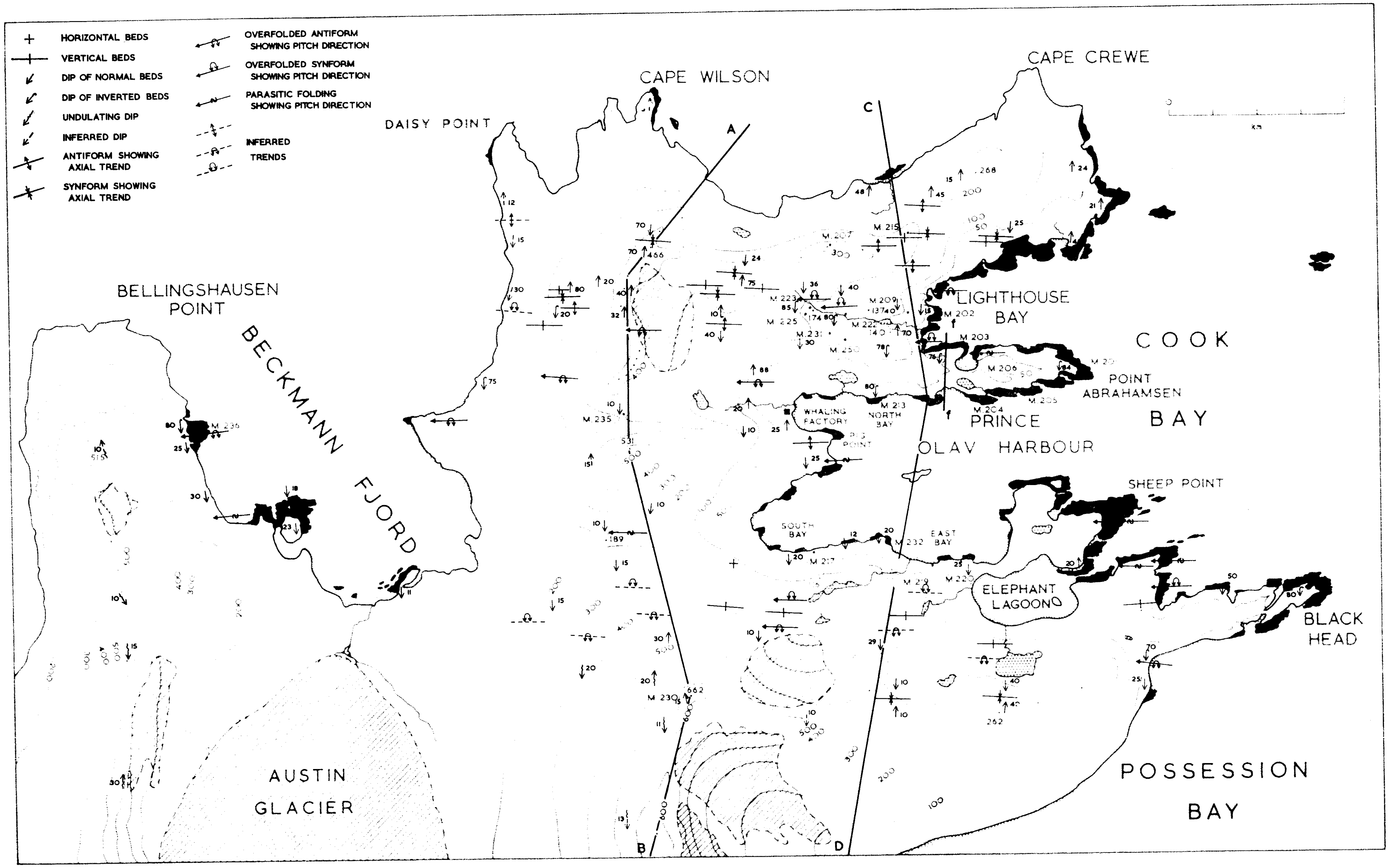


FIGURE 4

Geological sketch map of the Prince Olav Harbour area with station numbers, showing bedding dip, major overfolds and geological sections A–B and C–D (in black). Form lines are at 50, 100 and thereafter 100 m. intervals. Permanent ice (hatched); wave-cut offshore platforms (grey); permanent lakes (coarse stipple); shore-line shingle beaches (fine stipple); spot heights (in m.).

[face p. 4

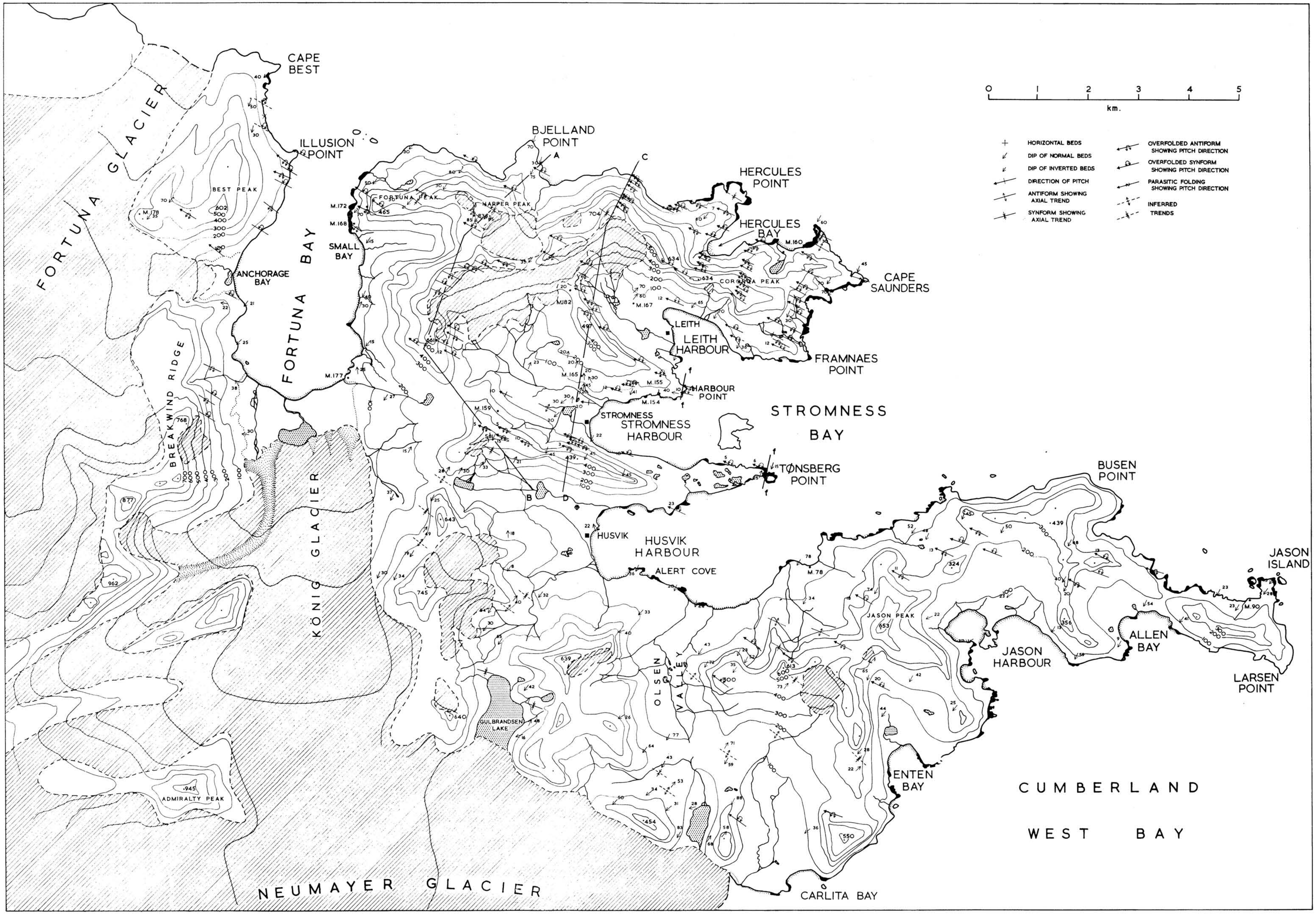


FIGURE 2

Geological sketch map of the Stromness Bay area with station numbers, showing major overfolds and geological sections A–B and C–D (in black). Form lines are at 100 m. intervals. Permanent ice (hatched); wave-cut offshore platforms (grey); permanent lakes (coarse stipple); shore-line shingle beaches (fine stipple); spot heights (in m.).

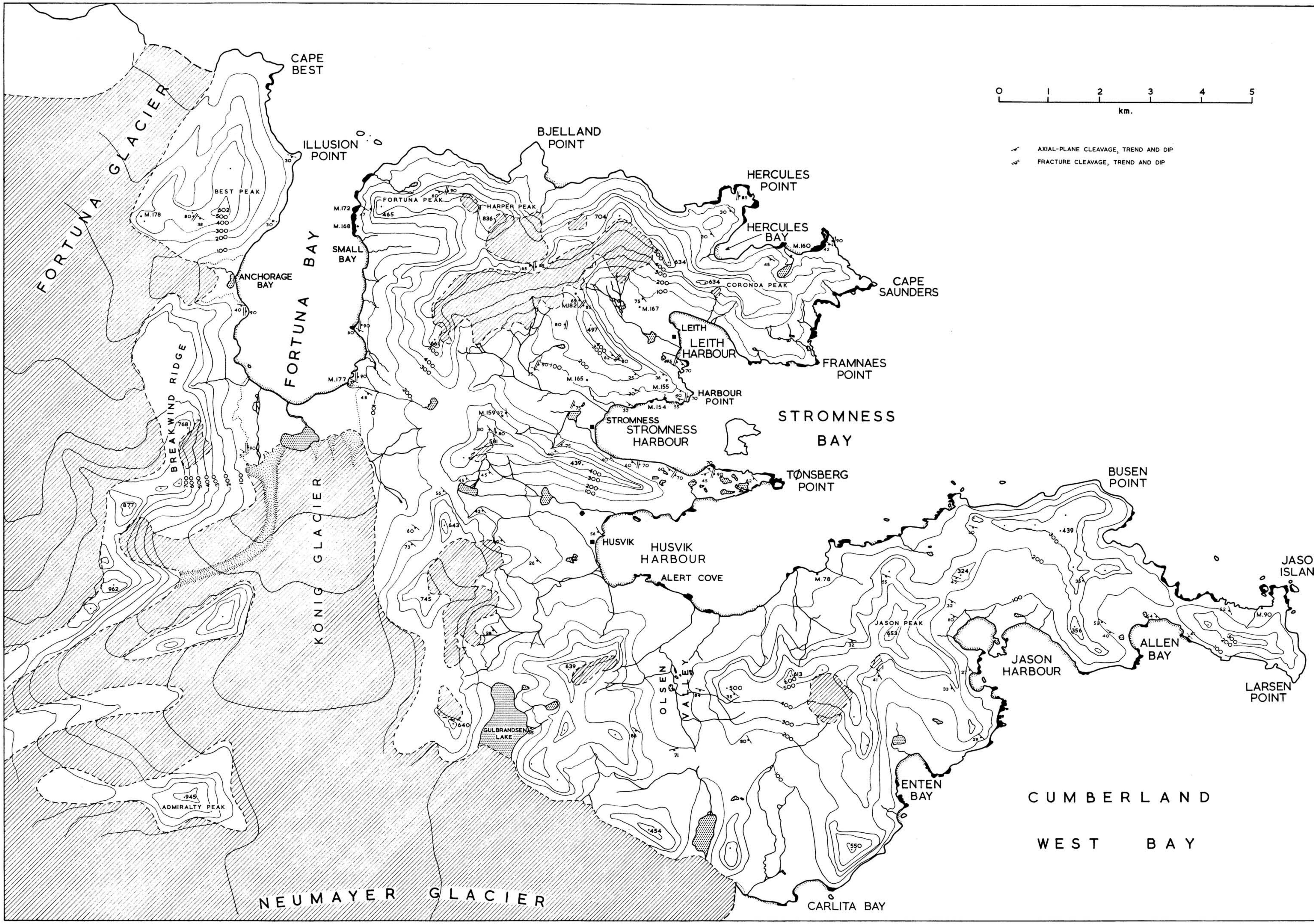


FIGURE 3

Geological sketch map of the Stromness Bay area with station numbers, showing axial-plane cleavage and later north-south-trending fracture cleavage (in red). Form lines are at 100 m. intervals. Permanent ice (hatched); wave-cut offshore rock platforms (grey); permanent lakes (coarse stipple); shore-line shingle beaches (fine stipple); spot heights (in m.).

[*face p. 4*

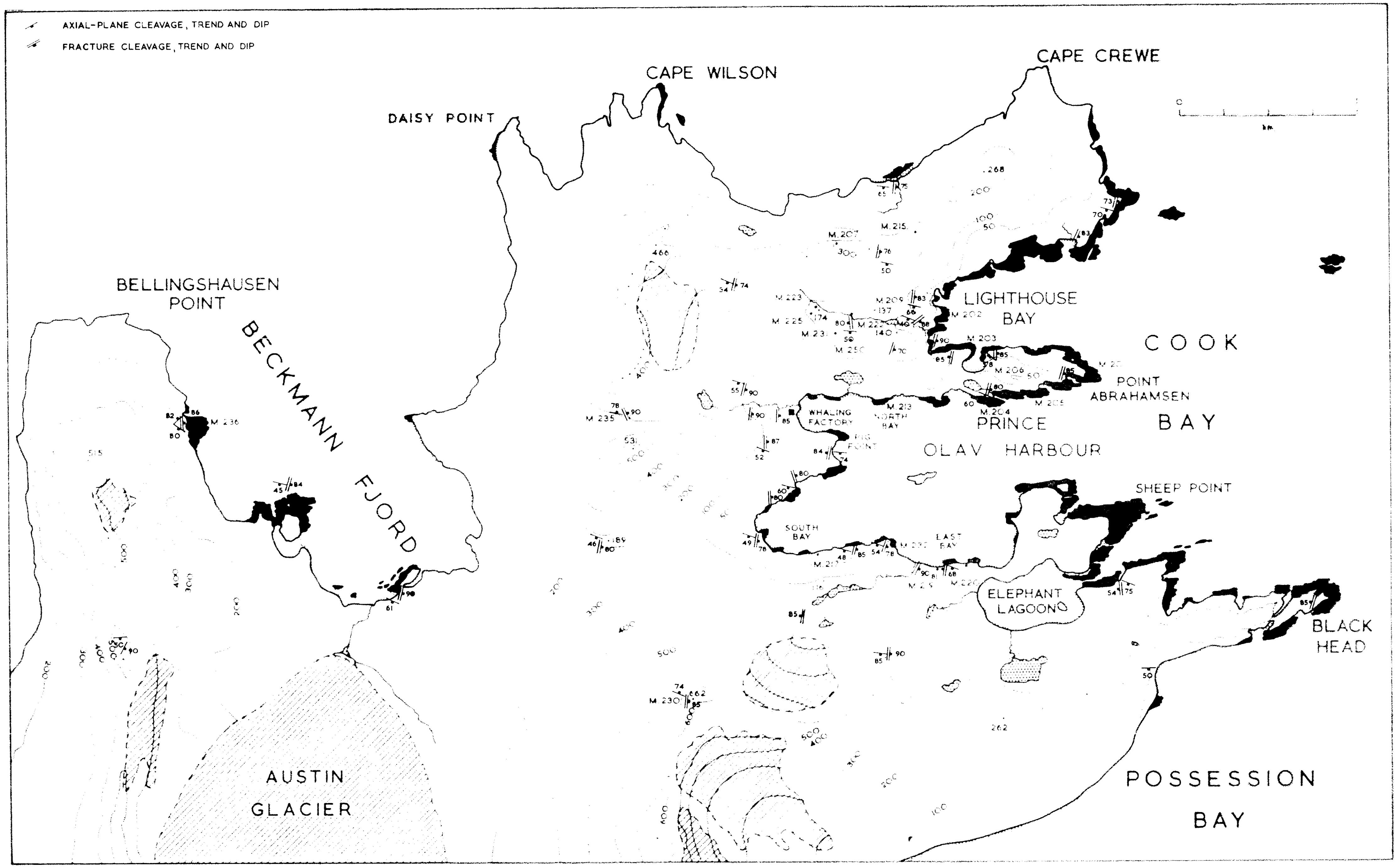


FIGURE 5

Geological sketch map of the Prince Olav Harbour area with station numbers, showing axial-plane cleavage and later north–south-trending fracture cleavage (in red). Form lines are at 50, 100 and thereafter 100 m. intervals. Permanent ice (hatched); wave-cut offshore rock platforms (grey); permanent lakes (coarse stipple); shore-line shingle beaches (fine stipple); spot heights (in m.).

[face p. 4

D. Brook examined the area between Stromness Bay and Cumberland West Bay in 1965–66 and the author later extended this work towards the Fortuna Bay area.

Fig. 6 extends Trendall's (1953, p. 3, fig. 2) diagram summarizing the development of workers' conclusions on the geological relationships in South Georgia. Additions have been made following the conclusions of Trendall (1959) and Aitkenhead and Nelson (1962). Fig. 7 illustrates the present known geological relations.

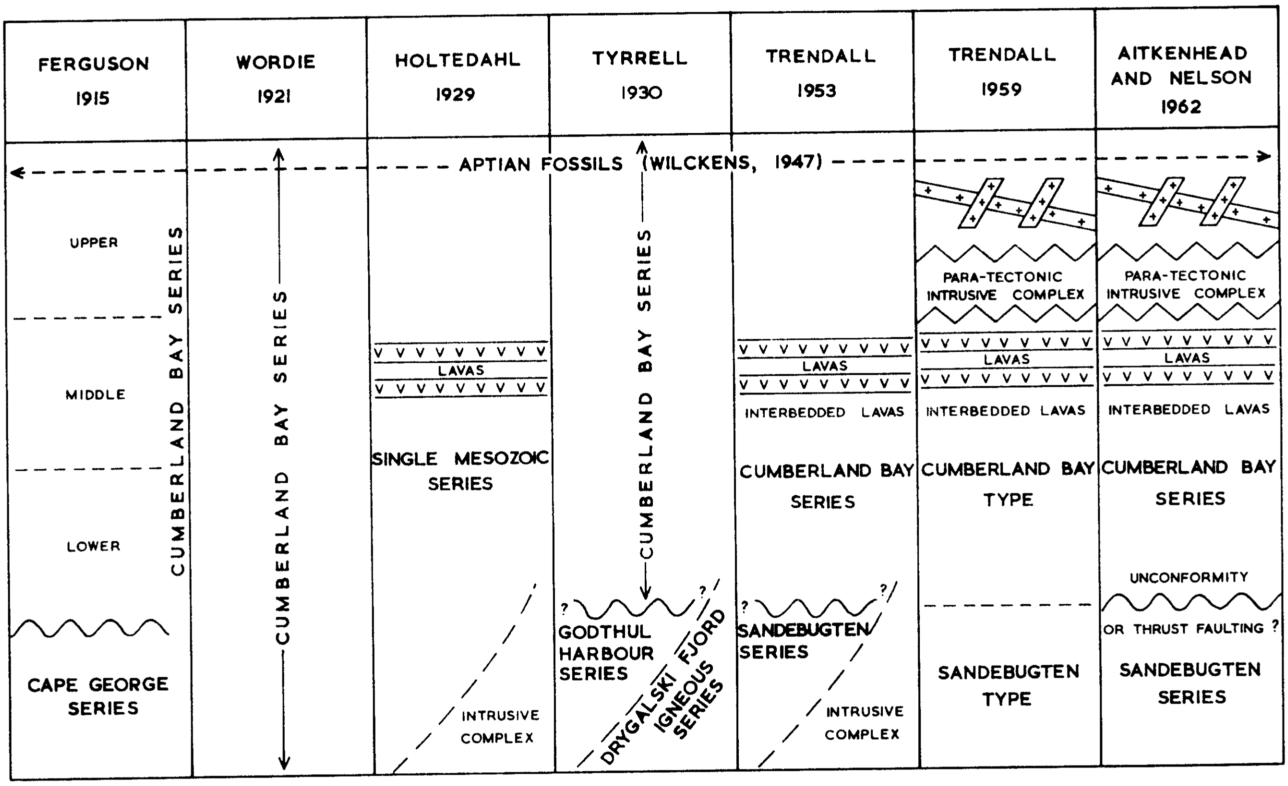


FIGURE 6

Diagram to show the development of opinion on the geological relations in South Georgia.

II. PHYSIOGRAPHY

A. GEOMORPHOLOGY

1. *Topographical description*

South Georgia, an island of considerable relief, is about 120 km. long and no more than 30 km. wide. On the north-east coast peaks 600 m. high rise to a central 1,800–2,400 m. ridge forming the Allardyce Range. Between Kohl-Larsen Plateau and Ross Pass this ridge, which presents a cirque-glacier eroded wall to the north-east, comprises a succession of horns from Smillie Peak (1,767 m.) to Mount Brooker (1,881 m.). The most prominent of these is Mount Sugartop (2,324 m.) (Plate Ia), although Mount Paget (2,934 m.) to the south-east is the highest peak on the island. South of Ross Pass, the peaks are generally of lower elevation but the central ridge continues to the south-eastern end of the island to form the Salvesen Range. West of Kohl-Larsen Plateau, where the island narrows from about 20 km. in width, the highest peaks reach only 800–1,000 m.

58 per cent of the island is covered by ice (Smith, 1960), but the north-east coast from Royal Bay to Possession Bay is largely glacier-free except for isolated coastal ice caps. It comprises many fjords of which several (Cumberland, Antarctic and Possession Bays) contain flat, broad mountain glaciers with floating snouts from which numerous icebergs calve and typify the more deeply incised fjords.

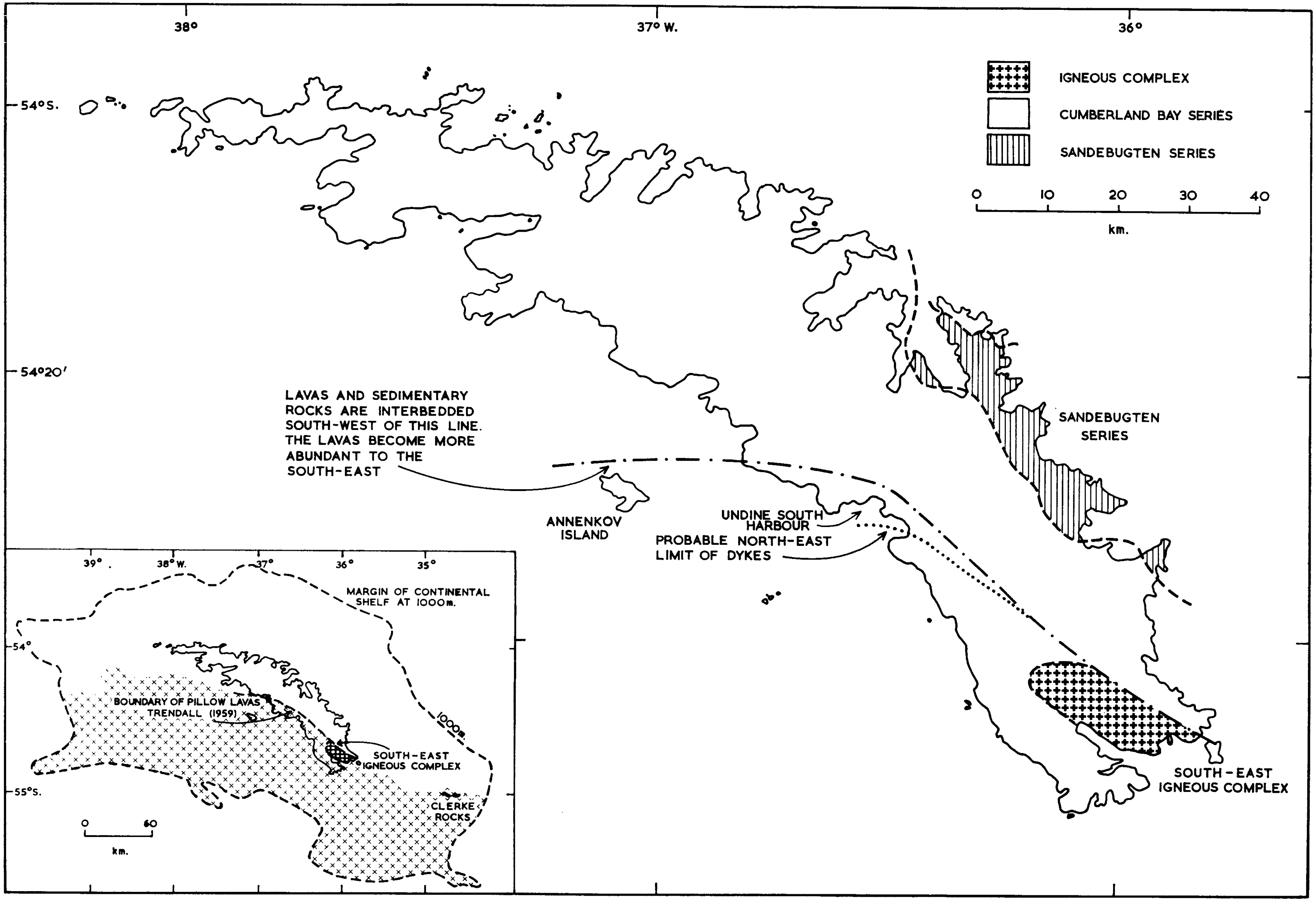


FIGURE 7

Trendall's (1959) geological sketch map with a modification to the outcrop of the Sandebugten Series (after Aitkenhead and Nelson, 1962). The inset shows the limits of the continental shelf of South Georgia. The boundary of the pillow lavas is continuous with the magnetic anomaly pattern (area with crosses).

Because of the cooler climate on the south-west slopes of the Allardyce Range compared with the north-east coast, glacierization is greater and the coastline is less deeply incised. However, west of Shackleton Gap, short north- and south-flowing glaciers enter the sea whereas fjords trend almost east–west.

A 30–35 m. cliff is a most prominent coastal feature abruptly terminating a concave foreland at the base of which a broad wave-cut offshore rock platform has been cut (Plate Ib).

2. *Early conclusions*

The first detailed account of the physiography was by Holtedahl (1929). He described the geomorphology of many parts of the north-east coast and discussed the development of bays, shore lines and submarine platforms with a description of the post-glacial physiographic evolution. He implied that a more mature topography existed in the deeply indented north-east coastline compared with the rest of the island. Cirque glaciers rapidly broaden into short, wide relatively flat valley glaciers which he considered could be compared with those on Spitsbergen or Novaya Zemlya. He discussed the evidence for a piedmont-type glacier around South Georgia which probably gave rise to the low forelands backed by smooth concave slopes. Such a piedmont glacier was possibly responsible for the peneplanation of the low islands in the Bay of Isles (Plate Ic), indicating past glacial extent. The remnants of one such glacier possibly exists at Rocky Bay ("Seal Bay"; Holtedahl, 1929, pl. XXXIX, fig. 2). Holtedahl was sceptical of Gregory's (1915) suggestion that there are indications of a pre-glacial plateau in the south-east of the island, and doubted whether peaks in any area reached one distinct level.

Douglas (1930) compared the possible physiographic evolution of South Georgia with that of Elephant Island where an ice cap has formed on a high plateau. He considered that South Georgia was once similarly glacierized, but due to the warmer climate the ice sheet on South Georgia has receded and glacierization has dissected any previous plateau. A profile south-west to north-east shows a steep rise from the south-west coast to the summit ridge of the Allardyce Range and then a sharp fall on the north-east side to a coastal plateau marked by peaks at about 600–650 m. altitude between Royal Bay and the Bay of Isles. Here, coastal ice caps indicate a once more extensive ice sheet and may possibly be compared to the plateau noted by Douglas on Elephant Island.

3. *Geomorphology*

The sedimentary sequence comprises repetitive lithologies, with regular alternation of coarse greywackes and silty slates, resulting in denudation comparable with that of the Annot Sandstone formation in the Tête de Georgias Vallon de l'Estrop region of the French Maritime Alps (Stanley and Bouma, 1964). Lithologically controlled channelling along the north-west–south-east-trending strike of the softer beds could have determined the present drainage system, but glacier development across the strike is possibly the result of fault control suggested by the dominant north–south fracture cleavage, although only minor parallel north–south faulting was observed which has resulted in the formation of narrow gullies.

The forms of minor embayments, such as Prince Olav Harbour, Stromness Harbour and Leith Harbour, are strongly structurally controlled. Flat-lying sediments have been more susceptible to ice erosion which has probably been channelled by the more resistant steeply inclined or vertical beds comprising the short limb of an overfold. Often such a structure marks the southern boundary of an embayment, and an asymmetrical inter-valley ridge has formed trending inland along the strike and characterized by steep northern slopes and gentler and smoother southern slopes dipping sub-parallel to the dip of the axial-plane cleavage.

Glacial benches with hanging valleys are the result of ice re-advance which has cut deeply into the floor of an earlier glacier valley. The benches are more prominently developed on the northern side of the inter-valley ridges because of the resistant nature of vertical strata to later subaerial erosion. They diminish from a height of 100 m. until imperceptible mergence with the old foreland level at the top of the sea-eroded cliffs at either side of the valley mouth (Plate Ia). Ice scour along the strike of vertical strata of glacial benches at Prince Olav Harbour has resulted in numerous elongate lakes up to 200 m. in length.

4. *Glacierization*

The isolated coastal ice caps may be characterized by remnant hanging glaciers such as at the headwall of Leith Harbour valley and south of Bjelland Point. Small, isolated mountain cirque glaciers are retreating with exposure below the firn line of glacier bands as thin hard ice layers caused by included dust. These bands dip at about 20–30° below the glacier surface thereby indicating considerable rotational movement during glacier flow (McCall, 1960).

Extensive 1–3 km. wide morainic plains with braided fluvio-glacial melt-water streams are characteristic of König and Austin Glaciers on the north-east coast. König Glacier has a well-developed medial moraine originating at the confluence with a tributary glacier 1·5 km. south of the snout. Two separate melt-water streams emerging from the snout originate either side of the medial moraine which suggests that it prevents the two glaciers from fully coalescing. The medial moraine provides a source for a considerable but local terminal moraine. Englacial drift becomes exposed on the glacier surface towards the snout but it does not form large morainic mounds, although they are sufficient to have dammed a pro-glacial lake.

Brook (1971) has described Gulbrandsen Lake, an ice-dammed lake adjacent to Neumayer Glacier, which shows several terraces indicating successive lowering of water level following abrupt drainage.

Patterned ground is locally developed in talus covering the glacial benches. It consists of small upstanding fragments arranged as elongated to sub-circular, partly sorted stone circles about 0·5–1 m. in diameter. They are usually developed in shallow gullies or channels between rock outcrops. The location of these circles and the elongation and sub-parallel orientation of the included talus parallel to the main drainage direction suggests that the orientation of the circles was determined by flowing water and possibly down-slope creep. Individual circles imperceptibly merge and there was no sorting immediately below the surface.

B. Glacial and Recent Glacial History

1. *Extent of glaciation in Antarctica*

Goodell and others (1968) have shown by palaeomagnetic dating, using polarity reversals of remanent magnetism in sedimentary cores and a study of ice-rafted debris distribution, that a glacial maximum occurred between 2·35 and 3·35 m. yr. ago. During this period the 0° C surface isotherm was more than 5° of latitude north of its present position. They suggested that this northward displacement would be accompanied by a northerly movement of permanent sea-ice limits and also, perhaps, of the Antarctic Convergence. Because the Antarctic and Greenland ice sheets survived the last interglacial, Mercer (1968) has inferred that they presumably accumulated during the Tertiary, but probably not prior to the Miocene (Denton and others, 1970) when the climates were becoming cooler although still warmer than during the Pleistocene.

Hamilton and Armstrong (1969) provided evidence from the Ross Sea area of continental glaciation in Antarctica prior to 7·4 m. yr. ago. Considerable erosion has occurred during the late Tertiary because ice-contact breccias at an altitude of 2,000 m. have been veneered by subaerial lavas dated at 5·5, 6·8 and 7·4 m. yr. Presumably this was only possible at higher altitudes during this warmer period and they were wrong in implying that ice cover during the late Miocene to early Pliocene was 2,000 m. thicker than at present. Sea-level glacierization may have only commenced about 5 m. yr. ago at the end of the period of global cooling, when, according to Mercer (1968), conditions were much like the present and there was a similar amount of ice in the Southern Ocean.

There has been a period of greater recession than at present indicated by Foraminifera in sediments south of lat. 70° S. (Goodell and others, 1968), although they considered that no proper Antarctic interglacial occurred. Thus it is possible that, due to the warmer global climate, relatively low altitude and distant location from Antarctica, glacierization did not occur in South Georgia in the late Tertiary prior to mid-Pliocene times. During this period the island may have been within the winter limits of sea ice and was no doubt similarly glacierized as are landmasses lying within the present winter limits of sea ice.

2. *Glaciation in the South Atlantic region*

Extensive glacierization of the Patagonian Cordillera marked the limit of the Antarctic glaciation and evidence of interglacial periods is well-preserved, although the extent of the last glaciation (Würm) cannot be precisely determined (Auer, 1970) (Fig. 8). Glaciation commenced once the influence of the cold Antarctic ice mass extended to the southernmost point of South America, and the numerous gravel layers occurring close to the Andes suggested the existence of glaciers during the Pliocene (Auer, 1956). A study of deep-sea sediment cores proved that the Pleistocene covered four humid glaciations and three long dry interglacial periods suggested by the occurrence of several salt-lake deposits.

From Fig. 8, which also shows the proximity of the Falkland Islands to the glaciation of South America, it is clear that the islands were possibly only preserved from glacierization by the climatic moderating influence of the South Atlantic Ocean. Andersson (1906) favoured a periglacial climate, a point which Joyce (1950) used to explain the formation of "stone runs", a characteristic feature of the Falkland Islands. Soundings on submarine shelves along the typical drowned coastline of the Falkland Islands (Adie, 1953) supported Andersson's belief of a 46 m. elevation in pre-glacial times but there is no definite evidence for any greater elevation. This "pre-glacial" low sea-level may, however, be much older than early Pleistocene because maximum glaciation in Antarctica apparently occurred in the Middle to Late Pliocene (Mercer, 1969).

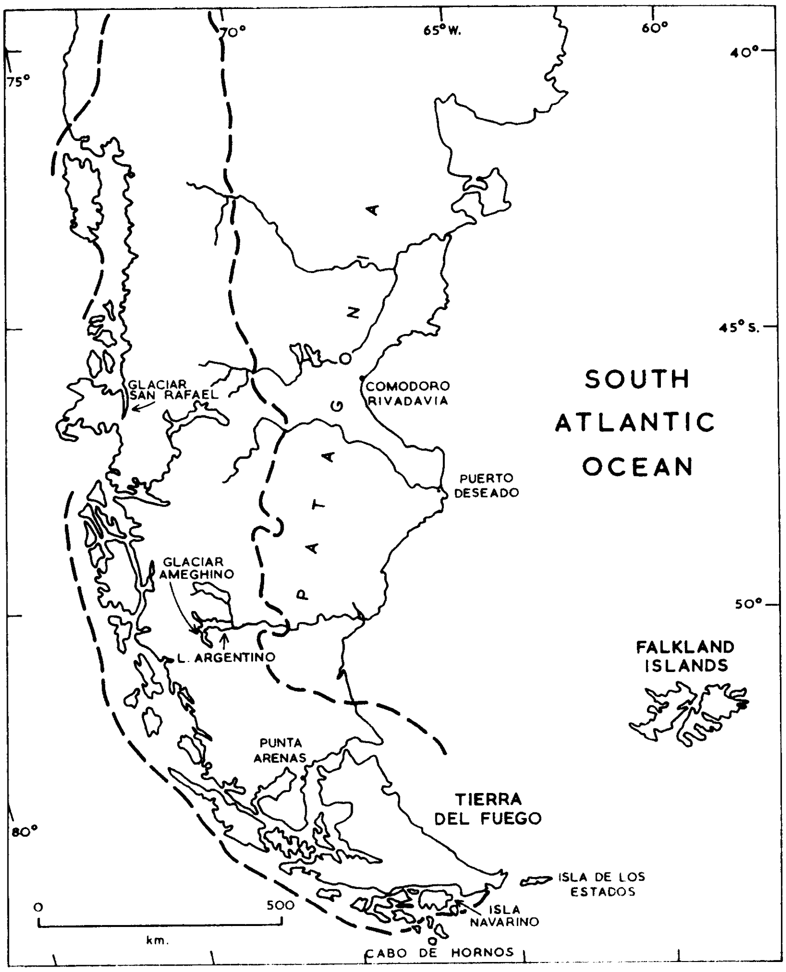


FIGURE 8

Limits of Pleistocene glaciation in South America (Auer, 1970, p. 39). The western limits are according to Feruglio (1950) and the eastern limits according to Auer (1964).

3. *Glacierization in South Georgia*

Ewing and others (1960) have suggested a revised estimate for a eustatic fall in sea-level of between 100 and 200 m., and possibly even as much as 300 m., during maximum glaciation. Holtedahl (1929) observed that the extreme western parts of South Georgia could be best explained as a "drowned" morphology and the existence of a submarine platform at a depth of 100–200 m. off South Georgia points to a previous higher stand of the land. He also noted that the larger "Royal Bay glacier" eroded down to 190 m. below sea-level, the greatest depth in the bay, and 250 m. below sea-level for the former Cumberland Bay glaciers. These lie within the range suggested by Ewing.

In South Georgia, secondary cirques originally at sea-level are now flooded such as at Jason Harbour (a completely circular embayment breached at its mouth by the rising sea-level) and Godthul, where the bay mouth is 50–60 m. deep. These were compared by Holtedahl (1929, p. 76) with similar cirques in the process of formation on Clarence Island, where, after retreat of the snow line, local glaciers cut secondary cirques at the foot of the cliffs below the ice cap at sea-level. Holtedahl implied that a sudden recession of the ice cap on South Georgia would enable similar secondary cirque development.

The 50–60 m. deep entrance to Godthul may possibly be correlated with the pre-Pleistocene 46 m. submarine level in the Falkland Islands, and incomplete isostatic recovery may account for the additional 10–15 m. depth of the sea floor at Godthul. Thus the sudden recession suggested by Holtedahl may be tentative evidence for a pre-Pleistocene interglacial in South Georgia.

It is possible that during this period the present topography of South Georgia was sculptured and the main drainage pattern established. The glacial benches at Stromness and Prince Olav Harbour are probably the result of an interstadial during the last severe glaciation which may possibly be correlated with the last or Alpine Würm glaciations.

4. *Recent glacial history of the South Atlantic region*

a. *Patagonia.* Auer (1964) stated that the rhythm of climatic changes after the last glaciation in Patagonia was similar to that in other parts of the world. That the glaciations were contemporaneous had already been established by several investigators who based their conclusions on identical and contemporaneous fluctuations in the temperature following the last of the Würm glaciation despite the differences in precipitation. A local climatic regime may influence differential movement by glaciers in adjacent areas, and thus correlation of glacier movements from Patagonia to South Georgia is unreasonable but the general climatic fluctuations in southern South America may broadly be extrapolated to embrace the Falkland Islands and South Georgia.

By using tephrochronology, raised beaches and marine clays, Auer (1964) has constructed a curve showing considerable sea-level movements since Late Glacial times, combined with a tentative correlation with the Baltic regions (Fig. 9). He identified three tephra layers:

Tephra III	2,240 ± 60 yr.
Tephra II	4,480 yr.
Tephra I	9,140 ± 90 yr.

but noted that tephra marked with the same number were apparently not of the same age everywhere, but there was clear synchronic grouping.

Tephra I was possibly the initial phase of the South American post-glacial period because of its well-defined white stratum and virtual coincidence with the bipartition of the Scandinavian ice cap which dates the beginning of the post-glacial period in northern Europe (De Geer, 1927). A 9 m. raised beach was shown to be due to an early post-glacial transgression because tephra of Tephra I age were eroded to the 9–10 m. level, and it was Auer's opinion that this transgression was synchronous with the Echineis transgression in the Baltic.

Auer (1970, p. 19) stated that it was possible to interpret climatic changes in Patagonia from an analysis of the pollen content of peat. It had been shown that prior to 7,000 yr. ago the average annual temperatures were higher than today. A warm dry interval lasted for several millenia beginning about 6,000 yr. ago and typified by pollen from a humified peat giving an age of 6,850 yr., but this was interrupted for a short time by a moist phase, the Témpanos glaciation, which occurred about 5,000–4,000 yr. ago. During this period the sea-level was low before rising to the 6 m. transgression, which corresponded to the transgression of the Baltic Litorina climatic period about 4,500 yr. ago.

There is a complete pattern of raised beaches in northern Patagonia at 6, 9, 15, 18 and 22–25 m. which Zeuner (1945) attempted to correlate with Mediterranean type localities. It is clear that Zeuner's interpretation is incorrect as Auer (1970) has shown that the 15–40, 6–19 and 5–6 m. raised shore lines belong to the late Pleistocene and Recent sea-level fluctuations, but higher levels may belong to older interglacial periods. He was, however, uncertain whether the higher terraces of Patagonia reflected uplift

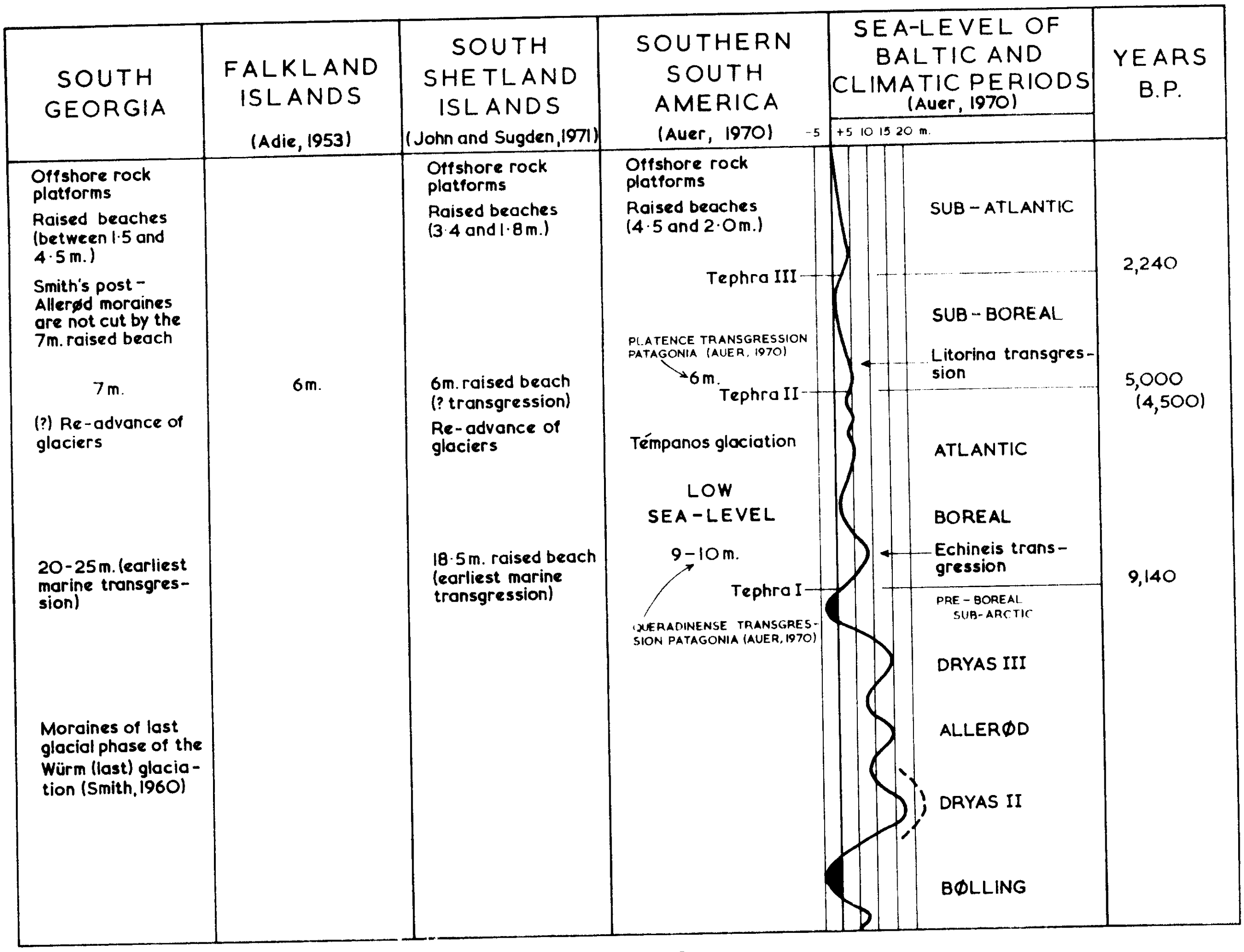


FIGURE 9

Tentative correlation of South Atlantic shore lines with Auer's (1970) correlation of shore lines of southern South America and the Baltic Sea area of Scandinavia.

of the land or eustatic changes, but he agreed with Fray and Ewing's (1963) conclusions that, because of the uniformity of depth below sea-level of a shell layer, there had been little if any warping of the Argentine continental shelf since the last glaciation. However, Richards and Broecker (1963) pointed out that some doubt on the stability of the continental shelf in the Comodoro Rividavia area must exist because of the discovery of a 9 m. elevated beach which was only 5,000 yr. old.

b. *Falkland Islands and South Georgia.* A comparison of post-glacial raised beaches with those in Patagonia has been made by Adie (1953), who concluded from a 6 m. raised beach at Shell Point and Yorke Bay that it could be directly correlated with the 5–6 m. raised beach of Patagonia, which Auer (1964) has shown to be equivalent to the Baltic Litorina transgression. Adie considered that the 69 m. post-glacial submergence referred to by Andersson (1907) could be correlated with those of Natal thought by Fair (1943, p. 14) to be the result of glacio-eustatism and possibly of Milazzian age.

Moraines are the most widespread evidence of recent glacier movements in South Georgia. Their fluctuations may be broadly correlated with periodic climatic variations in southern South America. Smith (1960) stated that in 1875 glaciers in South Georgia were at their most advanced positions for several thousand years and that before then there was a long period when the climate was as warm or warmer than at present. Similar conclusions were reached by Nichols and Miller (1951), who summarized the physiographic history of Ameghino Glacier in Argentina (Fig. 8):

i. After maximum advance of the Wisconsin (Würm) glaciation the glacier retreated.
ii. Re-advance.

iii. Retreat to above the present position.
iv. Erosion of glacial deposits, formation of a weathering profile and development of forests. These required several hundred years.
v. More than 100 yr. ago the glacier started to re-advance and reached in about 1870–80 a more advanced position than any during the last 2,000 yr. before retreating a short distance. Tree-ring evidence from growth of new vegetation suggested these dates. After 1880 there was again a short advance then retreat to the present position.

Lawrence and Lawrence (1959) confirmed Nichols and Miller's (1951) work and suggested rapid recession from 1910 to 1935 in the San Rafael Glacier area, but by 1959 there had been an advance in some parts.

The history of the last 100 yr. of glacierization in South Georgia may be summarized from the records of observations by various research expeditions. In 1883, the German International Polar Year Expedition of 1882–83 noted a rapid retreat of Ross Glacier of about 1,200 m. from its advanced position of 1882. However, Holtedahl (1929) observed its snout was in a similar position to that shown by photography in 1882. Thus the retreat and re-advance described by Nichols and Miller on Ameghino Glacier is also represented in South Georgia.

The advance of the Royal Bay glacier, noted by Holtedahl in 1928, may be associated with the concentric terminal moraines developed between the bay-head beach of Beckmann Fjord close to the Austin Glacier snout. They are most pronounced, suggesting periodic but successive build-up due either to more prolonged periods of stagnation depositing large mounds of englacial moraine or successive seaward glacier advances pushing the moraine into heaps peripheral to the glacier snout. Between these and the snout, fluvio-glacial gravels form a narrow flat strip through which flow melt-water streams from a small pro-glacial lake.

The tussock-covered moraines cut by the 7 m. raised beach at the bay-head beach of Beckmann Fjord are possibly representative of the youngest Pleistocene moraines which Smith (1960) tentatively correlated with the post-Allerød moraines of northern Europe. A series of concentric terminal moraines, 1 m. high and about 12–15 m. apart occurs on the floor between the small inter-ridge valleys west of Stromness and Leith Harbours. These have possibly been preserved from a more recent glacierization by their isolation from the larger area of ice cover on South Georgia at the end of the last glaciation. They may therefore be contemporaneous with concentric moraines in the Hamberg Lakes area which Smith (1960, p. 706, fig. 8) considered to be pre-Allerød.

c. *Recent sea-level movements*. South Georgia is a small land area on an isolated and comparatively large continental shelf, the margins of which are a considerable distance from land (Fig. 7). Isostatic loading of the small ice cap on South Georgia may not have had as great an isostatic effect compared with the ice cap on the Antarctic Peninsula (John and Sugden, 1971). The post-Pleistocene eustatic variations described by Adie (1953) in the Falkland Islands (which were probably never glacierized and therefore were not subject to isostatic uplift) has no doubt influenced development of the South Georgia coastline (Table I). However, because there has probably been minor isostatic uplift maintaining South Georgia in a state of continuous juvenility since deglacierization commenced, a complex picture of the development of the coastal morphology emerges. The raised beaches are probably the result of marine transgressions due to eustatic rise which, if the period of stillstand was of a sufficient length, probably resulted in erosional platforms being cut at the wave base.

The 20–25 m. high-level platform is widespread in the sheltered bays but it has probably been destroyed by subsequent marine erosion on the exposed coastal forelands. It is usually backed by steeply rising tussock- and scree-covered slopes. A higher level occasionally occurs at about 33 m. but this may be part of an old glacial bench which merges with the foreland between 30 and 35 m.

Peat sections cut on the 20–25 m. high-level platform show evidence of washing because there are no gravelly deposits, which suggests either the absence of a later glacial cover or immediate recession of the sea after the platform formation leaving it above high water similar to the present shingle-free 0·5 m. wave-cut offshore rock platform. Strand lines observed by D. Brook in 1966 in the low-lying Olsen Valley above the 20–25 m. level indicate a subsequent higher beach which may have been deposited by material eroded from the 20–25 m. erosional platform. In most areas the strand lines but not the erosional platforms have probably been destroyed by melt-water run-off from a subsequent glacial

TABLE I

HEIGHTS OF HIGH-LEVEL EROSIONAL PLATFORMS AND RAISED BEACHES AT STROMNESS BAY AND PRINCE OLAV HARBOUR, SOUTH GEORGIA

Major levels of South Georgia (Stromness Bay and Prince Olav Harbour)		*Approximate height* (m. a.s.l.)
Glacial benches		100–35
Approximate level of wave-cut coastal cliffs of truncated foreland		35–30
High-level erosional platform		25–20
Raised beaches	Occasionally preserved (near Stromness Bay)	18 15 13
	(Stromness Bay)	7·5–7 5·0 2·5–2
		1·5
Offshore wave-cut platforms		0·5

retreat, which may have resulted in isostatic uplift before a stillstand during which the 7 m. raised beach was formed.

As the 20–25 m. elevated platform is the earliest post-glacial level in South Georgia, it may be correlated with the 9 m. raised beach, the earliest post-glacial level in Patagonia, to which Auer (1970) gave an age of 9,000 yr. on Tephra I evidence and considered to be equivalent to the Baltic Echineis transgression (Fig. 9). This is supported by Coope's (1963) evidence from Jason Island, Larsen Point. He recorded the recent beetle *Hydromedion sparsutum* occurring in peat which he considered to be older than 6,000 yr. The peat occurs at an altitude of 15·2 m., which is probably the 17 m. raised beach that occasionally occurs in other parts of Stromness Bay. Because this beach represents a transgression between those which developed the 20–25 m. high-level erosional platform and the prominent 7 m. raised beach thereby suggesting an intermediate date, a tentative correlation may be established between raised beaches in the Falkland Islands and Patagonia (Fig. 9), although the higher levels on South Georgia may have resulted from isostatic uplift.

The most extensively developed raised beach varies between 1·5 and 4–5 m. before rising abruptly to the next level at about 7 m. This level is well developed in Olsen Valley and on the tombolo joining the island of Sheep Point to the shore line of East Bay, Prince Olav Harbour (Plate IIa). The storm beach on the tombolo is 1–3 m. wide and about 1 m. above high water. It rises in successive levels to the 1·5–5 m. raised beach which is densely vegetated with tussock (Fig. 10).

5. *Conclusions*

Evidence from South America suggests that during the Témpanos glaciation between 5,000 and 4,000 yr. ago there was a re-advance of San Rafael Glacier, which Auer (1970) dated just prior to the 6 m. raised beach in Patagonia. Assuming that the glacial increase in Antarctica influenced the re-advance of San Rafael Glacier, it is possible that it also influenced the formation of the 7 m. raised beach in the South Shetland Islands which John and Sugden (1971) attributed to a temporary halt in the isostatic recovery of the Antarctic Peninsula. They were able to show that erosional platforms and raised beaches could be separated by two glaciations and they could see no reason why the development of these phenomena should not be similar on South Georgia. Therefore, the 7 m. raised beach in South Georgia may well have been the result of the same glacial re-advance. Thus tentative correlation of the South Atlantic shore lines may be made (Fig. 9).

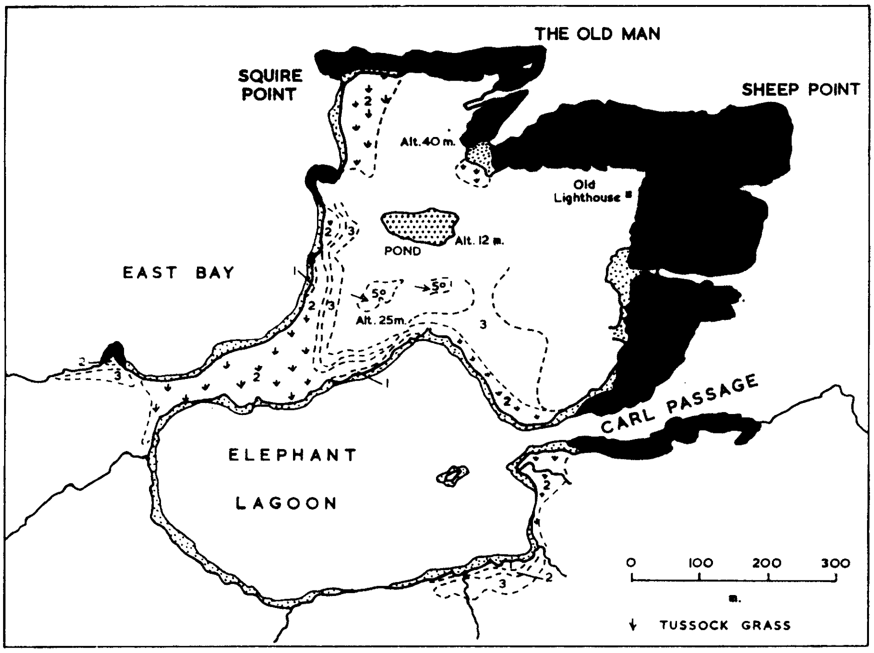


FIGURE 10

Map of the raised beaches at Elephant Lagoon and Sheep Point, Prince Olav Harbour. Wave-cut offshore rock platforms (black), 0·5 m. above high water. Back of the storm beach (fine stipple), 0·5 m. above high water. Level 1, 1·5 m. above high water; thin tussock. Level 2, 1·5–3·0 m. above high water; mosses and thick tussock. Level 3, 7·0 m. above high water; thin tussock, mosses and grasses on thick peat deposits.

III. STRATIGRAPHY

THE outcrop of the igneous intrusions and two sedimentary sequences in South Georgia is summarized in Fig. 7, which is basically Trendall's (1959) geological sketch map with modification following the work of Aitkenhead and Nelson in 1959–60 in the area between Cumberland East Bay and Royal Bay. The relationships between the igneous intrusions and the two sedimentary sequences are not clearly known and the development of opinion is outlined in Fig. 6, but Fig. 11 is a more detailed stratigraphy and explanation.

Trendall was incorrect in continuing to call the immature sandstones containing epiclastic volcanic fragments "tuffaceous greywackes" because there is a virtual absence of any pyroclastic ejectamenta in these sediments (Pettijohn, 1957). Therefore, the author proposes to use the term "volcanic greywacke" in the present account.

Trendall (1959) estimated that the Cumberland Bay Series was unlikely to be less than 10 km. thick. It comprises an irregularly alternating sequence of graded bedded volcanic greywacke turbidites with interbedded slates and is characterized by the absence of invertebrate fossils, although these are present in the younger parts of the succession, notably on Annenkov Island. According to Wilckens (1937, 1947), these fossils are Upper Aptian in age. Greater grain distortion and a higher proportion of non-volcanic constituents, with differing structural trends and an absence of fossils, distinguishes the rocks of the Sandebugten Series from those of the Cumberland Bay Series.

Trendall (1959) concluded that the Cumberland Bay Series is possibly Cretaceous in part, whereas the age of the Sandebugten Series is still a matter of speculation. It is known that the Sandebugten Series underlies the Cumberland Bay Series, and Trendall thought a major palaeogeographical change occurred before the deposition of the Cumberland Bay Series. However, the tectonics associated with this change may have caused early folding in the still plastically deformable Sandebugten Series during a major orogeny which folded the Cumberland Bay Series. Thus, Trendall thought it probable that the Sandebugten Series is Mesozoic, although there remained a possibility that it is Palaeozoic in age.

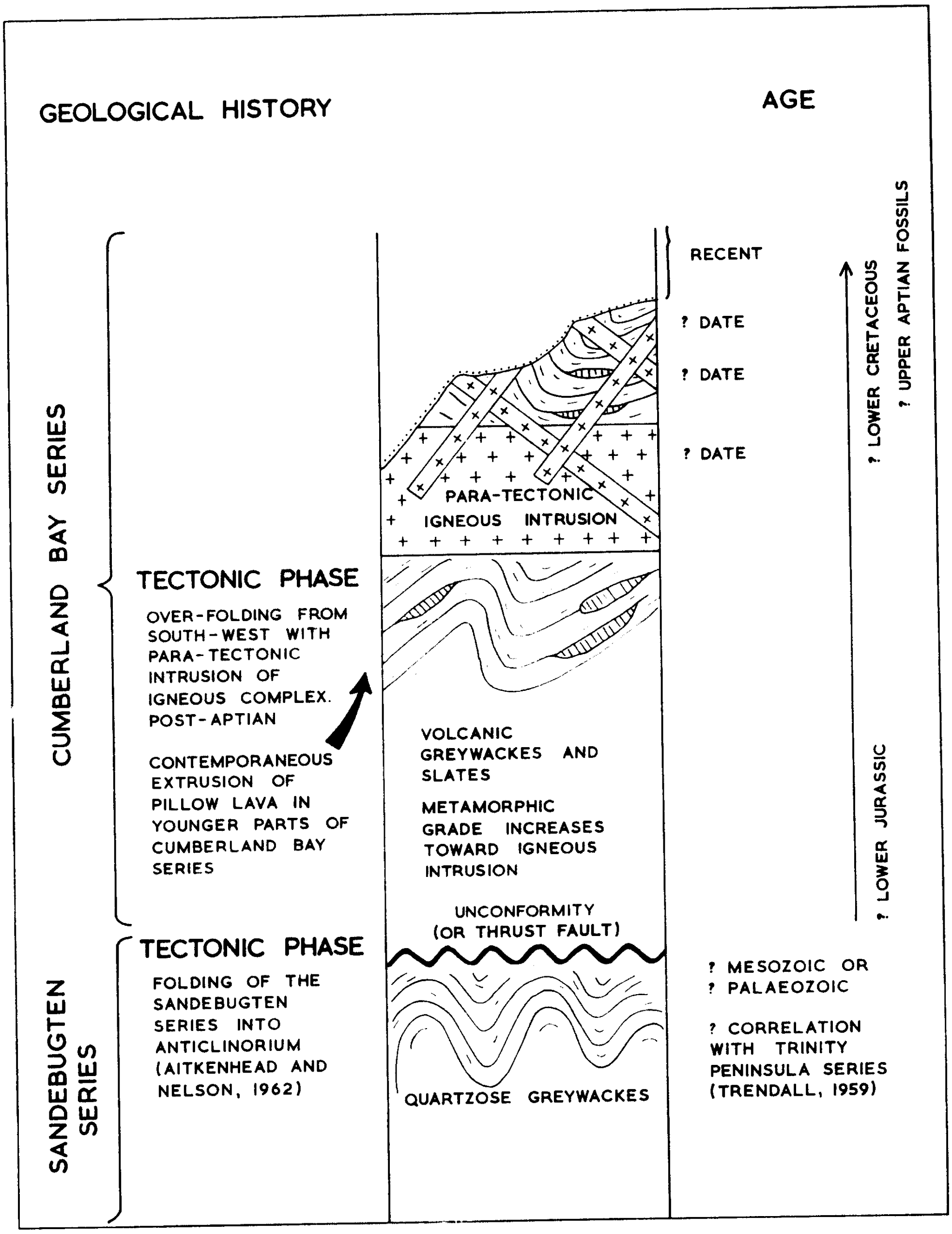


FIGURE 11

Diagram summarizing the structural and lithological relationships in South Georgia.

IV. SEDIMENTOLOGY

A. SANDEBUGTEN SERIES

Trendall (1953, p. 5) described the nature of the well-cleaved greywacke lithofacies of the Sandebugten Series as varying in grade from dark structureless slates to grits. With increasing grain-size, the rock becomes more massive with less marked and irregular cleavage. The proportions of coarse- and fine-grained material vary throughout the rock and all grades weather easily especially along the cleavage.

Laterally consistent sequences of coarse- and fine-grained rocks may form thick sections but there is an absence of repeated alternation in thinner-bedded strata. Sequences of graded beds occur irregularly and are characterized by equally thick sequences in which graded bedding is either absent or relatively abundant. Deviations from an "ideal" gradation from a grit to a slate were so abundant that Trendall (1953, p. 7, fig. 14) introduced the term "inter-grade" to describe similar features to incomplete turbidite sequences (Bouma, 1962; Walker, 1965).

Current bedding and minor slumping occurs in the dark striped slates especially between sequences of graded beds. Greywackes are frequently characterized by angular elongated pelitic fragments composed of black slate (possibly pull-apart structures) varying in abundance from isolated chips scattered along bedding planes to virtually loosely brecciated slate beds with interstices filled by greywacke. Trendall thought such brecciation appeared to have taken place *in situ*. The occurrence of bleached aureoles was very similar in both sedimentary sequences. A succession of cross-bedded units indicated derivation from the east-north-east but, because scattered observations revealed no consistent current orientation, Trendall (1959, p. 10) was uncertain of the dominant current direction.

Trendall's descriptions of the sedimentology of the Sandebugten Series sediments suggest that they belonged to a similar part of a depositional basin as that occupied by the Cumberland Bay Series. However, the quartzose greywackes with an absence of volcanic debris imply a more acidic provenance. The inconsistency of the graded bedding sequences and the current directions may characterize the more distal and deeper-water facies at an early period in the history of the geosyncline. The Sandebugten Series shows close petrographic similarities to the Greywacke-Shale Series of the South Orkney Islands (Tyrrell, 1930, p. 53; Trendall, 1953, p. 25) and the Trinity Peninsula Series (Adie, 1964) which are probably Palaeozoic in age.

B. Cumberland Bay Series

1. *Types of sedimentation*

a. *Sedimentary facies.* The Cumberland Bay Series of South Georgia exhibits the main characteristics of a "flysch lithofacies" as defined by Dzulynski and Walton (1965, p. 3), and is composed predominantly of thick bedded sandstones representing only a facies or part of a phase of deposition as neither basal conglomerates nor mollasse occur. A high percentage of epiclastic volcanic debris, derived from a partly volcanic source area, is present in most of the greywackes whereas, in common with most flysch lithofacies, pyroclastic debris is virtually absent. The extrusion of spilitic pillow lavas in the younger parts of the succession at Annenkov Island suggests that the Cumberland Bay Series is just pre-orogenic and deposited on the margins of a eugeosynclinal basin (Folk, 1959, p. 122). It is therefore apparent that the succession was probably deposited by the distal and more dispersed parts of the turbidite currents and it seems unlikely that sole marks and current bedding will give precise directional data.

One particular sequence could be traced along the strike for 1–2 km. but no lateral or vertical gradation into non-flysch sequences within the Cumberland Bay Series was recognized in the field. There are extreme observational difficulties in South Georgia and in any case such boundaries would probably be imprecise (Dzulynski and Walton, 1965).

Initially, the Cumberland Bay Series was subdivided into three parts on coloration differences (Ferguson, 1915) but subsequently Tyrrell (1930) discredited this scheme because of the petrographic similarity of the parts, and no recent workers have since recognized Ferguson's sub-divisions. The flysch facies of the Cumberland Bay Series probably represented the most prolonged phase in the depositional history of the eugeosynclinal basin and the author concurs with Trendall's (1959) suggestion that turbidity currents were mainly responsible for the deposition of these sediments.

The marginal axial facies represented by the Cumberland Bay Series are characterized by an absence of mass-flow deposits, mixing of sediments and large-scale slumping, whereas the elongated load casts and the intrastratal convolutions suggest down-slope gravity creep.

Deposition by turbidity currents of modern marine graded sandstones has not been observed. There is, however, substantial indirect evidence in the form of submarine cable breaks and displaced faunas to conclude that such phenomena exist. While turbidity currents have been credited with carrying sediments over 160 km. from their place of origin (Lovell, 1969, p. 936), the distance of transport will depend on the impetus which initially triggered off the turbidite, the distance and inclination of the slope or shelf edge down which the turbidity current has to flow, and both the density of the current and the density of the water through which it flows.

b. *Current direction.* Recent observations at South Georgia on current directions have demonstrated their great complexity and have suggested that, although there was no proof of directly opposed currents, there was also no regional palaeocurrent trend. Because of this, it may be difficult to explain gravity-driven palaeocurrents originating from a single source area as a predominantly southerly flow direction at Grytviken and a northerly flow direction at Leith Harbour has been observed (Frakes, 1966). Indications of longitudinal flow along the trough may show the influence of an inter-basin ridge rather than demarcation of a northern margin of the trough (Dzulynski and others, 1959; Frakes, 1966).

At Point Abrahamsen, Prince Olav Harbour, flute casts suggest an east to north-east source for the sediment (Plate IIb). Extensive groove casts at the same locality (probably produced by laminar flow during the later, more quiescent stages of earlier turbidite sequences), and small-scale current bedding in the mudstones show similar current directions. McBride (1962, p. 58) concluded that the flute casts in the flysch of the Martinsburg Formation were earlier than the groove casts in the same sequence, whereas Dzulynski and Sanders (1959) believed that flute and groove casts were dependent on the load-flow regimen and that there was no age relationship between them. In Plate IIb the groove casts pre-date the flute casts and also indicate a difference in current direction.

Turbidity-current deposition undoubtedly accounts for much of the Cumberland Bay Series, but the occurrences of dumbell-shaped Domichnia and intensive bioturbation of the upper few centimetres of some mudstones suggest periods of prolonged quiescence.

The most reliable palaeoslope indication on directional data from intrastratal deformation suggest that the location of the sedimentary basin was to the north-west and that the palaeoslope shelved in that direction. Exposures in Right Whale Bay, in the north-western part of the island, show minor slumping from a southerly direction (Trendall, 1959, p. 6 and 7, figs. 2 and 3). However, at Prince Olav Harbour, elongated load casts indicate a north-westerly dipping palaeoslope, whereas the groove casts suggest a palaeocurrent flow from the east to north-east, all of which may indicate inconsistencies in palaeoslope direction within the basin during phases of its depositional history.

c. *Turbidity currents*. The criteria established by Kuenen (1953, 1964, p. 16) as characteristic of ancient turbidites indicate the Cumberland Bay Series sequences are a thick succession of this type of sediment (Trendall, 1959, p. 9). The "idealized" five-part turbidite sequence (Bouma, 1962, p. 49) is uncommon and compares with only about 10 per cent of the beds examined by this author from the Piera Cava flysch of France. Incomplete sequences (e.g. base absent, truncated or top absent, or middle absent) or repetition due to pulsation of individual currents are more common (Plate IIc). The terminology used here has been modified from that of Walker (1965), who amended Bouma's (1962) terminology. The complete "idealized" five-part sequence of units is illustrated in Fig. 12.

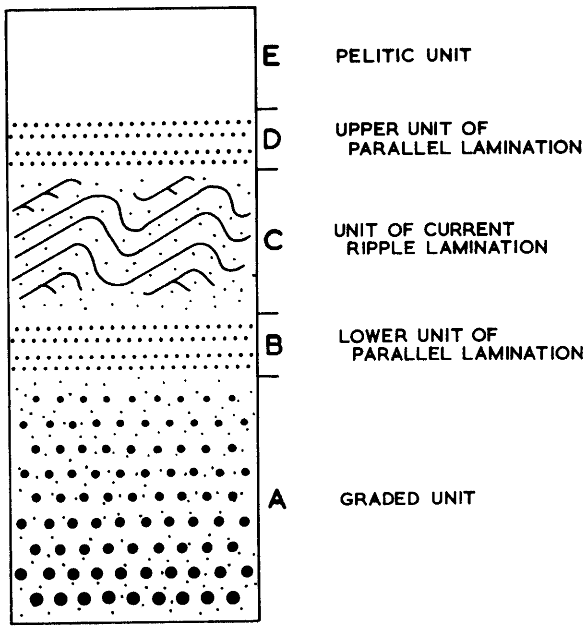


FIGURE 12

A complete "idealized" turbidite sequence (after Walker, 1965, p. 2).

In the Cumberland Bay Series, the graded unit stratum is generally massive with variable amounts of matrix with a distribution of clasts of all sizes, but grading is not always present. Grading suggests that these particular beds were deposited by "autosuspension"* from a low-velocity turbidite (Walker, 1965).

Ungraded greywacke beds suggest sudden cessation of movement and instantaneous deposition of sediment (possibly caused by an abrupt termination in the impetus). Walker (1965) suggested that this indicated a "high-shear" factor in a "traditional" current with a traction carpet (fluidized sediment mass). Sudden "freezing" of a high concentration of dispersed grains occurs when the movement causing shear becomes insufficient to keep them in motion. Where a current is just capable of transporting its entire load in suspension, it lacks sufficient energy to scour the bottom (Dzulynski and Sanders, 1959). As these "saltation carpets" prevent turbulent eddies in the higher part of the flow from eroding the lutite substratum, Dzulynski and Sanders (1959) inferred that scour marks were produced by currents whose entire load was in suspension and which possessed sufficient excess energy (in the form of turbulent eddies) to abrade the surface over which it flowed. Mixed scour and impact marks further suggested saltating fragments were present, while impact marks on the substratum indicated the presence of a thin "saltation carpet".

The lower unit of parallel lamination comprises parallel laminae of coarser and finer (pelitic) material (Bouma, 1962) and probably represents re-working of the upper parts of a graded bed, an upward increase in grain-size indicating primary current deposition (Walker, 1965).

In the Cumberland Bay Series this unit is occasionally absent or represented by another graded bed due either to two turbidity currents or to the splitting of a low-density turbidity current, the denser part traversing the sea floor, while the lighter part moves over the denser part and extends beyond it.

In the unit of current-ripple lamination true cross lamination was not observed in South Georgia but some of the convolute lamination may represent deformed ripple marks (Plate IIId). Convolutions, which are confined to the upper parts of each unit, are rarely uniform in amplitude and may form slight undulation to isoclinal "folding". The origin of convolute lamination is usually attributed to synformational or post-depositional sliding of semi-mobile sediments in a water-saturated state, the impetus often being motivated by seismicity or volcanicity in the vicinity of the sedimentary basin. Ten Haff (1956, p. 192), in discussing intricate small-scale lamination, suggested that convolute lamination was distinct from slumping and not directly conditioned by the slope, and that the trend or the alignment of the convolutions, if marked at all, would not be related to the current direction and might be either longitudinal or transverse to the strike of the depositional slope.

Within this same unit there are further sedimentary features which, like the convolutions, may be attributed either to current rippling on a water-saturated bed (Kuenen, 1953) or post-depositional intra-stratal flow.

Prehnitized pseudo-nodules (Plate IVa), probably formed by differential loading and earthquake shocks, occur at several horizons; the "white weathering" is the prehnite essentially replacing the matrices.

The upper unit of parallel lamination in the Cumberland Bay Series rarely occurs. The absence of the laminae may be due either to a lack of mixed silt and mud in the current after depositing the current-ripple unit, or to differences in the settling velocities in the wake of the turbidity current which may inhibit segregation of the mixed sediment (Walker, 1965). Occasionally small-scale current bedding occurs in this unit, as at Prince Olav Harbour where the current flowed from an easterly direction.

Predominantly structureless siltstones of the pelitic unit, probably deposited during a relatively quiescent period after cessation of the turbidity current, occur through the succession. The upper parts of this unit represent a period of normal pelagic sedimentation in the basin, and small procerithiid gastropods (identified by M. R. A. Thomson as *Rhabdocolpus* (Plate IVb)) and trace fossils are present.

2. *Sedimentary structures*

a. *Load structures.* Linguiform load casts and asymmetrical flame structures occur at Pig Point, Prince Olav Harbour. The overturning of the flame structures towards the west suggests interstratal down-slope creep in this direction.

* "Autosuspension" has been described by Walker (1965): "If the power expended by gravity directly on the sediment in suspension over an inclined bed exceeds the power expended by the fluid in supporting the suspended load, the suspended grains impart energy to the fluid and cause it to flow faster."

b. *Injection structures.* Only two sandstone dykes have so far been recorded at South Georgia, one at Right Whale Bay (Trendall, 1959, pl. Ic) and the other at Lighthouse Bay, Prince Olav Harbour. The latter, although not completely exposed, probably represents an injection structure as it is tabular and straight-sided. The 20 cm. wide dyke, which strikes due south, cuts approximately 30 m. of country rock perpendicularly. The straight-sidedness of the walls suggests that the host rocks were almost completely consolidated before intrusion took place, possibly into a pre-existing joint system or fault plane. No source bed was observed.

Where the dyke cuts the more argillaceous sediments near the top of the exposure, the harder dyke rock protrudes as a wall. This dyke was only superficially examined because of the difficulty of access, but no internal structures were found and there is no apparent orientation of the clasts of the dyke rock sampled. However, the dyke rock is finer-grained and has a higher percentage of partly prehnitized volcanic clasts than the host sediments, which are almost vertical-standing at this locality. Sandstone dykes are frequently associated with an unstable environment, characterized by extensive slumping and earthquake shocks (Bailey and Weir, 1932; Dzulynski and Walton, 1965).

c. *Sole marks.* Most of the sole marking is in hypo-relief because of the relatively steep dip of the beds (Plate IIb). In this plate the grooved and fluted horizon strikes 112°, dips at 84° to the south and is overturned. The current direction was west-north-west.

d. *Calcareous concretions.* In many of the thicker, undifferentiated coarse sandstones of the "idealized" turbidite sequence, large calcareous "cannon-ball" concretions with well-defined margins occur (Plate IIIa). The concretions, which are less common within the upper laminated and pelitic units, are particularly abundant at Prince Olav Harbour. They are similar in colour to the host rock, between 10 cm. and 1·5 m. in longitudinal section, are ellipsoidal and flattened in the plane of the bedding.

A thin section showing bedding planes passing through one of the concretions suggests that this specimen (and probably most of the others) was post-depositional and diagenetic in origin, and distortion of the bedding around the concretion is probably due to differential compaction.

Concretions contain approximately 60 per cent calcite partly masking a characteristic volcanic greywacke texture similar to that of the matrix rock, which contains only a small amount of calcite. X-ray diffractometer analysis on the concretions shows that the carbonate is entirely calcite. At least one of the concretions contains a lamellibranch shell as an organic nucleus (Plate IVc), but other larger concretions broken open in the field contained no obvious nuclei. The concretions do not protrude from their matrices but weather out leaving ellipsoidal hollows.

In south-eastern Alexander Island, similar "cannon-ball" concretions occur in massive sandstones and have been described from other circum-Pacific successions which show lithological, faunal and structural similarities to the Cretaceous succession in Alexander Island (Horne and Taylor, 1969).

Bedded limestones are not present in the Cumberland Bay Series, and so the carbonate forming the concretions may have been produced by CO_2 (released by energetic bacterial activity) combining with water to produce carbonic acid and ultimately soluble bicarbonates (Chilingar and others, 1967). These bicarbonates may have been precipitated as insoluble carbonates around nuclei which were already alkalized due to the release of ammonia from the decomposition of organisms or amines (Weeks, 1953).

The modes of calcareous concretions and their matrix rocks from the Cumberland Bay Series, with a comparison of two from Alexander Island (Horne, 1967), are given in Table II. The calcite modes for those from South Georgia show a variability in the increase in concentration of nucleated calcite over the matrix, possibly reflecting the influence of differing diagenetic conditions within the sediment during the formation of the nodule. The modes calculated by Horne (1967) for two concretions from feldspathic sandstones of Alexander Island each show a five-fold increase in the percentage of calcite over that of the matrix rock, suggesting greater stability of the post-depositional environment.

An etched thin section (column 1) of the calcareous concretion (column 2) illustrates the normality of the matrix rock, and the apparent masking created by the nucleation of calcite. Plate IIIb demonstrates this and the homogeneous nature of a "cannon-ball" concretion, because both the concretion and its matrix rock are cut by a quartz-filled tension gash with no apparent variation at the contact.

e. *Bleached aureoles.* Discrete pelitic fragments, which occur more frequently in the pelitic units, are often but not always surrounded by distinct bleached aureoles 2–3 cm. wide (Plate IVd). In thin section the pelitic fragments appear to be unaltered and are generally very dark, essentially of silt or mudstone composed of minute polycrystalline quartzite with occasional micas, feldspar microlites and

TABLE II

COMPARISON OF "CANNON-BALL" CONCRETIONS AND THEIR ENCLOSING MATRIX ROCK FROM THE CUMBERLAND BAY SERIES, SOUTH GEORGIA, WITH A SIMILAR TABLE BY HORNE (1967) ON CONCRETIONS FROM A SANDSTONE SEQUENCE IN ALEXANDER ISLAND

Constituent minerals	*Modal analyses of some "cannon-ball" concretions from the Cumberland Bay Series, South Georgia*						*Constituent minerals*	*Modal analyses of "cannon-ball" concretions and their matrix sandstones from Alexander Island (Horne, 1967)*			
	Prince Olav Harbour		*Stromness Bay area*								
	1	2	3	4	5	6		7	8	8	10
Quartz	tr.	0·5	2·5	0·3	0·3	0·3	Quartz	19·0	12·3	18·3	13·3
Feldspar	5·5	4·4	6·9	0·9	4·2	7·1	Feldspar	55·6	26·3	53·3	44·7
Prehnite	1·3	1·1	2·5	1·3	1·0	tr.	Prehnite	9·3	2·4	–	–
Volcanic fragments	57·9	28·1	30·7	17·2	24·3	41·9	Rock fragments	2·8	1·0	16·4	–
Sedimentary fragments	–	–	–	–	–	–	Muscovite	–	–	0·4	–
Matrix	32·1	–	56·3	–	27·9	–	Biotite	2·1	2·4	8·5	10·1
Chlorite	–	0·7	1·2	–	–	5·9	Chlorite	1·2	0·8	1·2	11·0
Epidote	–	–	tr.	tr.	–	–	Hornblende	–	–	–	13·5
Opaques	0·5	0·5	tr.	0·3	0·1	0·5	Opaques	–	–	0·5	–
Calcite	2·6	66·0	–	80·3	42·0	47·2	Calcite	10·1	55·0	1·4	7·5

1. M.220.1 Etched and stained concretion.
2. M.220.1 Concretion.
3. M.155.1 Matrix rock.
4. M.155.2 Concretion.
5. M.167.2 Concretion.
6. M.172.2 Concretion.
7. KG.51.6 Matrix.
8. KG.51.7 Concretion.
9. KG.70.13 Matrix.
10. KG.70.14 Concretion.

probably fine-grained graphite, giving a turbidity to the matrix. Epidote and authigenic pyrite were found in some sections, although prehnite may be absent, or present as sparse discrete spheroids or as an almost complete incipient development masking the sedimentary texture.

The amount of carbon present as graphite obscuring the matrix, or idiomorphically developed authigenic pyrites, suggests an alkaline reducing environment within the exotic pelitic fragment. Thus the aureoles may well have developed in a similar manner to that of the nucleation of calcite in the development of calcareous concretions (Weeks, 1953). In both occurrences, prehnite has developed in association with calcite, and it seems likely that the high proportion of available calcium led to the prehnitization during burial metamorphism.

Irregular intercalation of exotic muddy fragments or "pull-apart" structures with a less distinct aureole occurs in some of the pelitic units, whereas occasionally an aureole or bleached margin exists in slightly coarser sediment at the contact of one stratum with another. The aureole is predominantly calcareous but, unlike nodular concretions, it is about the same hardness as the matrix rock. Calcite usually forms in isolated tabular rhombs with strong cleavage development, and prehnite is almost always present as patchy incipient aggregates or as a discrete amoeboidal development of low-birefringent exolved quartz and prehnite, principally nucleating around calcite; this suggests subsequent authigenic development from the calcite and other aureole silicate minerals. However, Dickinson (1962, p. 498) considered that the prehnitization and re-mobilization of sediments indicated that connate water released by thixotropic liquification may have acted as a catalyst and transporting agency for the migrating lime which probably derived from the break-down of detrital plagioclase and clay minerals in the sedimentary matrix.

V. PALAEONTOLOGY

INVERTEBRATE fossil remains from the Cumberland Bay Series exposed on the north-east coast of South Georgia are rare, whereas carbonized wood, trace fossils (mainly *Chondrites*) and micro-fossils are more common.

1. *Invertebrates*

Eight small gastropods were collected at the south-west corner of Lighthouse Bay, Prince Olav Harbour (Plate IVb). M. R. A. Thomson (personal communication) examined this material and concluded from their small size, turriculate shell form and coarse axial ornament that they had affinities with the procerithiid *Rhabdocolpus* Cossman, which is Lower Triassic to Lower Cretaceous in age. The South Georgian specimens differ from *Procerithium* (*Rhabdocolpus*) sp. from Crabeater Point, east coast of the Antarctic Peninsula (Thomson, 1967, p. 6, fig. 3a and b) in having a narrower mean spire angle, fewer and straighter axial costae and in possessing a median spiral chord. Of closer affinity is probably *Cerithium greenhoughensis* (Moore, 1870, p. 256, pl. X, fig. 22) from the Middle Jurassic of Western Australia.

Other invertebrate remains include a recrystallized (?) lamellibranch shell in a "cannon-ball" concretion (Plate IVc), broken echinoderm plates and fragmentary Porifera. These are too sporadic in distribution to be of value in determining either the age or palaeoecology of the sediments.

2. *Trace fossils*

Trace fossils are common in the upper parts of some pelitic units, and they are often well-exposed as radiating clusters or dendritic branching systems in rounded pelitic beach boulders and pebbles. More rarely they occur along weathered joint planes in slate as pinnate structures with a slight micro-relief. The radiating and dendritic structures are probably those of *Chondrites*, produced either by a siphunculoid worm with a single extendable proboscis (Simpson, 1957) or by an animal with many tentacles (Taylor, 1967). Larger, attenuated prehnite-filled bioturbation structures, probably representing the Domichnia of *Planolites* sp. (a cosmopolitan ichnogenus of worm trails), are similar to those from the Upper Cretaceous Fort Hays Limestone Member of the Niobrara Chalk (Frey, 1970, pl. 5, fig. 3b). As most of these burrows were probably open at the surface, the uppermost few centimetres of the sea bed were re-worked by the organism during a period of quiet sedimentation (Plate IVe).

Dumbell-shaped Domichnia of *Arenicolites*-like organisms are commoner and occur at several separate horizons in the succession at Prince Olav Harbour.

3. *Carbonized wood*

A specimen of poorly preserved fossil wood was collected from loose debris during the Shackleton–Rowett "Quest" Expedition, 1921–22 (Gordon, 1930, p. 21). The fossil wood was identified as *Dadoxylon* (*Araucarioxylon*), suggesting that the sediments were not older than Carboniferous and not younger than Jurassic (Gordon, 1930).

At Harbour Point (Fig. 2), fragments of a somewhat compressed (?) carbonized wood were collected, the largest being 6 cm. wide and over 8 cm. long. Crude but regular longitudinal striations, probably representing fibres, are visible.

4. *Micro-fossils*

Several specimens of siltstone and poorly cleaved slate were macerated in hydrofluoric acid, followed by washing and gravity separation in zinc bromide solution. The light-fraction residue was stained with safferine dye, mounted in glycerine jelly and examined for microscopic organic debris. Broken organic material was abundant but no recognizable micro-fossils were found.

However, in several thin sections, minute spherical bodies (15–20 μm. in diameter) are common and these unornamented spherules are, on the basis of their small size, considered to be algal in origin (Plate IVf). Somewhat similar spherules in the Precambrian Fig Tree Formation of South Africa have been compared with coccoid blue-green algae (Barghoorn, 1971, p. 34).

Radiolaria, recrystallized by quartz or authigenic prehnite, are occasionally found in the slates. Gregory (1915), recording Hinde's observations concerning eight fossil Radiolaria genera from Cape

Paryadin, considered ". . . that they are post-Palaeozoic and pre-Tertiary in age, and that they might come in between the Triassic and the Cretaceous". Due to their poor preservation and the wide faunal range, these Radiolaria cannot be used for dating the Cumberland Bay Series.

VI. STRUCTURE AND TECTONICS

A. Tectonics and the Relationship between the Sandebugten Series and the Cumberland Bay Series

Trendall (1959) observed that the folding in the Cumberland Bay Series becomes less intense in the south-western parts of the island, where massive lavas have been intruded along the flow planes of previously extruded pillow lavas. Both lavas are found together at Undine South Harbour, but only the massive lavas (which are also spilitic) are interbedded with deep-water sediments at Annenkov Island. Both lavas are thought to have a common origin because of their petrographic and field associations. They are widespread and form much of the continental shelf, giving rise to an area of magnetic anomaly patterns south of Annenkov Island (Fig. 7).

Trendall (1959, p. 42) stated that the major period of folding is unknown, except that it is post-Aptian; he was of the opinion that the intrusive complex in the south-east of the island is paratectonic (Fig. 11) because there is marginal foliation in the acid rocks at the north-east edge of the complex. Also, some chlorite in the chloritic phyllites near the contact margin is bent and some not, implying that there were suitable pressure and temperature conditions for the crystallization of chlorite both before and after movement during the tectonic phase. However, the order of intrusion within the complex is far from clear. The dykes are post-tectonic but they are partly affected by some later faulting and shearing in the area north-west of Cooper Bay. The dykes which trend north-east to south-west are later than those trending north-west to south-east. Their petrography is comparable with that of the pre-tectonic lavas and, like the lavas, they are only present in the less deformed rocks, so that dyke injection and deformation by folding appear to have been mutually exclusive.

The contact between the Cumberland Bay Series and the Sandebugten Series is strongly discordant. It is either an unconformity or a thrust fault, or a combination of the two, because the folding of the beds above and below the contact is dissimilar. The Cumberland Bay Series rocks are overfolded from the south-west, whereas the tightly folded Sandebugten Series immediately below the contact probably belongs to part of the north-east limb of an anticlinorium. The strike of the axial planes of the anticlinorium in the Sandebugten Series and of the Cumberland Bay Series appears to be sub-parallel, trending north-west–south-east. Because the dip of the plane of discordancy is about 45° to the north-north-east, thrust along such a plane would have been expected from a north-north-easterly direction. However, the Cumberland Bay Series has been overfolded from the south-west and it seems unlikely that the whole plane has been tilted from dipping slightly to the south-west through at least 50° to dip at about 45° to the north-north-east.

If the contact is an unconformity, it should have been folded when the Cumberland Bay Series was folded. It does not show folding of similar intensity to that in the Cumberland Bay Series, nor is there any folding above the contact in the bottom 100 m. of the Cumberland Bay Series. No basal conglomerate, mylonite or fault breccia has been recorded, but there is evidence of some shearing movement as strong undulating cleavage is present above the contact. Aitkenhead and Nelson (1962) concluded that the "unconformity" represents a long pause in deposition and that the Sandebugten Series must have been folded and considerably eroded before the deposition of the Cumberland Bay Series.

B. Regional Structures

The Cumberland Bay Series has possibly undergone one major period of folding which has been followed by a minor tectonic phase resulting in faulting and a fracture cleavage trending north–south, nearly at right-angles to the strike of the fold axes. It may also have been responsible for the tightening observed in some folds and local undulation in the sub-horizontal plunge of the fold hinges.

1. *Regional folding*

There is considerable local variation in the fold dimensions but generally little regional change of type of folding within the areas examined (Figs. 2 and 4). Reports by Trendall (1953, 1959) and Aitkenhead and Nelson (1962) suggested that, except in the vicinity of the intrusive complex in the south-east of the island, the folding present in the Stromness Bay and Prince Olav Harbour areas is typical (although overfolding may not be so marked) of the forms present in South Georgia.

The Cumberland Bay Series folds are moderately inclined, open-to-close, asymmetrical, deformed, concentric and similar, with usually a slight inversion of the shorter limb (Fig. 13). There is an inconsistent dip of the axial plane between 40° and 60° in a south to south-westerly direction, although locally it may become steeper. The major folds are frequently characterized by small parasitic folds but occasionally complex disharmonic folding is present. Measurement of the asymmetrical fold dimensions across the strike at Stromness Bay and Prince Olav Harbour shows that the limbs are of unequal length and symmetry, indicating irregular (disharmonic) folding, but with similar axial-plane dip which is probably a characteristic in South Georgia. The disharmonic folding is more notable towards the north-east coastline away from the direction of overthrow. It is absent from the highest and basal parts of the Cumberland Bay Series (Trendall, 1959) and possibly represents intraformational deformation on the margins of a tectonic area.

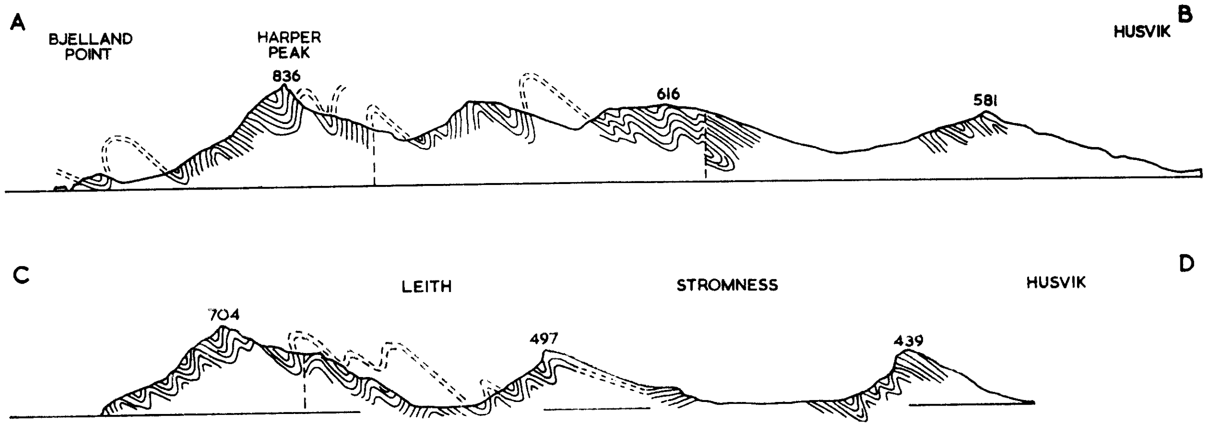


FIGURE 13

Sections A–B and C–D (Fig. 2) demonstrating the relationships betwen Leith, Stromness and Husvik Harbour embayments with flat-lying or gently dipping strata and the steeply dipping beds of the inter-valley ridges with major overfolds and the associated chevron and the parasitic folding (C–D). The unequal limb dimensions and symmetry are clearly shown, as is the inconsistent dip of the axial-plane cleavage across the section (A–B).

Large-scale complex disharmonic folding, similar in appearance to intraformational slumping, occurs due north of the Prince Olav Harbour whaling station (Fig. 14, A–B). Although no thrust plane is visible, movement was possibly due to tectonic loading on vertical sediments of the shorter overfolded limb, but it is unlikely that there was fluidity of the rocks under high confining pressure because tension gashes indicate brittle folding and fracture of some of the sediments.

The slight westerly regional plunge observed in the folds at Prince Olav Harbour are more marked at Stromness Bay; indefinite lineation data suggest about 5–14° to the west-north-west. The minor tectonic phase resulting in the north–south fracture cleavage and vertical faulting may have given rise to an undulation of the plunge.

2. *Cleavage*

Axial-plane cleavage is syntectonic with fold formation. It is not present in the graded greywacke units but occurs frequently as slaty cleavage in thinner pelitic units where it may be pronounced and intensively developed at the interface with a more competent greywacke stratum.

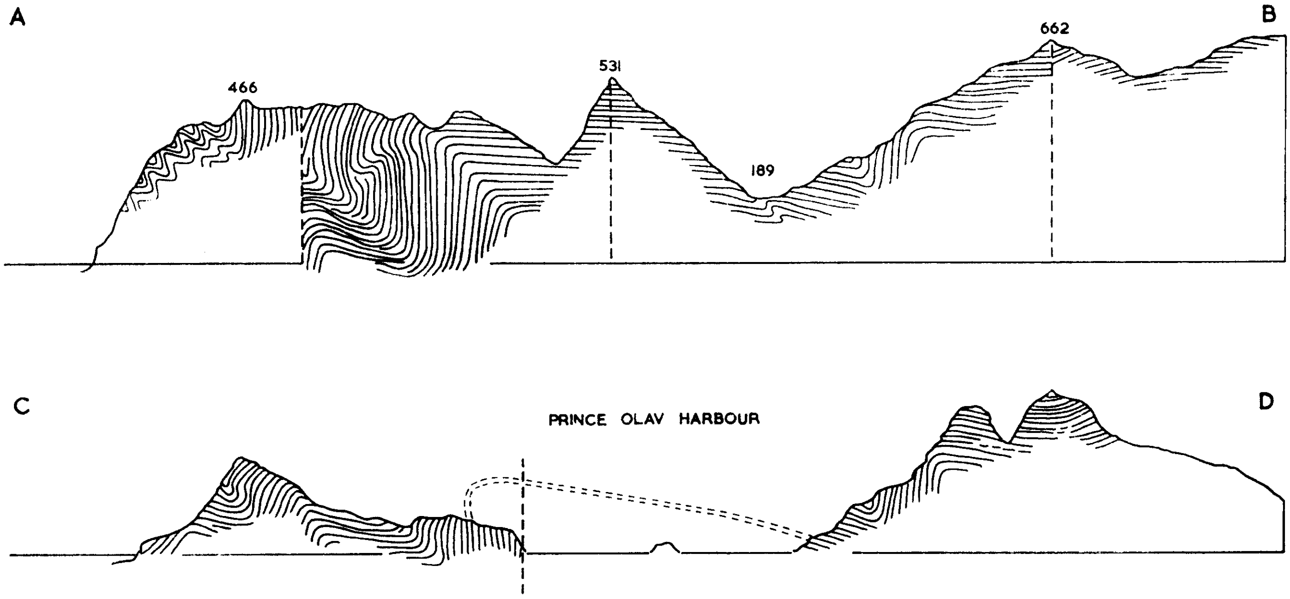


FIGURE 14

Sections A–B and C–D (Fig. 4) illustrating the irregular folding with locally variable axial-plane dip (southerly at about 45°), parasitic folds, chevron folds and the configuration of a large intraformational slump fold occurring in the ridge north-west of the Prince Olav Harbour whaling station.

The change in the strike of the axial-plane cleavage between Stromness Bay (Fig. 3) and Prince Olav Harbour (Fig. 5) is very slight but it is clearly shown on the stereographic plots of poles to dip of axial-plane cleavage (Fig. 15). These clearly show from axial-plane cleavage (crosses) that the Cumberland Bay Series has undergone only one phase of folding. At Stromness Bay, axial-plane cleavage strikes approximately 315° true, dipping south-westerly at about 37°, whereas at Prince Olav Harbour it strikes about 290° true, dipping southerly at about 45°. The variation in strike of the structural trend is reflected in the general arcuate outline of South Georgia.

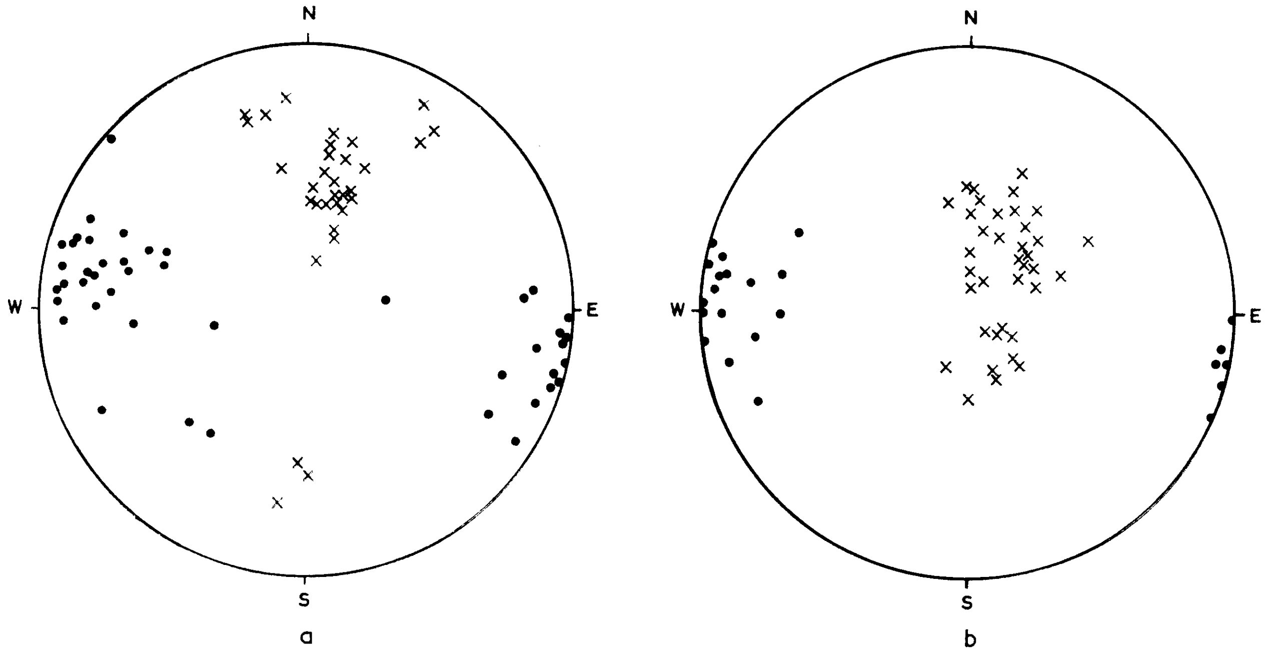


FIGURE 15

Stereographic plots on the southern hemisphere of poles to dip of cleavage planes. Poles to dip of axial-plane cleavage (crosses); poles to dip of fracture cleavage (solid circles). a. Prince Olav Harbour; b. Stromness Bay area.

The fracture cleavage (solid circles) strikes about 015° true and has a consistently high dip, but more to the east than the west in both areas. The easterly dominance may be increased at Stromness but there are too few points to confirm a relatively greater dip.

The intersection of axial-plane cleavage and bedding was rarely observed, but poorly preserved lineation in silty slates at Prince Olav Harbour gave a westerly plunge of 9°.

A probable minor post-tectonic phase resulted in the prominent north–south jointing and almost vertical fracture cleavage. The cleavage is infilled with vein quartz. Quartz veinlet swarms (some of which show anastomosing bifurcation) trend north–south and occasionally develop in massive greywackes which have been under high stress usually in the vicinity of but not at the apices of folds.

3. *Small-scale folding*

Frequently, small discrete parasitic folds with a short-limb length of 2–3 m. develop near major fold hinges. Thrusting sub-parallel to the dip of the axial-plane cleavage may merge into the bedding, and this is expressed by shearing in the more competent rocks and by parasitic folding in less competent sequences.

Intraformational chevron folding, a characteristic of beds of similar thickness and competence is occasionally developed in the shorter limbs of overfolded strata. Axial-plane dip of the chevron folding is parallel to that of the major overfold, and shows consistency in the axial-plane separation of about 75 m. at both Hercules Bay (Stromness Bay) and at Cape Wilson (Prince Olav Harbour). The limbs are typically straight-sided and of equal length with sharp equi-angular apices, and an absence of axial-plane faulting.

4. *Jointing*

Jointing is minor but occasionally in some of the massive greywackes and pelitic units two sets of steeply dipping joints trend parallel to the vertical north–south fracture cleavage. In the more competent beds, especially near fold apices, quartz-filled sigmoidal gash veins demonstrate that the rocks underwent either post- or syntectonic movement. Numerous straight tapering gashes, nearly normal to the dip of the bedding, are of irregular appearance and indicate tensional stress in the *b–c* plane of the deformation ellipsoid due to continued or renewed movement of the beds. At Prince Olav Harbour, horizontal zones of easterly dipping *en échelon* tension gashes have developed in a vertically dipping pelitic stratum, thereby suggesting post-tectonic deformation due to some longitudinal stress possibly during tightening of the folds. Later steeply dipping joint planes (trending parallel to the fracture cleavage) have cut the *en échelon* tension gashes (Plate IIIb).

5. *Faulting*

Small thrust faults with a displacement never more than a few metres, which are sub-parallel to the axial plane and merge into parasitic folds (Plate IIIc), are the result of shear due to the tightness of the major overfolds. Field relations of adjacent strata in a cliff exposure at Stromness (Fig. 2) suggest normal faulting trending north–south with successive downthrows of 3–5 m. to the east, but no data could be obtained at others, such as at Prince Olav Harbour, where a vertical to easterly dipping normal fault post-dates the main period of folding because it cuts a parasitic fold at Lighthouse Bay. It is clear that there is an association between the prominent north–south-trending fracture cleavage, jointing and faulting, and a possible relationship of both with tightening of fold axes and the apparent slight undulation in the regional plunge of the fold hinges.

VII. SEDIMENTARY PETROLOGY

A. Petrology of the Cumberland Bay Series

1. *Discussion of the term "greywacke"*

The term "greywacke" is open to much discussion because it has been used to describe both a rock type and a texture. A typical greywacke from the Devonian and early Carboniferous rocks in the Harz mountains of Germany is characterized by 25 per cent or more unstable fragments, containing feldspar grains and sand-sized rock fragments, and an interstitial matrix 15 per cent or more, present as an alternative to mineral or chemical cement normally present in sandstones or arkoses. Pettijohn (1957) considered that texture has the most definitive property because it distinguishes a greywacke from other sandstones. A fresh rock is notably dark in colour with a preponderance of matrix and, because of a random distribution of extremely angular quartz and feldspars, the term *micro-breccia* would seem more appropriate.

Cummins (1962) pointed out that there has been difficulty in precisely defining a greywacke because different arbitrary size and percentage limits for the matrix have been taken in defining greywackes. Matrix is the distinctive characteristic of a greywacke and most workers agree that a sandstone becomes a greywacke when there is about 10–15 per cent matrix present, irrespective of the texture *or* nature of the fragments in the matrix, and the mode of origin. Thus the term "greywacke" is very broad and covers a wide variety of texturally similar rocks of varying and complex mineral composition. The precise location of the boundary between one greywacke type and another, and also of other rocks of similar appearance, can be rarely deduced in the field, but the fact that they are at once obvious in the laboratory led Dickinson (1970) to suggest the restriction of the term to field use only.

2. *Petrogenesis of a greywacke*

Cummins (1962) pointed out the problems involving the petrogenesis of greywackes and considered that most authors accepted that the fine-grained matrix of greywackes is an original detrital feature resulting from turbidite cement deposition. Although Kuenen and Migliorini (1950) have shown from experimental methods that a turbidity current could be responsible for some typical greywacke characteristics, Cummins demonstrated that turbidity currents can produce the characteristic grain-size distribution of a greywacke. He stated that greywackes differ from other sandstones in having a peculiar grain-size distribution. Cummins (1962) showed the relative abundance of greywackes over arenites with increasing age, and he illustrated the different grain-size distribution patterns of other sandstones and greywackes, from which he concluded that it was clear that the ancient greywacke turbidites formed distinct patterns compared with all other turbidites, including Kuenen's experimental ones. Cummins stated "a major difficulty with any hypothesis involving detrital origin for the characteristic greywacke matrix is the failure to find a modern sediment of the greywacke type". Thus he suggested that the formation of a greywacke was a diagenetic process and concluded that modern sediments of comparable origin, whether found in nature or deposited experimentally, were not greywackes. Thus a greywacke texture was a problem of post-depositional cementation and not sedimentation. Hawkins and Whetten (1969) tested Cummins' (1962) post-depositional hypothesis and concluded that a greywacke texture possibly occurred when chemically unstable components of an immature sediment are hydrated and recrystallized to produce interstitial hydrosilicates and zeolite matrix minerals. By using river-bed sediments of similar mineral and chemical composition to a greywacke, they were able to synthesize matrix minerals at conditions equivalent to 3–4 km. burial and at geothermal gradients equivalent to 60–80° C/km. These results supported the hypothesis but they added that it could not be implied that all greywackes are formed in this manner. It is also unlikely that such secondary products could be naturally produced in modern sediments even if they are mineralogically and chemically similar, and thus the ancient turbidite greywacke texture is characteristic and probably formed as a result of burial metamorphism.

3. *Classification of the volcanic greywackes of the Cumberland Bay Series*

Folk (1959, p. 122) regarded the mineralogy of a greywacke to be completely controlled by that of the source area, and that its maturity depended on the time lapse and conditions of the differing environments through which the bulk passed before deposition. There seems little cause to doubt that the characteristics of the sediments in the Cumberland Bay Series are consistent with those he outlined for a eugeosynclinal basin. The term greywacke is used in the sense defined by Pettijohn (1949, p. 244) but, in preference to using the misleading term "tuffaceous", the more suitable term "volcanic" is used throughout. Tuffs and related rocks are of an explosive volcanic origin (Pettijohn, 1957) where subaerial ejectamenta form pyroclastic deposits. In "tuffaceous" greywackes, even after a period of devitrification and alteration, pyroclastic shards, threads, cusps and vesicles might be expected to appear. However, such materials are virtually absent from thin sections of the Cumberland Bay Series and, because of the sub-angular to sub-rounded epiclastic volcanic content, the term "volcanic" is used.

a. *Classification.* After a review of the literature (Pettijohn, 1957), the minerals of the average greywacke are mainly of quartz and feldspar. It may have a varied assemblage of unstable materials (25 per cent or more) including both feldspar grains and sand-sized rock fragments, with interstitial matrix (15 per cent or more) which takes the place of the chemical or mineral cement, characteristic of normal sandstones. Lithic greywackes contain a greater proportion of rock fragments than feldspar and may be specified according to the particular types of rock fragments for instance, the volcanic greywackes of South Georgia. The extremely low proportion of detrital quartz is characteristic of the volcanic greywackes of the Cumberland Bay Series.

The main detrital constituents are epiclastic microlitic volcanic fragments, discrete feldspar laths now predominantly albitized, and probably only a small amount of matrix material, notably siliceous resistates. Accessory minerals are possibly detrital epidote, occasional mafic fragments, sphene, apatite and possibly zircon. Calcite, prehnite, penninite, authigenic epidote and pyrite are products of low-grade burial metamorphism. Other rock fragments are uncommon but occasionally polycrystalline sutured quartzite and slaty fragments occur. Therefore any classification must be based only on detrital modes of volcanic fragments, feldspars and matrix. Fig. 16 illustrates a suggested scheme, which could be used for any quartz-deficient greywacke where detrital volcanic fragments constitute a characteristic member.

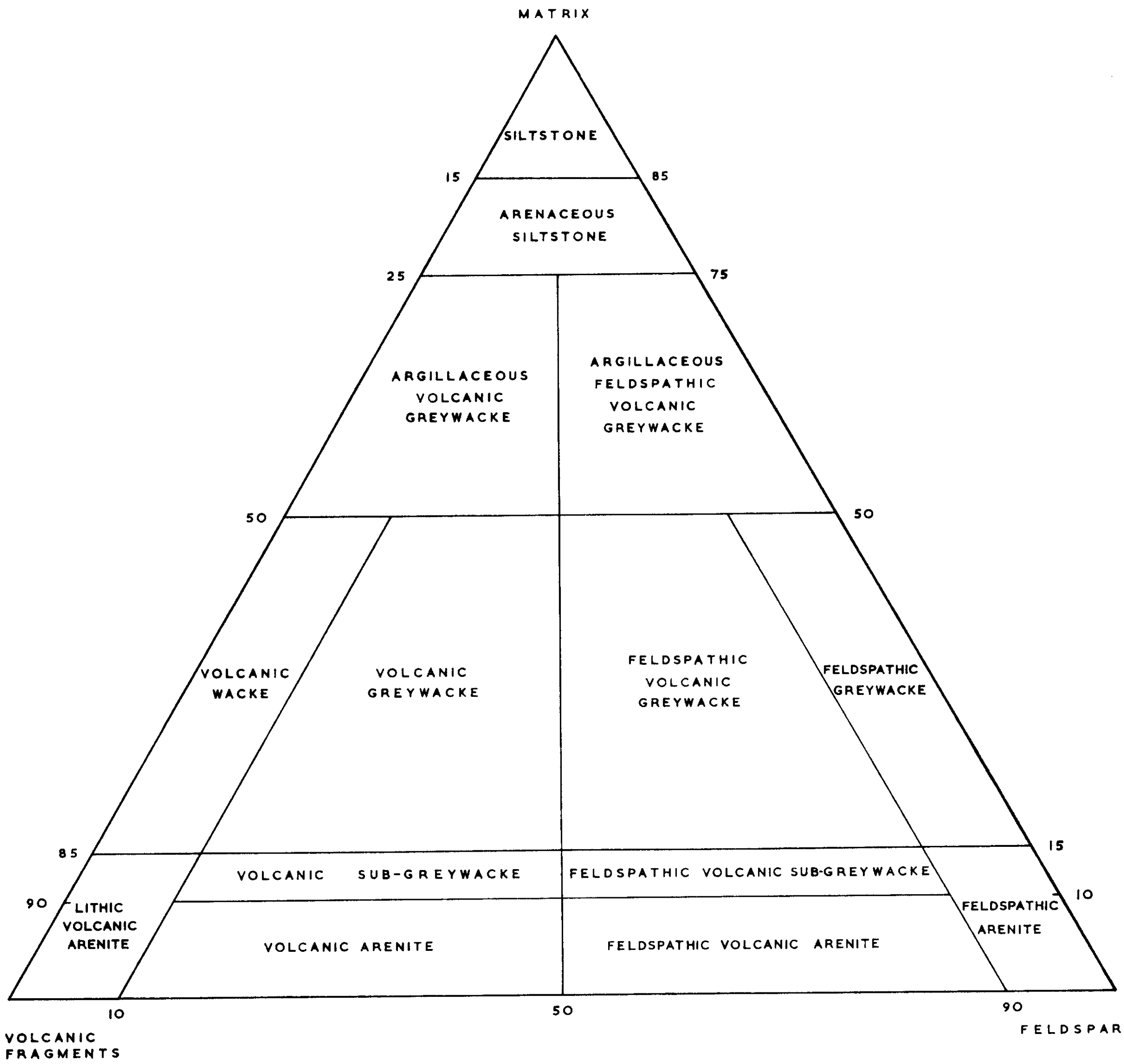


FIGURE 16

Proposed scheme for the classification of the volcanic greywackes of the Cumberland Bay Series, based on detrital modes.

Classification by textural grouping in addition to modal percentages is largely unrealistic because by definition a greywacke implies considerable textural variation. Cummins (1962, p. 67) showed a restriction of textural variation in ancient greywackes which, if superimposed on a simplified diagram of major textural groups (Folk, 1954, p. 349, fig. 1b), shows a restricted field comprising predominantly sandy mud (10–50 per cent mud) and a muddy sand (15–50 per cent mud in coarse sand) (Fig. 17). As there may be considerable composition variation within a greywacke unit (i.e. due to graded bedding), such a textural description is largely academic.

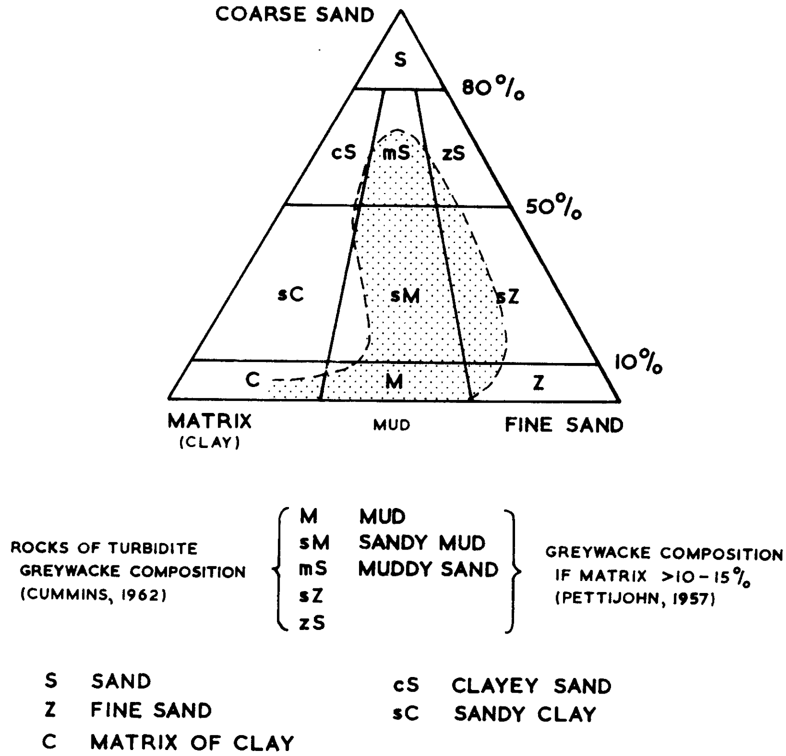


FIGURE 17

Possible classification by textural grouping. The average composition field of an ancient turbidite greywacke (Cummins, 1962, fig. 4) is superimposed on major textural groups (Folk, 1954).

Folk (1959) regarded the proportion of matrix as indicative of the degree of textural maturity and he implied that it is one of the most important keys to the physical nature of the environment of deposition. Dott (1964) considered that the maturity of any sedimentary rock could be expressed by the relationship of the degree of sorting (percentage matrix), the degree of fragment durability (angularity and size of the fragments) and the component stability (percentage siliceous resistates) (Fig. 18; after Dott, 1964, p. 629).

Hawkins and Whetten (1969) cast doubt on textural schemes of greywacke classification because of the unknown proportion of alteration products and they have suggested that to avoid ambiguities consideration should be given to chemical composition and mineral content as a major parameter in classification of clastic rocks.

As modal analyses presuppose the originality of the matrix, the usefulness of a classification and comparison of ancient greywackes (where secondary alteration is possible) with others of the same age or a modern greywacke is doubtful. Dott (1964) considered that it was irrelevant when the matrix of a greywacke originated for it to be classifactorily distinctive, because classification is descriptive, and therefore any sub-division of a greywacke is possibly best made on modal analysis.

b. *Method adopted.* In a descriptive scheme using Fig. 16 based on the detrital modes of greywackes from Stromness Bay and Prince Olav Harbour no distinction concerning the composition of the matrix was made.

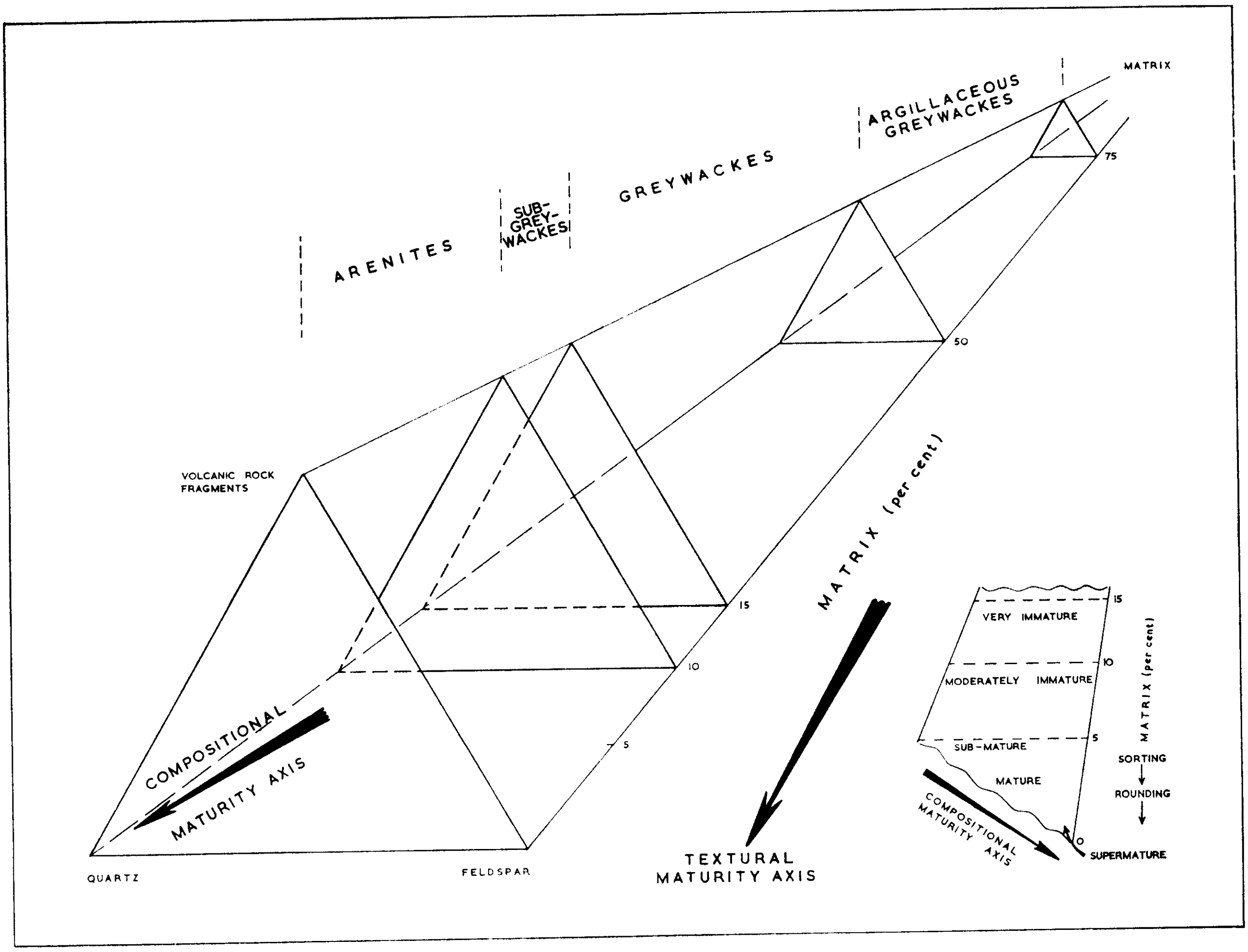


FIGURE 18

The complex classification of volcanic greywackes of the Cumberland Bay Series showing the axes concept of textural and compositional maturity (after Dott, 1964, p. 630).

Certain difficulties are introduced into counting of modes because of the low-grade metamorphism, and these must be overcome if any confidence is to be placed in the results. Rocks which are strongly sheared or marked by incipient authigenic mineral development, as are many from the Cumberland Bay Series, cannot be used. However, if the process of authigenic alteration both due to burial metamorphism and secondary matrix development can be mentally reversed, then through this screen the detrital framework can be detected and thus detrital modes will be of value.

It is still possible to readily identify primary detrital fragments such as volcanic clasts, feldspars and matrix, with very low percentages of heavy detrital minerals. The authigenic minerals such as albitized feldspars, prehnite, calcite and chlorite are minor but only albitized feldspar is of major modal significance. Etching followed by sodium cobaltinitrite staining of many thin sections prior to counting showed a virtual absence of alkali-feldspars. Therefore, all feldspar counts are undifferentiated in these detrital modes, and detrital matrix, post-depositionally formed matrix and secondary matrix are combined in the total matrix. No less than 2,000 counts were made by point counter across each thin section. Volcanic fragments, altered (albitized, sericitized and prehnitized) and unaltered feldspars, prehnite (in any form) and matrix were totalled individually. In addition, one of the following components was counted depending on the thin section: detrital quartz, chlorite (penninite), calcite, opaque minerals, and other rock fragments such as quartzite and slates. The results are listed in Table III.

c. *Discussion of detrital modes*. Because there has been considerable authigenic mineral development, such minerals (albite, quartz and prehnite) have been mentally related to their possible origin. Although

TABLE III

MODAL ANALYSES OF VOLCANIC GREYWACKES FROM THE CUMBERLAND BAY SERIES, SOUTH GEORGIA

Constituent minerals		*Rocks from the Prince Olav Harbour area*														*Rocks from the Stromness Bay area*											*Rocks from Rosita Harbour*		
		1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28
Quartz		0·7	0·1	0·8	1·3	tr.	0·2	0·3	0·6	1·0	0·7	0·3	0·4	3·3	tr.	0·6	3·6	0·1	tr.	0·5	1·9	1·4	4·1	1·5	1·1	2·5	2·4	1·4	3·3
Feldspar		30·9	10·2	18·4	12·6	10·1	7·7	16·6	17·5	13·7	13·2	6·2	10·1	17·6	5·5	11·7	25·1	19·9	9·8	14·3	25·2	15·8	12·8	13·7	18·2	6·9	13·8	7·8	6·8
Prehnite		tr.	1·4	tr.	0·4	1·5	7·1	0·6	1·1	4·5	2·8	1·3	8·8	tr.	1·3	0·5	1·5	5·6	18·4	1·5	tr.	11·7	0·3	5·2	2·4	2·5	7·4	19·8	16·4
Volcanic fragments		38·1	53·9	41·6	51·2	63·2	43·8	49·2	55·9	30·6	26·3	21·5	14·7	15·9	57·9	39·3	27·6	37·7	25·0	33·1	9·7	7·2	–	–	16·5	30·7	45·2	31·9	20·4
Sedimentary fragments		–	tr.	0·7	–	–	0·1	0·4	–	–	–	–	–	–	–	–	–	6·3	3·4	4·4	12·7	4·2	5·3	23·7	15·1	–	–	–	–
Matrix		29·1	30·8	37·9	29·4	25·1	24·7	32·4	23·1	46·3	56·6	67·7	63·0	58·3	32·1	47·1	36·5	27·9	41·7	45·4	47·2	61·9	77·0	55·0	40·1	56·3	32·9	44·9	51·8
Chlorite		1·2	0·1	–	0·2	–	0·1	0·4	0·4	1·0	0·8	0·3	1·9	tr.	–	tr.	0·5	2·0	1·5	0·5	tr.	0·3	–	0·3	5·3	1·2	0·4	–	–
Calcite		–	3·0	–	3·2	tr.	–	–	–	0·3	0·3	0·3	–	–	2·6	–	0·3	–	–	–	1·5	0·8	5·4	–	–	–	–	–	–
Epidote		–	tr.	–	tr.	tr.	–	0·2	–	–	tr.	–	–	tr.	–	tr.	–	–	–	–	–	–	–	–	–	tr.	0·2	–	–
Opaques		0·5	0·2	–	0·4	0·3	0·7	0·1	1·5	1·7	0·3	2·3	1·1	4·8	0·5	tr.	0·8	0·9	0·2	0·4	1·3	0·9	1·1	0·5	1·9	tr.	0·3	2·8	0·4
	M	29·1	30·8	37·9	29·4	25·1	24·7	32·4	23·1	46·3	56·6	67·7	63·0	58·3	32·1	47·1	36·5	27·9	41·7	45·4	47·2	61·9	77·0	55·0	40·1	56·3	32·9	44·9	51·8
Fig. 19	L	70·1	69·1	61·3	69·3	74·9	75·1	67·3	76·3	52·7	42·7	32·0	36·6	38·4	67·9	52·3	59·9	72·0	58·3	54·1	51·0	36·7	18·9	43·5	57·8	41·2	64·7	53·7	44·9
	Q	0·7	0·1	0·8	1·3	tr.	0·2	0·3	0·6	1·0	0·7	0·3	0·4	3·3	tr.	0·6	3·6	0·1	tr.	0·5	1·8	1·4	4·1	1·5	1·1	2·5	2·4	1·4	3·3
	Q	0·7	0·1	0·8	1·3	tr.	0·2	0·3	0·6	1·0	0·7	0·3	0·4	3·3	tr.	0·6	3·6	0·1	tr.	0·5	1·8	1·4	4·1	1·5	1·1	2·5	2·4	1·4	3·3
Fig. 20	R	68·4	88·2	80·8	85·6	88·4	85·0	82·5	80·9	80·7	83·3	92·2	80·7	79·1	93·3	87·7	69·8	74·3	71·8	83·7	73·0	71·2	82·8	79·6	78·4	88·1	76·4	71·0	73·5
	F	30·9	11·7	18·4	13·1	11·6	14·8	17·2	18·5	18·3	16·0	7·5	18·9	17·6	6·7	11·7	26·6	25·6	28·2	15·8	25·2	27·4	13·1	18·9	20·5	9·4	21·2	27·6	23·2
	M	29·1	30·8	37·9	29·4	25·1	24·7	32·4	23·1	46·3	56·6	67·7	63·0	58·3	32·1	47·1	36·5	27·9	41·7	45·4	47·2	61·9	77·0	55·0	40·1	56·3	32·9	44·9	51·8
Fig. 21	R	39·3	57·4	42·9	56·2	63·3	60·3	50·1	57·8	34·4	26·7	24·5	17·7	20·8	61·2	40·6	33·3	46·4	30·1	38·3	25·8	9·3	5·8	24·6	38·3	31·8	43·5	26·1	21·7
	F	31·6	11·8	19·2	14·4	11·6	15·0	17·5	19·1	19·3	16·7	7·8	19·3	20·9	6·7	12·3	30·2	25·7	28·2	16·3	28·1	28·8	17·2	20·4	21·6	11·9	23·6	29·0	26·5

Volcanic greywackes
1. M.203.2
2. M.204.1
3. M.205.1
4. M.209.1
5. M.213.1
6. M.219.1
7. M.225.5
8. M.231.1
9. M.236.2

Argillaceous volcanic greywackes
10. M.206.1
11. M.217.1
12. M.225.4
13. M.231.2
14. M.220.1 Thin section of a calcareous concretion (Table II) but etched and stained with sodium cobaltinitrite solution.

Volcanic greywackes
15. M.160.1
16. M.168.1
17. M.178.1
18. M.182.1
19. M.183.1

Argillaceous volcanic greywackes
20. M.154.2
21. M.159.1
22. M.165.1
23. M.165.2
24. M.165.3
25. M.155.1 Argillaceous volcanic greywacke matrix rock surrounding a calcareous concretion (M.155.2; Table II).

26. M.247.2 Volcanic greywacke.
27. M.249.2 Volcanic greywacke.
28. M.248.3 Argillaceous volcanic greywacke.

albitized feldspars usually comprise not more than 20 per cent, and prehnite 8 per cent, the modes of all other authigenic minerals rarely exceed 3 per cent. Nodular "cannon-ball" concretions are, however, an exception and their modes are tabulated separately (Table II).

The position of the siliceous resistates and clay minerals which comprise the matrix remains a problem, because occasionally considerable interstitial areas have been completely altered to prehnite or patchy calcite by diagenesis or burial metamorphism. These modes are considered to comprise the present matrix parameters.

Volcanic fragments have usually undergone some alteration and the detrital modes of the volcanic greywackes are listed in Table III, from which MLQ, QRF and MRF ternary diagrams have been produced (Figs. 19, 20 and 21).

From the MLQ diagram (Fig. 19) the very restricted compositional field illustrates their low detrital quartz content. This may also be observed from the QRF diagram (Fig. 20) but a well-defined distinction

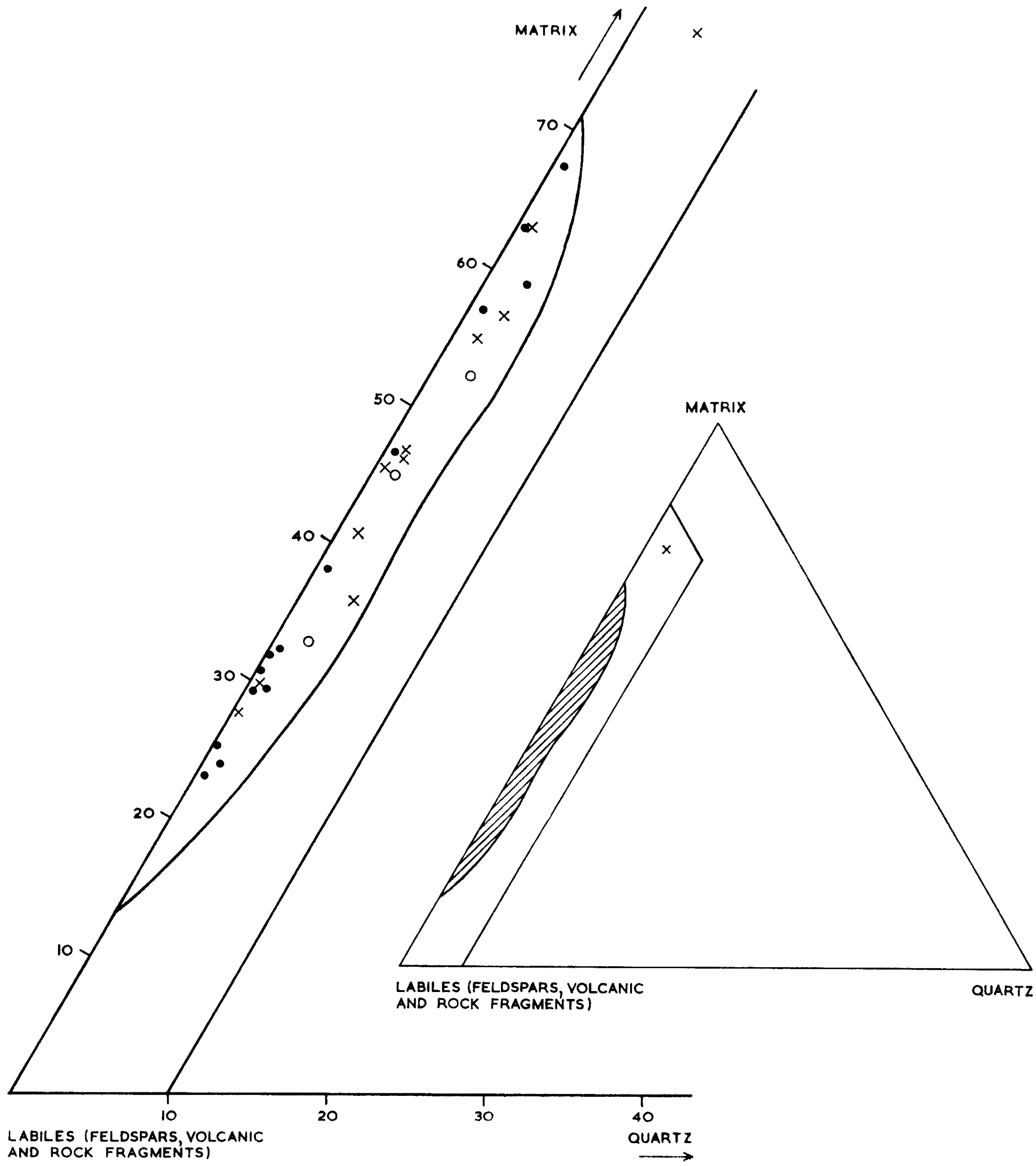


FIGURE 19

An MLQ diagram illustrating the restricted compositional field of the greywackes of the Cumberland Bay Series and showing the very low detrital quartz content. Greywackes from Prince Olav Harbour (solid circles); Stromness Bay area (crosses); Rosita Harbour (open circles). M, matrix; L, labiles: feldspars, volcanic and sedimentary rock fragments, and heavy minerals; Q, detrital quartz.

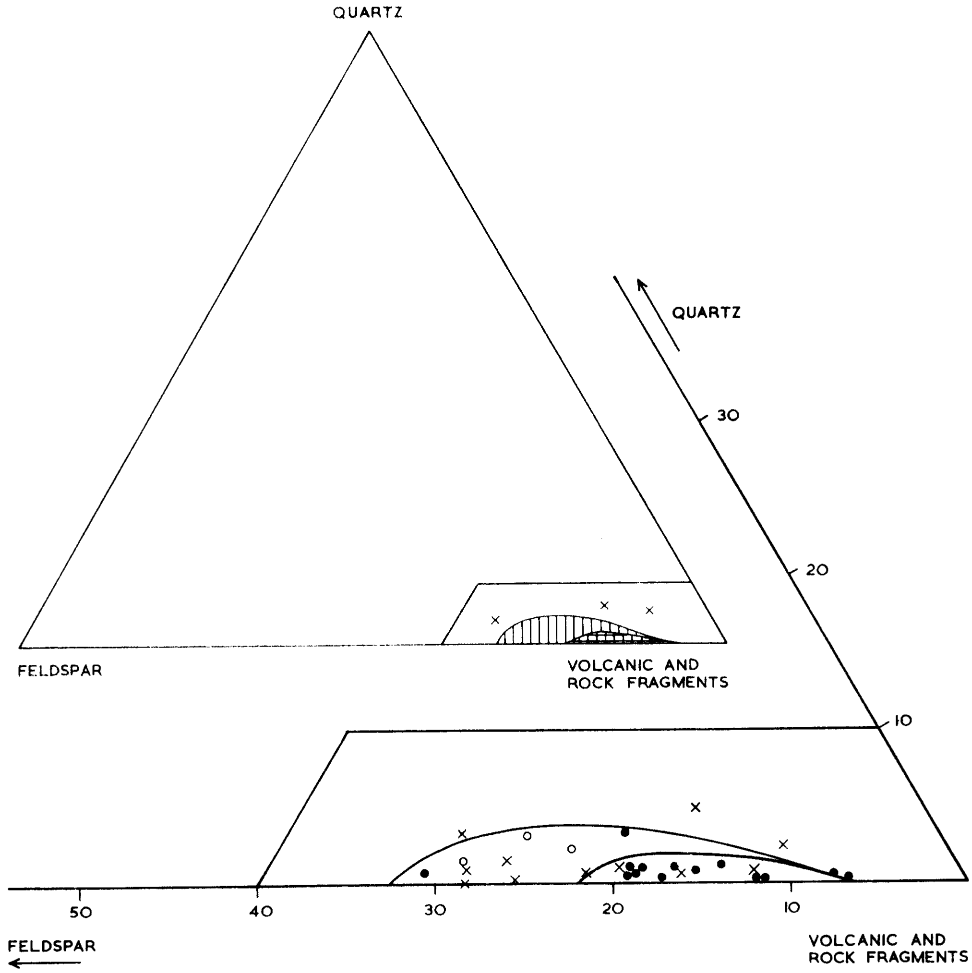


FIGURE 20

A QRF diagram illustrating the well-defined sub-division of the greywackes from Prince Olav Harbour (solid circles and cross hatching) and the Stromness Bay area (crosses and vertical hatching). Greywackes from Rosita Harbour (open circles). Q, detrital quartz; R, rock fragments: volcanic and sedimentary rock fragments, heavy minerals and matrix; F, feldspars.

of those from Prince Olav Harbour (solid circles) and Stromness Bay (crosses) can be made. The three analyses from Rosita Harbour (solid triangles) are similar to those of the Stromness Bay area. The dominance of the detrital modes by volcanic rock fragments is shown on an MRF diagram (Fig. 21), which (from Fig. 16) is broadly divisible into predominantly volcanic greywackes from the Prince Olav Harbour area and argillaceous and feldspathic volcanic greywackes from the Stromness Bay area, which have a higher plagioclase feldspar content.

The low detrital quartz content and lack of potash feldspar suggests that these greywackes were formed from the initial detritus eroded from an intermediate terrain of a volcano-plutonic source. The presence of occasional vitroclastic shards suggests contemporaneous volcanic conditions with seismic activity probably triggering off the turbidity currents.

The ratio of plagioclase feldspar to total feldspar is approaching unity, which strongly suggests that the provenance outlined above was possibly that of an adjacent structural arc, probably initiated by plate tectonics (Dickinson, 1971). However, as volcanic fragments from an active structural arc, such as Japan or the South Sandwich Islands, are considerably more basaltic than those of South Georgia (which have been compared by Tyrrell (1930) in one instance to that of a rock "... intermediate between spilite or albite-dolerite and a keratophyre"), a differing provenance may have existed.

Mafic material is notably absent, both in the microlitic groundmass of the sub-angular to sub-rounded

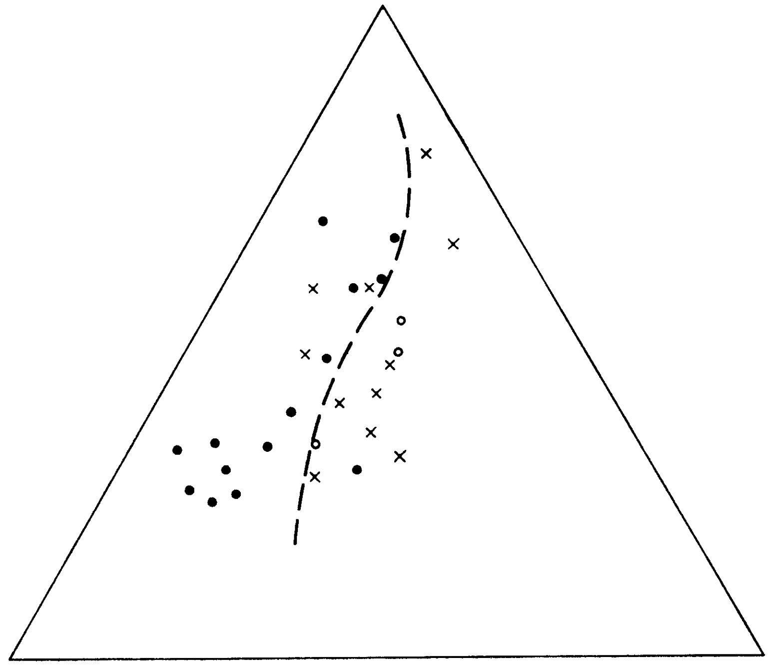


FIGURE 21

An MRF diagram showing that a sub-division similar to that in Figure 20 is possible and that the volcanic and argillaceous volcanic greywackes from the Stromness Bay area differ from those of Prince Olav Harbour in that there is a higher plagioclase content. Greywackes from Prince Olav Harbour (solid circles); Stromness Bay area (crosses); Rosita Harbour (open circles). M, matrix; R, rock fragments, almost exclusively of volcanic origin; F, feldspars and detrital quartz.

volcanic fragments and as a detrital constituent, and is therefore not absent due to weathering in transport. The only heavy minerals are occasional sub-rounded sphene, epidote and minute angular zircons.

Progressive exposure of a pluton would result in more acid debris, and a tendency for the plagioclase: total feldspar ratio to trend towards zero. Examination of available greywacke thin sections from Annenkov Island, which Trendall (1959) considered to be a younger part of the Cumberland Bay Series revealed a greater proportion of potash feldspars incorporated with the volcanic debris. Thus the slightly more acid nature of the few available thin sections, including an arkose, enchances the possibility that erosion of the upper parts of a volcanic terrain had by that time proceeded to reveal more granitic parts of the pluton. However, the nature of the provenance which may well have been of an intermediate volcano-plutonic association remains uncertain, but it is possible that it might well have been part of a much larger continental volcanic tract now absent, either due to complete erosion, or more likely, drift of South Georgia.

d. *Comparison of the detrital modes of the Cumberland Bay Series with those of other circum-Pacific areas.* The detrital modes of the Cumberland Bay Series suggest that they have been derived from a provenance completely dissimilar from that of other circum-Pacific orogenic areas. Miocene greywackes of the Aure trough, Papua (Table IV), are mineralogically similar except for a distinct mafic content from which Edwards (1950*a*) concluded that they were derived from andesitic tuffs rather than lava flows because of the highly weathered feldspars and ferromagnesian minerals. In contrast, the detrital modes of the Cretaceous greywackes from the Purai Valley, Papua (Edwards, 1950*b*), have a high proportion of feldspars and clear quartz and a dearth of volcanic fragments which indicate a more acid and perhaps granitic provenance.

Mesozoic greywackes from Mount Olympus, Washington State (Table IV), are characterized (like the Cumberland Bay Series) by minerals of the prehnite-pumpellyite facies of low-grade metamorphism (Hawkins, 1967). The relatively high feldspar, quartz and mafic content suggests similarities of provenance with that of the greywackes of Papua. Jurassic andesite strata from central Oregon derived from

Table IV

DETRITAL MODES OF VOLCANIC GREYWACKES FROM CIRCUM-PACIFIC OROGENIC AREAS

Constituent minerals	*Analyses of five volcanic greywackes from the Miocene Aure trough, Papua (Edwards, 1950a, p. 129)*					*Average of four greywackes from the Cretaceous of the Purai Valley, Papua (Edwards, 1950b, p. 165)*	*Average of three Mesozoic greywackes from Mount Olympus, Washington State, U.S.A. (Hawkins, 1967, p. 806)*
Quartz	0·2	0·1	tr.	tr	tr.	9·1	11·2
Plagioclase	32·2	24·3	23·5	29·5	21·8	43·9	35·0
Volcanic fragments	20·0	28·2	25·7	15·8	24·3	3·8	} 4·6
Sedimentary fragments	3·5	2·4	3·7	4·2	5·0	6·0	}
Matrix	33·6	35·7	41·5	41·7	31·6	25·3	21·7
Pyroxene and hornblende	10·5	9·2	5·8	9·1	6·3	3·4	–
						+6·1% glauconite, mica and chlorite.	+14·2% muscovite. +11·0% opaques and accessories. + 2·1% prehnite.

	Middle and Upper Triassic volcanic greywackes of Taringatura, Southland, New Zealand (Coombs, 1954, p. 90)		
Quartz	1·0	6·0	7·0
Feldspar (plagioclase)	20·0	28·0	30·0
Volcanic rock fragments	37·0	15·0	25·0
Other rock fragments	8·0	12·0	15·0
Matrix	33·0	30·0	23·0
Carbonate cement	–	8·0	–
Ores, biotite and apatite	1·0	1·0	1·0

Averages of typical moderately sorted medium-grained sandstones from the Jurassic andesite strata, central Oregon, U.S.A. (Dickinson, 1962, p. 488)		
Plagioclase crystals and altered products	25·0	24·0
Originally glassy rock fragments and shards	56·0	54·0
Ferromagnesian mineral crystals, chiefly augite	3·0	4·0
Interstitial chlorite, celadonitic matrix and cement	16·0	18·0
Averages from	Middle Jurassic tuffs	Lower Jurassic tuffs

Averages of the Cretaceous flysch of the Cerro Toro Formation, southern Chile (Scott, 1966, p. 88)		
Quartz	24·8	
Mosaic quartz	12·9	
Chert	5·4	
K-feldspar	0·9	
Plagioclase	4·7	
Rock fragments	17·2	
Mica	10·6	} of which 18·3% is matrix
Carbonate	13·5	}
Accessories and opaques	1·9	}
Mud	7·2	}

the pyroxene-andesite magmas (which gave rise to the continental suites of andesite rocks) were deposited as thick-bedded marine tuffs and volcanic greywackes in a group of basins within a tectonically active geosynclinal belt along the western margin of North America (Dickinson, 1962). The average composition is comparable only to the clastic volcanic rocks from the Triassic of New Zealand and the Miocene of Papua.

The provenance of the Cerro Toro Formation, a Cretaceous flysch sequence in the Patagonian Andes, was a dominantly volcanic terrain with areas of plutonic and metasedimentary rocks (Scott, 1966). He stated that the proto-Andean range was the site of extensive pre-Cretaceous volcanic activity and was part of an island-arc system continuously emergent north of Tierra del Fuego throughout the late Cretaceous. Comparison of the detrital modes with the Cumberland Bay Series is unrealistic on facies differences. The Cerro Toro flysch probably represents the final stages of basin deposition and the presence of mafic rock fragments contrasts with the Cumberland Bay Series greywacke lithofacies.

Katz and Watters (1966, p. 341) stressed the similarity in age and lithology of the Cumberland Bay Series to the Yahgan Formation on Navarino Island, Tierra del Fuego. The widespread prehnitization of the Cumberland Bay Series was thought to be similar to that of the Yahgan Formation, from which they concluded that at some time the two areas must have been in closer proximity.

e. *Comparison of detrital modes with those of other greywacke sequences.* The average of Upper Devonian volcanic greywackes from the Baldwin Formation, New South Wales, Australia (Table V), closely resembles greywackes of the Cumberland Bay Series except that minor quantities of pyroxene are present. The Baldwin Formation belongs to the prehnite-pumpellyite facies with occasional well-developed pumpellyite, and prehnite developing as an alteration product of the detritus and cement. However, the volcanic content is higher and the plagioclase content is lower than that of the Cumberland Bay Series. Chappell (1968) estimated burial conditions of the Baldwin Formation were at a pressure of 2–2·5 kbar (6,500 m.) and a temperature of about 200–250° C, assuming a normal geothermal gradient. This compares well for prehnite-pumpellyite development in other sequences, i.e. 7,000 m. for the Taringatura district, Southland, New Zealand (Coombs and others, 1959), and 8,500 m. for the Wahgai Valley, New Guinea (Crook, 1961).

Although there is a similarity of detrital modes with the Cumberland Bay Series, the presence of pumpellyite in the Baldwin Formation is due possibly to its more basic composition and a much lower potash content (less than one-third of other volcanic greywackes). X-ray fluorescence spectrography of the Cumberland Bay Series volcanic greywackes indicates about double the potash content of the greywackes of the Baldwin Formation.

The detrital modes of greywackes from the western marginal facies of New Zealand (Dickinson, 1971) illustrate the changing detrital content during sedimentation of a provenance from the Lower Permian to the Lower Jurassic, revealing progressively more acidic rocks (Table V).

f. *Conclusions.* A comparison of the detrital modes of the Cumberland Bay Series with those of other circum-Pacific greywackes demonstrates the unique characteristics, from which it is difficult to make a precise analogy with any of the above sequences. It is suggested that the depositional basin of the Cumberland Bay Series may have functioned independently from the tectonically active geosynclinal belt of the circum-Pacific orogenic areas because:

i. The position of the Sandebugten Series, which underlies the Cumberland Bay Series, is not precisely known, but it demonstrates the two-part history of the basin which is alien in nature to that of other circum-Pacific sedimentary basins.
ii. Contemporaneous intrusion of lavas is restricted to the younger parts of the Cumberland Bay Series, which suggests that only occasionally and within defined limits (Fig. 7) was the area of deposition affected by volcanicity.
iii. The absence of mafic minerals, in particular pyroxenes and amphiboles, from the groundmass of volcanic clasts and the detrital framework suggests a continental provenance of wholly volcanic terrain rather than a structural arc.
iv. The relatively little pyroclastic debris suggests the absence of (or very distant) volcanism, although turbidity currents indicate a tectonically active area.

As these conditions are uncharacteristic of other Mesozoic circum-Pacific orogenic areas, it is suggested that the sedimentary basin (eugeosyncline) now comprising South Georgia is either

TABLE V

DETRITAL MODES FROM OTHER GREYWACKE SEQUENCES

	Average of 31 analyses of Upper Devonian volcanic greywackes; Baldwin Formation, New South Wales, Australia (Chappell, 1968)	*Average of six greywackes (Pettijohn, 1957, p. 304)*
Quartz	0·4	45·6
K-feldspar	–	16·7 (K-feldspar and plagioclase)
Plagioclase	12·7	
Rock fragments (volcanic detritus)	63·6	Rock fragments 6·7
Matrix	20·3	25·0
Pyroxene	1·5	–
Hornblende	–	–
Heavy minerals	0·6	–
Carbonate	0·4	4·6
Cement	0·5	–

Detrital modes of five representative greywackes from the western marginal facies, New Zealand, with low detrital quartz and K-feldspar percentages (Dickinson, 1971, p. 46)

Framework minerals					
Quartzose grains	3	0	1	3	2
Plagioclase	26	25	29	42	46
K-feldspar	0	0	0	4	1
Rock fragments (volcanic detritus)	63	66	63	47	46
Sedimentary fragments	4	0	0	1	2
Pyroxene and hornblende	3	6	5	1	1
Opaque	1	3	2	1	2
Cement	8·8	12·7	7·2	10·4	7·8
Matrix	3·0	8·4	13·2	2·9	11·6
Framework minerals	88·2	78·9	79·6	86·7	80·6
Age	Lower Permian	Upper Permian	Lower Triassic	Upper Triassic	Lower Jurassic

atypical or that it may be regarded as separate from but contemporaneous with other circum-Pacific areas and experienced associated tectonism before Eocene drift.

B. Petrography of the Cumberland Bay Series

1. *Hand specimens*

Jointing occurs parallel to both the slaty and fracture cleavage, and along a parting sub-parallel to a bedding plane or grain orientation. Typical greywacke talus caused by freeze-thaw processes is invariably iron-stained along the joint planes. Thus, rhombohedral-shaped blocks may be produced from the weathering of the more massive beds, but structureless finer-grained beds have a more chonchoidal fracture.

The freshly broken surfaces of volcanic greywackes vary little in colour, usually being a pale blue or green-grey with numerous white feldspar grains and occasionally darker rounded clasts. Finer-grained and more argillaceous samples are darker and may be almost black with large dark pelitic inclusions. Mudstones and slates vary from dark blue-grey to black. The gradation of the generally sub-angular detrital components through to matrix size suggests a texturally immature sediment. Very coarse greywackes with grains approaching 10 mm. are rare and a maximum size of 3–4 mm. is usual. Generally, any one hand specimen is of even texture but poorly sorted with sub-angular to sub-rounded clasts, although occasionally rounded volcanic grains suggest that at least some components have undergone considerably more attrition than others possibly by re-working in the littoral zone.

Occasionally, orientation of the grains is apparent although it is probably not due to flow imbrication as steady currents are unlikely along the sea bed in turbidite conditions. Flattening of the clasts is therefore due either to pressure of burial or re-orientation during folding. A 6:1 grain orientation has developed in some of the more elastic clasts and a crude lineation is occasionally present with parallel parting suggesting a relict bedding-plane cleavage. Thus a two-phase grain deformation has possibly occurred and this is mainly determined by the major tectonic phase, which is more notable in close proximity to a fold hinge, although the effects of the north–south fracture cleavage are unknown.

2. *Microscopic texture*

In thin sections cut normal to the bedding a grain lineation with minute parallel parting planes may dominate the fabric. These sections, which show signs of intrastratal movement, such as fractured feldspars and a lenticular matrix produced by stretching or micro-flow-banding, suggest an inducement of foliation or semi-schistose texture by shear in the plane of the bedding. These textures depend on the degree of competency of the greywackes. Re-orientation and shearing is absent in massive greywacke beds because these develop a characteristic brittle fracture with quartz-filled sigmoidal tension gashes. Differential compaction around the clasts and feldspar phenocrysts suggests considerable compression and flattening on burial. However, such a parting is typically absent in nodular calcareous "cannonball" concretions. Because of the tendency for the bedding to bend round them, it is suggested that the concretions became more competent than the matrix rock during diagenesis.

Texturally, thin sections of greywackes from Stromness Bay and Prince Olav Harbour are comparable and, although there has been considerable recrystallization during the tectonic phase, the texture probably remains essentially that developed on deposition. The proportion of matrix varies considerably, but it is generally between 25 and 75 per cent of the rock. Detrital modes of greywackes from Stromness Bay show a greater proportion of matrix than those from Prince Olav Harbour or Rosita Harbour.

There appears to be no marked variation in the angularity of the clastic content but Trendall (1959, p. 12) noted that the rocks from Annenkov Island, which he considered to be the youngest exposed part of the Cumberland Bay Series, showed a slight difference. Here, large grains were more angular and closer packed with calcite-filled interstices and, although sorting was poor, there was less pelitic material.

3. *Labile constituents*

Volcanic fragments comprise up to 60 per cent of the total detrital fraction and are generally less angular than plagioclase laths. Most commonly, volcanic clasts are those of a microlitic or occasionally felty texture. The minute plagioclase laths of andesine composition show little albite twinning and are arranged in a parallel or sub-parallel manner. The long axes of each clast may be sub-parallel to the microlitic texture but usually there is little relationship between the microlites and the clast boundary. Occasionally a volcanic clast groundmass accepts sodium cobaltinitrite staining which shows that it is probably a mixture of quartz and potash feldspar, common in andesites (Williams and others, 1954). Some of them gave almost complete even stains whilst others were of a more patchy appearance.

Commonly there is augen development of the microlites around occasionally albitized intratelluric feldspar phenocrysts. Feldspar laths have probably been worked from the volcanic clasts due to attrition because they are more angular than their host material and rarely comprise more than 20 per cent of the detrital constituents, although they do occur in equal proportions with the volcanic clasts in argillaceous sediments. The larger feldspar laths are sand-sized, sub-angular and rarely completely clear, but more fragmented and angular feldspars occur in all grades down to that of the matrix size.

Plagioclase laths are frequently wholly or partly pseudomorphed by prehnite following albitization. Occasionally they are sericitized with development of minute secondary mica flakes but usually the tendency to secondary alteration has commonly resulted in the formation of prehnite, occasionally calcite but rarely epidote.

Sedimentary rock fragments comprise only a small percentage of the detrital modes. Mostly, they are small angular clasts of silt-sized argillite (possibly of intraformational origin), and rounded fine-grained clear polycrystalline quartzites possibly of a similar provenance as the volcanic fragments.

Detrital epidote is uncommon but it occurs as weakly pleochroic, turbid lemon-yellow rounded grains in coarser-grained and more granular sections. Sphene is characteristically detrital, small and granular.

4. *Matrix*

Difficulty in deciding what part of the matrix is original, secondary or the product of the burial metamorphism phase can confuse modal estimates if any attempt at differentiation is made. The composition of the original matrix is not known but it probably consisted of siliceous resistates and clay material.

The possibly secondary post-depositionally formed matrix of a turbidite greywacke (Cummins, 1962), consisting of phyllosilicates and zeolites (Hawkins and Whetten, 1969), has in any case most probably been recrystallized to the higher prehnite-pumpellyite facies during low-grade burial metamorphism. Typically, prehnite, chlorite and albitized plagioclase are present, with a turbid pseudomatrix (discontinuous interstitial paste) but rarely an orthomatrix (recrystallized matrix) of inert siliceous resistates.

VIII. LOW-GRADE BURIAL METAMORPHISM OF THE CUMBERLAND BAY SERIES

THE widespread occurrence of prehnite in the Cumberland Bay Series has been described by Tyrrell (1930), Barth and Holmsen (1939) and Trendall (1953, 1959). Recrystallization is prominent in all the coarser-grained greywackes and where prehnite is authigenically developed interstitially there is entire retention of the primary sedimentary or semi-schistose deformation fabric.

A. Petrography of the Authigenic Minerals

The marked absence of zeolite mineralization suggests metamorphic recrystallization at a higher temperature than during diagenesis. A broad non-zeolitic transition stage between the zeolite and greenschist facies is represented by the development of prehnite, chlorite and albite. Both zeolites and aragonite (which is characteristic of the commencement of the greenschist facies) are absent.

Coombs and others (1959) recognized the broad non-zeolitic transitional stage characterized by prehnite and pumpellyite which was named by Coombs (1960) the prehnite-pumpellyite metagreywacke facies. The following assemblages are formed: quartz-prehnite-chlorite or quartz-albite-pumpellyite-chlorite. In the Cumberland Bay Series, quartz is very minor, as a detrital component, as a matrix mineral of the groundmass of volcanic fragments associated with alkali-feldspar, or as an authigenic product of prehnitization. Pumpellyite has not been observed in the rocks of the Cumberland Bay Series. Brown and Thayer

(1963) regarded it as characteristic of basaltic and pillow lavas where it forms in veins or vermicular clots with chlorite amygdales.

1. *Albite*

Authigenic albite has generally replaced detrital plagioclase, although relict grains of oligoclase and andesine are still present. Albitization is characterized by a cloudy appearance with frequent amygdales containing a pale green or yellow, almost isotropic chlorite, probably penninite. It is unzoned, consisting of minute unidentifiable cryptocrystalline inclusions, possibly sericite with very small intratelluric colourless needles (possibly apatite). Overgrowths of fresh feldspar on older grains have not been observed. Occasionally prehnite has developed parallel to the cleavage or twin planes (Plate Vb) and may be associated with minute aggregates of calcite or possibly even sericite. Typical twin lamellae in albitized laths are not always sharp but they are often broad and combined with Carlsbad twinning, suggesting a compositional range of An_{8-15}. Authigenic albite may also occur as a devitrification product in conjunction with the authigenic quartz in microlitic and felty volcanic clasts.

2. *Quartz*

Occasional exotic detrital quartz crystals are cloudy and show a slight undulose extinction due to stress in some lineated sections. More commonly, however, minute aggregates of clear authigenic quartz showing a slight undulose extinction, which indicates their formation prior to folding, occur due to replacement of albitized plagioclase by prehnite (Plate Vc). Volcanic clasts with granular amygdales of authigenic quartz contain penninite and suggest secondary development of the quartzo-feldspathic groundmass (Plate Vd). Clear authigenic quartz may pseudomorph Radiolaria in siltstones where replacement may be complete, or as an annular development or associated with prehnite.

Quartz veinlets occurring in zones of shear near fold hinges, and sigmoidal tension gashes have radial or platy quartz which occasionally shows an undulose extinction indicating that it has been bent or strained. Prehnite or calcite are commonly associated in these veins, but they are mutually exclusive and the presence of opaque pyrite indicates a relatively high pH of the hydrothermal fluids (Hawkins, 1967).

3. *Chlorite*

Penninite, identified principally on its pale green colour and anomalous "Berlin blue" birefringence, is the major chlorite throughout the greywacke sections. It develops interstitially and occasionally totally replaces the matrix of sheared greywackes. It may occur as an amygdaloidal mineral in albitized plagioclase laths and in some volcanic clasts it develops a spherulitic habit where there may be an association with secondary quartz or aggregates of minute epidote crystals (Plate Ve).

It most commonly occurs as the matrix mineral in microlitic and felty volcanic clasts (Plate Va) but never as a pseudomorph. Authigenic chlorite is an alteration product of both detrital and volcanic ferromagnesian materials, and also results from low-grade burial metamorphism transgressing the zeolite facies, whereby chlorites form interstitially from celadonite and clay minerals in the sediment.

4. *Calcite*

Calcite may occur as discrete interstitial flakes, as a secondary vein mineral both in association with quartz or by itself, or more occasionally marginal to albitized feldspars. Except in nodular concretions and veins, it rarely forms more than 3 per cent of the total modal content.

Authigenic calcite results from lime and alumina, released during albitization of the plagioclase, contributing to the formation of prehnite, epidote and calcite. Hawkins (1967) suggested that under suitable P–T conditions calcite was newly crystallized at the expense of anorthite in the plagioclase, leaving some alumina retained as sericite inclusions. These possibly give the albitized plagioclases in the volcanic greywackes their cloudy appearance.

No aragonite has been identified but this does not preclude the possibility that it may have been present at an earlier phase and has since inverted to calcite because occasionally a very low relict biaxial angle can be found in some tabular calcite crystals.

Nucleation of calcite on diagenesis as nodular concretions around decaying organic material (Weeks,

1953) has, due to burial metamorphism, resulted in the growth of subhedral calcite with the development of penninite, occasional prehnite, pyrite and leucoxene (Plate Vf). Etched thin sections of nodular concretions show that calcite does not develop as an interstitial cement because it is removed, revealing a matrix practically indistinguishable from that of the matrix rock in texture and authigenic mineral content.

5. *Epidote and opaque minerals*

Epidote is a widespread minor authigenic component observed in all thin sections except those of siltstones and slates. It occurs interstitially as a minute aggregate throughout the rock, giving rise to a characteristic turbid coloration due to a brownish green or yellow aggregate of cryptocrystalline material.

Opaque minerals most commonly occur interstitially or in proximity to either secondary quartz or calcite veinlets or in the groundmass of particularly well-rounded volcanic grains where a pilotaxitic texture is retained.

Haematite is most commonly opaque with blood-red borders in transmitted light when it has developed authigenically, but more commonly it occurs as a cavity, vein or joint infilling due to recent surface weathering, where a rust-red translucent solution mineralization product is typical. Notably, discrete authigenic granular *pyrite* develops throughout the matrix and is more commonly associated with calcite and quartz or penninite but rarely prehnite. Occasionally it occurs as a secondary mineral in veinlets of platy quartz due to cavity filling in the absence of prehnite.

Leucoxene is lustreless and creamy white in reflected light. It is widespread in most thin sections but it forms the darkened margins to platy calcite in calcareous nodules (Plate Vf); it may also comprise the dark turbid borders of other minerals. An ivory white coloration of larger opaque grains suggests possible authigenic development from altered andesitic and intermediate to basic fragments of volcanic origin.

Magnetite is mostly anhedral, irregular, interstitial and is lustreless dark grey to black in reflected light. The groundmass of some rounded pilotaxitic volcanic fragments has been replaced by authigenic magnetite development but leaving the fabric of feldspar microlites. *Ilmenite* has not been observed.

6. *Prehnite*

Prehnite is a common and characteristic component in virtually all of the thin sections of coarser-grained greywackes and it is also occasionally found masking the texture in thin sections of siltstone and slate. Hawkins (1967) implied that, under differing P–T conditions for the formation of calcite, anorthite resulting from the albitization of plagioclase will react to produce prehnite. Thus it is possible that either prehnite or calcite may form and that they are mutually exclusive, because it is unlikely that calcite has since been removed by percolating hydrothermal fluids. Occasionally, calcite has developed bordering the albitized plagioclase, but never when prehnite is present.

Prehnite develops in several varying and characteristic textures, each reflecting a different mode of origin. All appear to be independent of and pre-date structural deformation as some prehnitized clasts are severed by quartz-filled axial-plane cleavage veinlets which have an undulose extinction indicating subsequent stress. Each prehnite form shows a characteristic birefringence, apparently dependent on the amount of available calcium principally as lime in the plagioclase, or in solution as a percolating hydrothermal fluid during burial metamorphism.

a. *Association with authigenic quartz*. Clear prismatic prehnite, of high relief and showing second- and third-order birefringence colours (Plate VIa), is in characteristic association with authigenic quartz, especially in fine-grained quartzites. Also, globular reniform masses approaching spherulites about 0·1 mm. in diameter, recrystallizing to form a prehnite aggregate, are occasionally present showing upper third-order birefringence colours (Plate VIb).

b. *Pseudomorphs*. Irregular prehnite patches, present within albitized plagioclase, suggest the re-adjustment of the detrital plagioclase to an equilibrium position determined by the P–T conditions and the lack of deformation suggests static alteration. Frequently, prehnite development occurs marginally, preferentially parallel to the twin or cleavage plane (Plate Vb) or internally (Plate VIc). Birefringence varies depending on the amount of available calcium and may reach lower second-order colours, although first-order yellows and oranges are normal. Complete prehnite pseudomorphs after plagioclase are rare but they are of second-order birefringence and a relief only slightly less than prehnite in association with authigenic quartz.

Commonly, prehnite pseudomorphs Radiolaria and shards, but these are of typically poor relief and low birefringence. Some larger radiolarian pseudomorphs are marked by the development of patchy prehnite out of optical continuity, which suggests successive stages of replacement (Plate VId).

c. *As a vein mineral.* Platy quartz deposited radially in veinlets (possibly from hydrothermal fluids) and showing an undulose extinction with slight suturing of the grain boundaries is the host to columnar prehnite with a wavy extinction and first-order straw yellow to grey birefringence (Plate VIe). Opaque pyrite is commonly associated while calcite is typically absent.

At one locality, bioturbate structures in the upper surface of a pelitic unit (Plate IVe) have become replaced and infilled with exsolved prehnite and quartz in solid solution of moderate relief and low second-order birefringence (Plate VIf). A partly developed "bow-tie" structure has been cut by later quartz veinlets indicating pre-tectonic origin for prehnitization, where remnant discrete quartz and feldspars have become incorporated in the prehnite. An excavated sample from the bioturbate cavities confirmed prehnite and quartz by X-ray diffraction.

d. *Amoeboidal development.* In thin sections of finer greywackes, especially those of a more argillaceous type, scattered and patchy areas not greater than 0·25 mm. in diameter have become completely masked by incipient or amoeboidal prehnitization showing slight radial development which obscures the sedimentary texture. The birefringence is variable but of low second-order colours, and the margins of the affected areas can be either indefinite or abrupt. This phenomenon is common and particularly well developed in the upper units of some turbidite sequences. A hand specimen has a characteristic spotted appearance (Plate IVd) but in thin section the patchy development did not occur marginally to fracture cleavage, which suggests transportation away from the cleavage margins by percolating solutions following the deformational phase.

B. Petrogenesis of the Quartz-Prehnite Zone of the Prehnite-Pumpellyite Metagreywacke Facies

Prehnite in these rocks varies between 0·25 and 8·0 per cent. Its mode of occurrence depends largely on the character and content of the sediments, for example complete pseudomorphs may appear more commonly in argillaceous rocks in contrast to an irregular partial alteration present in wholly coarse-grained types.

Although the evidence suggests a pre-tectonic origin in the Cumberland Bay Series, it is probable that there has been movement of prehnite in areas under stress during tectonism such as in the vicinity of fold hinges where it has developed in quartz-filled veinlets.

Prehnite in the Cumberland Bay Series has crystallized in a physical environment determined by burial metamorphism due to lithostatic load. The depth of burial necessary for the formation of a prehnite-pumpellyite facies depends on the local chemistry and is therefore uncertain. Hawkins (1967) has stated that a depth of burial of 3 km. may be regarded as a minimum (Otalora, 1964; Hay, 1966) and it appears to be stable to depths of 16·7 km. (Hay, 1966) but here formation took place under syntectonic or post-tectonic conditions, possibly where reaction kinetics largely determined its nature.

Experimental data (Fyfe and others, 1958) indicate that temperatures of about 300° C are necessary for the development of prehnite. Thus, considering a normal geothermal gradient, it is probable that depths of 7–10 km. and a temperature of about 300° C are required at a pressure of about 2–3 kbar.

Fig. 22 illustrates the metamorphic facies relationships of sedimentary rocks from diagenesis to anatexis, and the possible position of the prehnite association of the Cumberland Bay Series is marked. Epidote is extremely common as a minute authigenic aggregate and thus, in order to produce a prehnite association without pumpellyite, the geothermal gradient was possibly between 40° and 50° C/km., a rate which is too high, and pressures which are too low for the development of pumpellyite in association with prehnite. Furthermore, these sediments are possibly insufficiently basic, for most occurrences of pumpellyite have been described from more basic greywackes, basaltic flows or pillow lavas.

The absence of aragonite may be misleading in suggesting an upper limit for environmental pressure because the aragonite–calcite inversion may be different in a natural system to that artificially determined, or aragonite produced initially may have retrograded on later tectonic deformation. Authigenic calcite

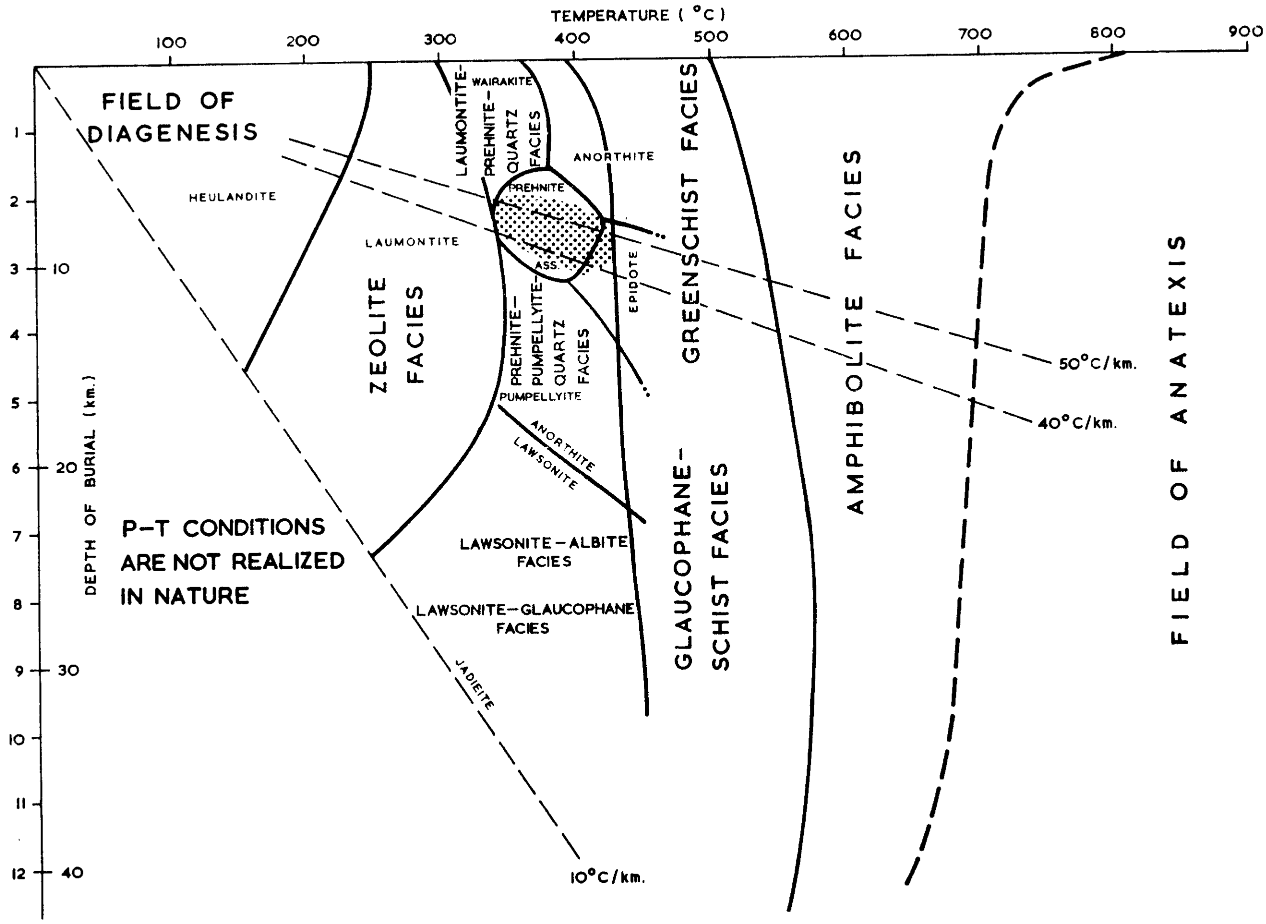


FIGURE 22

The relationships between the metamorphic facies of sedimentary rocks from diagenesis to anatexis, indicating the possible position of the quartz-prehnite zone of the Cumberland Bay Series (stippled) within the prehnite-pumpellyite metagreywacke facies. The absence of pumpellyite and the restricted field of occurrence of epidote delimit the geothermal gradient to between 40° and 50° C/km. during burial metamorphism at a depth of 7–10 km. and between 300° and 400° C.

is occasionally biaxial with a small 2V suggesting possible inverted aragonite but X-ray diffraction of powdered calcareous nodular concretions confirms the complete absence of aragonite. However, Vance (1968) reported partly inverted aragonite from a prehnite-pumpellyite facies in the north-west of Washington State, U.S.A. He concluded that either aragonite can no longer be regarded as a diagonostic indicator mineral of greenschist metamorphic facies, or the prehnite-pumpellyite facies developed at higher pressures than hitherto accepted.

Hawkins (1967, p. 812) has discussed possible reactions representing the alteration of plagioclase and the production of prehnite following albitization. He showed that as the plagioclase became albitized, under particular P–T conditions, the remaining anorthite reacted to form prehnite:

$$\underset{\text{anorthite (in plagioclase)}}{2CaAl_2Si_2O_8} + \underset{\text{water}}{2H_2O} + \underset{\text{quartz}}{3SiO_2} \longrightarrow$$

$$\underset{\text{prehnite}}{Ca_2Al_2Si_3O_{10}(OH)_2} + \underset{\text{aluminous silicates (e.g. pyrophyllite)}}{Al_2Si_4O_{10}(OH)_2}$$

In a different P–T environment, Hawkins (1967, p. 814) has shown that calcite will form from anorthite and therefore either prehnite or calcite will be present.

No zeolites have been identified in any of the thin sections from the Cumberland Bay Series and it appears that a transition through the zeolite facies was completed because there is an absence of remnant zeolite minerals in a lithology notably susceptible to their formation due to alteration from glassy volcanic matter. Thus it is considered that authigenic development of prehnite occurred once P–T conditions were favourable, and that these were sufficiently stable to permit complete alteration with mobility allowing incipient development.

Silicification of parts of a stratum containing pyroclastic and epiclastic volcanic debris is suggested because of the occurrence of occasional granular secondary quartz with indefinite sutured boundaries and aggregates of small particles of brownish green epidote. Although zeolitization of the volcanic products is possible, it is considered more likely that some epiclastic volcanic debris and the few pyroclastic shards have been pseudomorphed by secondary quartz in addition to those by authigenic prehnite, because these show textural similarities to the incipiently silicified parts.

From Brown and Thayer's (1963) classification (Table VI), which illustrates the relationship between the zeolite and prehnite-pumpellyite facies and itemizes the associated minerals, it is possible that the Cumberland Bay Series probably belongs to the lower-grade quartz-prehnite zone of the prehnite-pumpellyite metagreywacke facies. It is suggested that, had conditions been less stable, the preservation of the zeolite laumontite might have been expected.

IX. PALAEOGEOGRAPHY AND REGIONAL CORRELATION

A. Palaeogeography and Evolution of the Scotia Arc

The islands bordering the Scotia Sea have, until recent geophysical investigation, apparently misled many earlier workers into the conclusion that the arc they form represents a continuation of the circum-Pacific fold-mountain belt in an easterly loop from the Andean Cordillera to the Antarctic Peninsula. This has been enhanced by the active late Cenozoic volcanic archipelago of the South Sandwich Islands which has formed at the contact between two converging oceanic plates at the easterly apex of the arc. In fact, the large loop (Fig. 1, inset) consisting of the submerged Burdwood Bank (south of the Falkland Islands), South Georgia, the South Sandwich Islands, South Orkney Islands and the South Shetland Islands is purely a geographical arc and, except for the South Sandwich Islands, they are of entirely continental origin and marked by a distinct continental shelf.

Hawkes (1962) suggested a palaeogeographic link connecting Tierra del Fuego and the Antarctic Peninsula which was possibly a continuation of the circum-Pacific fold belt. During break-up of this link and drift of the islands of the Scotia arc, crustal movements caused an eastward flexure of Trinity Peninsula and Tierra del Fuego. Hawkes was able to re-position the islands of the Scotia arc so that there was continuity of structure within his postulated palaeogeographic link. Recent geophysical work (Barker, 1971) has shown that Hawkes's diagram is complicated by several recently found submarine plateaux composed of continental material occupying large areas of the floor of the Scotia Sea. It is possible that these were originally parts of a once continuous continental connection between South America and west Antarctica, but it is not possible to include these in Hawkes's reconstruction. Before mid-Tertiary displacement along a north-westerly trending transcurrent fault beneath Drake Passage, Tierra del Fuego may have been joined to the Antarctic Peninsula at Elephant Island, possibly the easterly apex of a cuspate Pacific margin. Dalziel and Elliot (1971) considered that the Andean-type intrusions into platforms supporting the islands of the Scotia arc and the mafic volcanic rocks interbedded with the flysch-like sediments of South Georgia are comparable to sedimentary rocks of the Pacific side of the Andean Cordillera, and indicated that the sediments of the Cumberland Bay Series comprised a fragmented portion of that side of the palaeographical link. The late Mesozoic sediments of Navarino Island and South Georgia are of a comparable lithofacies to the sediments of similar age now confined to the South Shetland Islands and Alexander Island. Dalziel and Elliot (1971) considered this indicated a common sedimentary basin west of the link.

However, petrographical evidence shows the sediments of Navarino Island and South Georgia are dissimilar which possibly suggests that the Cumberland Bay Series did not comprise the same sedimentary basin as described by Dalziel and Elliot (1971). On stratigraphical differences and the same petrographical grounds, doubt is also thrown on Hawkes's (1962) hypothesis. This lends support to Barker's (1971) palaeogeographical model which is partly based on magnetic lineation data from the Scotia Sea floor

Table VI
THE RELATIONSHIP BETWEEN THE ZEOLITE AND THE PREHNITE-PUMPELLYITE FACIES, ITEMIZING THE ASSOCIATED MINERALS (AFTER BROWN AND THAYER, 1963)

Facies	*Zone*	*Diagnostic mineral assemblage*	*Associated minerals*
Prehnite-pumpellyite metagreywacke Without zeolites, jadeite or lawsonite	(higher grade)	Some combination of	Albite Chlorite Calcite Sphene Actinolite Muscovite Stilpnomelane Epidote Quartz Pumpellyite
	(lower grade) Quartz–prehnite	Some combination of	Albite Chlorite Calcite Quartz Prehnite Sphene Orthoclase Muscovite Pumpellyite
Zeolite	Laumontite	Laumontite–quartz	Albite Chlorite Adularia Celedonite Sphene Calcite
	Heulandite–analcime	Heulandite–quartz or analcime–quartz	Montmorillonite Chlorite Celedonite Sphene Calcite

which shows the possible north-easterly movement of the South Georgia block from the east side of the link during separation of the north and south submarine ridges of the Scotia arc.

Thus a pre-Cretaceous palaeogeographical picture emerges with a possible sedimentary basin in which the Cumberland Bay Series greywacke lithofacies was deposited in a eugeosyncline, marginal to inter-continental seas east of the connection, and between South America, South Africa and Antarctica during late Gondwana times. Andean orogenesis pre-dates the separation of South America and the Antarctic Peninsula along the transcurrent fault if the south-east igneous complex on South Georgia is para-tectonic. Possibly, fragmentation of the continuous continental link, of which the Cumberland Bay Series comprises the youngest part of the sequence, combined with differential plate movement in the Scotia Sea region (Dalziel and Elliot, 1971), has resulted in the submarine plateaux and the fortuitous formation of the islands into a geographical arc.

B. Regional Correlation

1. *Detrital characteristics*

a. *Older sedimentary series.* Adie (1964, p. 143) stated that there is a lithological resemblance which allowed a tentative correlation between the Sandebugten Series of South Georgia, the Greywacke–Shale Series of Laurie Island (South Orkney Islands), the Miers Buff Series of Livingston Island (South Shetland Islands) and the Trinity Peninsula Series of the northern part of the Antarctic Peninsula.

b. *Younger sedimentary series.* Unlike the Cumberland Bay Series, detrital modes from the circum-Pacific fold belt show pyroclastic material and mafic detritus with sedimentary fragments of schist, volcanic or plutonic origin. The absence of such detritus from the Cumberland Bay Series may have been due to the extremely active weathering of a vegetated area, suggested by the carbonized wood remains, possibly in a hot climate, where this mineral fraction might well have been leached away during transport to the littoral zones. Because there are no mafic minerals in the volcanic clasts, it is possible that such minerals were not present in the source area. This would imply the absence of a provenance of varied terrain (usually associated with a structural arc) and indicates that the Cumberland Bay Series may have been derived from a more continental type of region.

Trendall estimated the thickness of the Cumberland Bay Series was not less than 10 km., a figure comparable with that suggested by Fig. 22. This great thickness indicates extremely rapid filling of the geosyncline by vigorous erosion and periodic seismic activity to trigger off turbidity currents.

2. *Structural similarities of the older sedimentary series*

The quartz-rich sedimentary sequences of the islands of the Scotia arc (except for the volcanic South Sandwich Islands) are of Upper Palaeozoic age and were deformed in the early Mesozoic (Adie, 1964). Dalziel (1971) considered that the Trinity Peninsula Series at Hope Bay and the Palaeozoic sediments of the Madre de Dios basin, Chile, have a structural style and a polyphase history of deformation comparable to that described for the Miers Bluff Series of Livingston Island and that of the Sandebugten Series of South Georgia. In view of the similar structural styles, it seems possible that these Upper Palaeozoic sediments may have, at one time, been in closer proximity and underwent the (?) Upper Triassic–Lower Jurassic period of folding attributed to the Trinity Peninsula Series by Adie (1964).

The structure of the Sandebugten Series is complex and the outcrop possibly forms part of the north-east limb of an anticlinorium with a north-north-west to south-south-east axial trend. This is comparable with the Trinity Peninsula Series on the south-east side of Trinity Peninsula. Elliot (1965) considered it forms part of one limb of a huge anticlinorium, of which the sediments were probably derived from a high, rapidly eroding landmass of varying lithologies. Dalziel (1971) concluded that the equally complex structure of the Miers Bluff Series of Livingston Island forms the inverted limb of a nappe-like recumbent fold more than 3 km. thick.

3. *Relationship between the Sandebugten Series and the Cumberland Bay Series*

The two-part history of geosynclinal sedimentation of the greywacke lithofacies of South Georgia, ranging in time from the (?) late Carboniferous to the (?) early Cretaceous, is atypical compared with other circum-Pacific orogenic sequences. The relationship between the Sandebugten Series and the

Cumberland Bay Series is uncertain. Trendall (1959) suggested that the contact may represent a depositional break following a major palaeogeographical change. Basal sequences, normally typical of the commencement of deposition following tectonism, such as that which folded the Sandebugten Series, are absent; this may be due to the distance of the basin from the source area which at the commencement of the deposition of the Cumberland Bay Series was probably not tectonically active. Aitkenhead and Nelson (1962) considered an area north-east of the contact was lithologically distinct from the Cumberland Bay Series at Grytviken and this could possibly be a lateral facies variant of the Cumberland Bay Series; a separate series or a basal type, because of the much higher proportion of non-volcanic constituents. If the contact is an unconformity, this is the correct interpretation. They considered a thrust-fault contact was unlikely because of the relationship between the dip of the contact and the folding of the Cumberland Bay Series; there is in any case an absence of mylonization and brecciation, and they concluded that the contact between the Sandebugten Series and the Cumberland Bay Series is probably an unconformity with possible sub-parallel thrusting in the contact zone.

An absence of folding for about 100 m. above the contact implies that the Sandebugten Series possibly acted as a stable block and suppressed the effect of the folding immediately above the contact in the Cumberland Bay Series. Therefore, it seems that the Cumberland Bay Series was plastically deformable and the large-scale intraformational folding only developed away from the unconformable contact.

Similar sediments equivalent to the Middle Jurassic volcanic sequences which rest unconformably on the folded Miers Bluff Series and Trinity Peninsula Series are absent above the Sandebugten Series in South Georgia. This suggests either non-deposition or that such sediments have been subsequently removed. Thus the apparent unconformity between the Sandebugten Series and the Cumberland Bay Series may possibly be an erosion surface.

4. *Similar Lower Cretaceous sequences*

Katz and Watters (1966) have stressed the similarities between the Yahgan Formation of Navarino Island, southern Chile, and the Cumberland Bay Series, and they suggested that the prehnite development indicated a general similarity in the post-depositional history of both areas. There is no record of an older quartz-greywacke sequence underlying the Yahgan Formation, but its lateral equivalents in the Patagonian Cordillera, the Zapata Formation, is underlain by the volcanic Upper Jurassic Quemendo Formation which may be contemporaneous with the Upper Jurassic volcanic sequence above the Miers Bluff Series and the Trinity Peninsula Series. Thus, the positions of the Cumberland Bay Series of South Georgia and the Yahgan Formation of Navarino Island are in many ways similar, and furthermore, equally unknown. It seems reasonable to propose that geochemical comparison will establish whether they are of similar provenance and were once in closer proximity. However, the presence of mafic material in the Yahgan Formation suggests similarities more in character with the provenance of other circum-Pacific areas, such as the Cerro Toro Formation and the Cretaceous sediments of Alexander Island. Similarly, by the same method, a closer relationship between the Sandebugten Series of South Georgia and other possibly contemporaneous (?) Carboniferous sequences of other islands of the Scotia arc and the Trinity Peninsula Series may be established.

5. *Intrusive rocks of possible Andean age*

Trendall (1959) was of the opinion that the south-east igneous complex of South Georgia is paratectonic. No ages for the intrusion are available but its petrography has similar characteristics to those of the Andean Intrusive Suite (Adie, 1964, p. 122). The geographical position of the Scotia arc between the Cretaceous Andean batholiths of the west Patagonian Cordillera and the late Cretaceous to early Tertiary intrusions of Graham Land suggests an age intermediate between the two. Intrusions post-date the folding on Navarino Island (Katz and Watters, 1966) and therefore the paratectonic (?) Andean intrusions of South Georgia are unique.

It seems, on lithological grounds, that South Georgia must have been part of some other geosynclinal area probably east of the South America–Antarctic Peninsula continental continuation and was folded contemporaneously with the circum-Pacific fold belt during the Andean orogeny before fragmentation of the continental link during the mid-Tertiary.

X. SUMMARY AND CONCLUSIONS

THE present geomorphology of South Georgia is no doubt largely the result of the main Antarctic glaciation which possibly reached its greatest extent about 3·5 m. yr. ago. Remains of recent glacial events probably only date from the last phase of the Würm glaciation with moraines probably of only post-Allerød age. The correlation of various levels of erosional platforms and raised beaches has been complicated by probable isostatic uplift of South Georgia and eustatic fluctuations, but tentative correlation has been made with Patagonian shore lines.

The complexity of folding in the Sandebugten Series is not completely understood, and the influence of the later folding of the still plastically deformable Cumberland Bay Series on the Sandebugten Series is not fully known.

The structural grain of South Georgia is parallel to the arcuate shape of the island, and the fold overthrow is from the Pacific side which is common to all folded Mesozoic sequences of the Scotia arc. The structural trends of both the Sandebugten Series and the Cumberland Bay Series are sub-parallel and thus the apparent repetition of fold styles suggests influence due to a similar tectonic regime. Thrusting is minor and generally a result of parasitic folding on major fold limbs. The effect of some later stress, causing the development of the north–south-trending fracture cleavage and minor faulting might well be attributed to the curving of the strike of the axial plane after folding; this is possibly associated with the drift of South Georgia after fragmentation of a newly formed continuous continental link following post-Andean separation of Tierra del Fuego and the Antarctic Peninsula.

The fossiliferous sediments of Alexander Island are of a Middle Jurassic to Lower Cretaceous (Aptian) age. The predominantly molluscan fauna of a flysch-like succession of the coastal cliffs contrasts with the poorly fossiliferous but contemporaneous Cumberland Bay Series of South Georgia. This enhances the author's view that the Cumberland Bay Series was deposited in a contemporaneous eugeosynclinal margin to an intercontinental sea but of a similar environment and in an area existing independently from adjacent circum-Pacific depositional basins. The absence of limestones, characteristic of flysch-like sedimentary successions, suggests euxinic waters, but the enrichment of the fauna in the higher parts of the Cumberland Bay Series was possibly due to the opening of a sea connection allowing colonization by a richer ammonite fauna.

Sedimentary characteristics suggest that the depositional environment was one of a flysch-like lithofacies, and the deformation of the secondary structures, load casting, flame structures, sandstone dykes and "cannon-ball" concretions, indicate water-saturated and thixotropic conditions after partial consolidation. Re-mobilization is probably due to continual microseisms after earthquake shocks triggered off multi-directional turbidity current flow indicated by sole marks of varied orientation. Considerable periods of quiescence between turbidite flow are indicated by the colonization by burrowing and sessile organisms in the surface layers of the slowly accumulating pelitic unit.

Apart from the frequent appearance of shear and lineation of grains, occasional white-weathering speckles in some of the finer-grained rocks, and the development of aureoles, the hand specimens do not appear to be metamorphosed. In most thin sections only prehnite and sericitized feldspar with patchy chlorite development are readily recognized as being of a metamorphic origin, whereas the presence of authigenic quartz, albitized plagioclase, minute authigenic epidote crystals and altered volcaniclastic fragments is not so apparent.

A flysch-like lithofacies sequence such as the Cumberland Bay Series of South Georgia is unique among the islands of the Scotia arc, but there are similarities with the Yahgan Formation of Navarino Island (southernmost Chile) in respect of the age, environment and degree of pre-tectonic burial metamorphism. The metamorphic alteration is comparable to that of the Cumberland Bay Series (Katz and Watters, 1966) and the author agrees with their view that there are grounds for a comparison of the Yahgan Formation with the Cumberland Bay Series, although in common with other Cretaceous sequences of the circum-Pacific fold belt the Yahgan Formation has characteristically a greater proportion of mafic material, thus implying a different provenance from that of the Cumberland Bay Series.

Recent work by Coombs (1960) concerning the lower grades of metamorphism has indicated the existence of a restricted transitional field of low-grade metamorphism within readily definable limits intermediate between the zeolite and greenschist facies. Fig. 22 shows the position of this field, and the authigenic mineralogy found within the lower part of the Cumberland Bay Series is characteristic of that demanded by the lower quartz-prehnite field of the prehnite-pumpellyite metagreywacke facies (Table VI). Coombs (1960), Winkler (1965) and Hawkins (1967) have given general P–T conditions, from which Fig. 22 has been drawn. An examination indicates that the Cumberland Bay Series has possibly been buried to about 10 km. depth, under a geothermal gradient between 40° and 50° C/km. assuming a normal heat flow.

The depositional environment and response to burial metamorphism are now more completely known. The similarities between the Cumberland Bay Series and the Yahgan Formation of Navarino Island suggest a close association between the two successions. Although both have been subjected to intrusion by what are probably phases of the Andean Intrusive Suite, the timing of this event with respect to tectonism is different. Trendall (1959) regarded the intrusion of the south-east igneous complex as para-tectonic, whereas Katz and Watters (1966) were of the opinion that the intrusions on Navarino Island are post-tectonic. Since both islands have similar fold styles, it seems that tectonism may have been contemporaneous and they were at one time in closer proximity to each other, but the timing of the intrusions suggests that each area may have been intruded by a different phase of the Andean Intrusive Suite due to their palaeogeographical separation. Should this be so, then support is added for the hypothesis of contemporaneous but separated geosynclinal areas suggested by the different petrologies. As yet there are no available ages for the south-east igneous complex of South Georgia but, if this proves to be contemporaneous with those phases of the Andean Intrusive Suite in southern South America or the northern Antarctic Peninsula, there are reasonable grounds for placing South Georgia much closer but to the east of the postulated palaeogeographical link, possibly comprising part of a continuous continental post-Cretaceous to mid-Tertiary landmass.

XI. ACKNOWLEDGEMENTS

I WISH to thank Professor F. W. Shotton for the use of the facilities of the Department of Geology, University of Birmingham, and Dr. R. J. Adie for guidance and criticism during the preparation of this report. I also wish to express my thanks to my field companions for their willing help, particularly to P. H. Noble who prepared the initial plane-table map of Prince Olav Harbour, South Georgia. Furthermore, my thanks go to D. Brook for permission to examine parts of his field work; to Dr. B. J. Taylor and Dr. M. R. A. Thomson for their advice on fossils and various aspects of the work on sedimentation; to Dr. I. Strachan and Dr. G. L. Hendry, of the Department of Geology, for their advice concerning micropalaeontological and geochemical techniques and, finally, to all other members of the Survey and the Department for their contribution to discussion.

XII. REFERENCES

ADIE, R. J. 1953. New evidence of sea-level changes in the Falkland Islands. *Falkland Islands Dependencies Survey Scientific Reports*, No. 9, 8 pp.

————. 1964. Geological history. (*In* PRIESTLEY, R. E., ADIE, R. J. *and* G. DE Q. ROBIN, *ed. Antarctic research.* London, Butterworth and Co. (Publishers) Ltd., 118–62.)

AITKENHEAD, N. *and* P. H. H. NELSON. 1962. The geology of the area between Cumberland West Bay and Cape George, South Georgia. *British Antarctic Survey Preliminary Geological Report*, No. 15, 13 pp. [Unpublished.]

ANDERSSON, J. G. 1906. Solifluction, a component of subaerial denudation. *J. Geol.*, **14**, No. 2, 91–112.

————. 1907. Contributions to the geology of the Falkland Islands. *Wiss. Ergebn. schwed. Südpolarexped.*, **3**, Lief. 2, 38 pp.

AUER, V. 1956. The Pleistocene of Fuego-Patagonia. Part I: The ice and interglacial ages. *Suomal. Tiedeakat. Toim.*, Ser. A.III, No. 45, 226 pp.

————. 1964. Lateglacial and postglacial shoreline displacements in South America as established by tephrochronology, compared with displacements of the Baltic shorelines. (*In* KUKKÄMAKI, T. J., *ed.* Symposium on recent crustal movements in Finland with bibliography, Helsinki, 1963. *Fennia*, **89**, No. 1, 51–55.)

————. 1970. The Pleistocene of Fuego-Patagonia. Part V: Quaternary problems of South America. *Soumal. Tiedeakat. Toim.*, Ser. A.III, No. 100, 194 pp.

BAILEY, E. B. *and* J. WEIR. 1932. Submarine faulting in Kimmeridgian times: east Sutherland. *Trans. R. Soc. Edinb.*, **57**, Pt. 2, No. 14, 429–67.

BARGHOORN, E. S. 1971. The oldest fossils. *Scient. Am.*, **224**, No. 5, 30–42.

BARKER, P. F. 1971. Magnetic lineations in the Scotia Sea. (*In* ADIE, R. J., *ed. Antarctic geology and geophysics.* Oslo, Universitetsforlaget, 17–26.)

BARTH, T. F. W. *and* P. HOLMSEN. 1939. Rocks from the Antarctandes and the Southern Antilles. Being a description of rock samples collected by Olaf Holtedahl 1927–1928, and a discussion of their mode of origin. *Scient. Results Norw. Antarct. Exped.*, No. 18, 64 pp.

BOUMA, A. H. 1962. *Sedimentology of some flysch deposits: a graphic approach to facies interpretation.* Amsterdam and New York, Elsevier Publishing Company.

BROOK, D. 1971. Scree benches around ice-dammed lakes in South Georgia. *British Antarctic Survey Bulletin*, No. 26, 31–40.

BROWN, C. E. *and* T. P. THAYER. 1963. Low-grade mineral facies in Upper Triassic and Lower Jurassic rocks of the Aldrich Mountains, Oregon. *J. sedim. Petrol.*, 33, No. 2, 411–25.

CHAPPELL, B. W. 1968. Volcanic greywackes from the Upper Devonian Baldwin Formation, Tamworth–Barraba district, New South Wales. *J. geol. Soc. Aust.*, **15**, No. 1, 87–102.

CHILINGAR, G. V., BISSELL, H. J. *and* K. H. WOLF. 1967. Diagenesis of carbonate rocks. (*In* LARSEN, G. *and* G. V. CHILINGAR, *ed. Developments in sedimentology. Vol. 8. Diagenesis in sediments.* Amsterdam, London, New York, Elsevier Publishing Company, 179–322.)

COOMBS, D. S. 1954. The nature and alteration of some Triassic sediments from Southland, New Zealand. *Trans. R. Soc. N.Z.*, **82**, Pt. 1, 65–109.

————. 1960. Lower grade mineral facies in New Zealand. *21st Int. geol. Congr., Norden, 1960*, Pt. 13, 339–51.

————., ELLIS, A. J., FYFE, W. S. *and* A. M. TAYLOR. 1959. The zeolite facies, with comments on the interpretation of hydrothermal syntheses. *Geochim. cosmochim. Acta*, **17**, Nos. 1/2, 53–107.

COOPE, G. R. 1963. The occurrence of the beetle *Hydromedion sparsutum* (Müll.) in a peat profile from Jason Island, South Georgia. *British Antarctic Survey Bulletin*, No. 1, 25–26.

CROOK, K. A. W. 1961. Diagenesis in the Wahgai Valley sequence, New Guinea. *Proc. R. Soc. Vict.*, **74**, Pt. 1, 77–81.

CUMMINS, W. A. 1962. The greywacke problem. *Lpool Manchr geol. J.*, **3**, Pt. 1, 51–72.

DALZIEL, I. W. D. 1971. Large-scale folding in the Scotia arc. (*In* ADIE, R. J., *ed. Antarctic geology and geophysics.* Oslo, Universitetsforlaget, 47–55.)

————. *and* D. H. ELLIOT. 1971. Evolution of the Scotia arc. *Nature, Lond.*, **233**, No. 5317, 246–52.

DE GEER, G. 1927. Late glacial clay varves in Argentina measured by Dr. Carl Caldenius, dated and connected with solar curve through the Swedish time scale. *Georgr. Annlr*, **9**, 1–8.

DENTON, G. H., ARMSTRONG, R. L. *and* M. STUIVER. 1970. Late Cenozoic glaciation in Antarctica: the record in the McMurdo Sound region. *Antarct. Jnl U.S.*, **5**, No. 1, 15–21.

DICKINSON, W. R. 1962. Petrology and diagenesis of Jurassic andesitic strata in central Oregon. *Am. J. Sci.*, **260**, No. 7, 481–500.

————. 1970. Interpreting detrital modes of greywacke and arkose. *J. sedim. Petrol.*, **40**, No. 2, 695–707.

————. 1971. Detrital modes of New Zealand greywackes. *Sediment. Geol.*, **5**, No. 1, 37–56.

DOTT, R. H. 1964. Wacke, graywacke and matrix—what approach to immature sandstone classification? *J. sedim. Petrol.*, **34**, No. 3, 625–32.

DOUGLAS, G. V. 1930. Topography and geology of South Georgia. (*In Report on the geological collections made during the voyage of the "Quest" on the Shackleton–Rowett Expedition to the South Atlantic and Weddell Sea in 1921–1922.* London, Trustees of the British Museum, 4–24.)

DZULYNSKI, S. *and* J. E. SANDERS. 1959. Bottom marks on firm lutite substratum underlying turbidite beds. *Bull. geol. Soc. Am.*, **70**, No. 12, 1594.

————. *and* E. K. WALTON. 1965. *Developments in sedimentology. Vol. 7. Sedimentary features of flysch and greywackes.* Amsterdam, London, New York, Elsevier Publishing Company.

————., KSIAZKIEWICZ, M. *and* P. H. KUENEN. 1959. Turbidites in flysch of the Polish Carpathians. *Bull. geol. Soc. Am.*, **70**, No. 8, 1089–118.

EDWARDS, A. B. 1950*a*. The petrology of the Miocene sediments of the Aure trough, Papua. *Proc. R. Soc. Vict.*, **60**, Art. 8, 123–48.

————. 1950*b*. The petrology of the Cretaceous greywackes of the Purari Valley, Papua. *Proc. R. Soc. Vict.*, **60**, Art. 11, 163–71.

ELLIOT, D. H. 1965. Geology of north-west Trinity Peninsula, Graham Land. *British Antarctic Survey Bulletin*, No. 7, 1–24.

EWING, M., DONN, W. L. *and* W. FARRAND. 1960. Revised estimate of Pleistocene ice volume and sea-level lowering. *Bull. geol. Soc. Am.*, **71**, No. 12, 1861.

FAIR, T. J. D. 1943. Pleistocene and Recent strand movements in southern Natal. *Trans. geol. Soc. S. Afr.*, **46**, 13–22.

FERGUSON, D. 1915. Geological observations in South Georgia. *Trans. R. Soc. Edinb.*, **50**, Pt. 4, No. 23, 797–814.

FERUGLIO, E. 1950. Edad de las terrazas marinas de la Patagonia. *18th Int. geol. Congr., London, 1948*, Pt. 9, 30–39.

FOLK, R. L. 1954. The distinction between grain size and mineral composition in sedimentary-rock nomenclature. *J. Geol.*, **62**, No. 4, 344–59.

————. 1959. *Petrology of sedimentary rocks.* Austin, Texas, University of Texas.

FRAKES, L. A. 1966. Geologic setting of South Georgia island. *Geol. Soc. Am. Bull.*, **77**, No. 12, 1463–68.

FRAY, C. *and* M. EWING. 1963. Pleistocene sedimentation and fauna of the Argentine shelf. I. Wisconsin sea level as indicated in Argentine continental shelf sediments. *Proc. Acad. nat. Sci. Philad.*, **115**, No. 6, 113–26.

FREY, R. W. 1970. Trace fossils of Fort Hays Limestone Member of Niobrara Chalk (Upper Cretaceous), west-central Kansas. *Paleont. Contr. Univ. Kans.*, Cretaceous 2, Art. 53, 41 pp.

FYFE, W. S., TURNER, F. J. *and* J. VERHOOGEN. 1958. Metamorphic reactions and metamorphic facies. *Mem. geol. Soc. Am.*, No. 73, 259 pp.

GOODELL, H. G., WATKINS, N. D., MATHER, T. T. *and* S. KOSTER. 1968. The Antarctic glacial history recorded in sediments of the Southern Ocean. (*In* TANNER, W. F., *ed.* Tertiary sea-level fluctuations. *Palaeogeogr., Palaeoclim., Palaeoecol.*, **5**, No. 1, 41–62.)

GORDON, W. T. 1930. A note on *Dadoxylon* (*Araucarioxylon*) from the Bay of Isles. (*In Report on the geological collections made during the voyage of the "Quest" on the Shackleton–Rowett Expedition to the South Atlantic and Weddell Sea in 1921–1922.* London, Trustees of the British Museum, 24–27.)

GREGORY, J. W. 1915. The geological relations and some fossils of South Georgia. *Trans. R. Soc. Edinb.*, **50**, Pt. 4, No. 24, 817–22.

[HAMILTON, W. *and* R. L. ARMSTRONG.] 1969. Late Tertiary glaciation of Antarctica. (*In* Geological Survey research, 1969. Chapter A. *Prof. Pap. U.S. geol. Surv.*, No. 650–A, A214.)

HAWKES, D. D. 1962. The structure of the Scotia arc. *Geol. Mag.*, **99**, No. 1, 85–91.

HAWKINS, J. W. 1967. Prehnite-pumpellyite facies metamorphism of a graywacke-shale series, Mount Olympus, Washington. *Am. J. Sci.*, **265**, No. 9, 798–818.

———. *and* J. T. WHETTEN. 1969. Graywacke matrix minerals. *Science, N.Y.*, **166**, No. 3907, 868–70.

HAY, R. L. 1966. Zeolites and zeolitic reactions in sedimentary rocks. *Spec. Pap. geol. Soc. Am.*, No. 85, 130 pp.

HOLTEDAHL, O. 1929. On the geology and physiography of some Antarctic and sub-Antarctic islands. *Scient. Results Norw. Antarct. Exped.*, No. 3, 172 pp.

HORNE, R. R. 1967. *The geology of part of south-eastern Alexander Island.* Ph.D. thesis, University of Birmingham, 164 pp. [Unpublished.]

———. *and* B. J. TAYLOR. 1969. Calcareous concretions in the Lower Cretaceous sediments of south-eastern Alexander Island. *British Antarctic Survey Bulletin*, No. 21, 19–32.

JOHN, B. S. *and* D. E. SUGDEN. 1971. Raised marine features and phases of glaciation in the South Shetland Islands. *British Antarctic Survey Bulletin*, No. 24, 45–111.

JOYCE, J. R. F. 1950. Stone runs of the Falkland Islands. *Geol. Mag.*, **87**, No. 2, 105–15.

KATZ, H. R. *and* W. A. WATTERS. 1966. Geological investigation of the Yahgan Formation (Upper Mesozoic) and associated igneous rocks of Navarino Island, southern Chile. *N.Z. Jl Geol. Geophys.*, **9**, No. 3, 323–59.

KUENEN, P. H. 1953. Significant features of graded bedding. *Bull. Am. Ass. Petrol. Geol.*, **37**, No. 5, 1044–66.

———. 1964. Deep-sea sands and ancient turbidites. (*In* BOUMA, A. H. *and* A. BROUWER, *ed. Developments in sedimentology. Vol. 3. Turbidites.* Amsterdam, London, New York, Elsevier Publishing Company, 3–33.)

———. *and* C. I. MIGLIORINI. 1950. Turbidity currents as a cause of graded bedding. *J. Geol.*, **58**, No. 2, 91–127.

LAWRENCE, D. B. *and* E. G. LAWRENCE. 1959. Recent glacier variations in southern South America. *Tech. Rep. Am. geogrl Soc. S. Chile Exped., 1959*, No. 1, 39 pp.

LOVELL, J. P. B. 1969. Tyee Formation: a study of proximality in turbidites. *J. sedim. Petrol.*, **39**, No. 3, 935–53.

MCBRIDE, E. F. 1962. Flysch and associated beds of the Martinsburg Formation (Ordovician), central Appalachians. *J. sedim. Petrol.*, **32**, No. 1, 39–91.

MCCALL, J. G. 1960. The flow characteristics of a cirque glacier and their effect on glacial structure and cirque formation. (*In* LEWIS, W. V., *ed. Investigations on Norwegian cirque glaciers.* London, Royal Geographical Society, 39–62. (R.G.S. Research Series, No. 4.))

MERCER, J. H. 1968. The discontinuous glacio-eustatic fall in Tertiary sea level. (*In* TANNER, W. F., *ed.* Tertiary sea-level fluctuations. *Palaeogeogr., Palaeoclim., Palaeoecol.*, **5**, No. 1, 77–85.)

———. 1969. Glaciation in southern Argentina more than two million years ago. *Science, N.Y.*, **164**, No. 3881, 823–25.

MOORE, C. 1870. Australian Mesozoic geology and palaeontology. *Q. Jl geol. Soc. Lond.*, **26**, Pt. 1, 226–60.

NICHOLS, R. L. *and* M. M. MILLER. 1951. Glacial geology of Ameghino Valley, Lago Argentino, Patagonia. *Geogrl Rev.*, **41**, No. 2, 274–94.

OTALORA, G. 1964. Zeolites and related minerals in Cretaceous rocks of east-central Puerto Rico. *Am. J. Sci.*, **262**, No. 6, 726–34.

PETTIJOHN, F. J. 1949. *Sedimentary rocks.* 1st edition. New York, Harper and Brothers.

———. 1957. *Sedimentary rocks.* 2nd edition. New York, Evanston and London, Harper and Brothers.

RICHARDS, H. *and* W. BROECKER. 1963. Emerged Holocene South American shorelines. *Science, N.Y.*, **141**, No. 3585, 1044–45.

SCOTT, K. M. 1966. Sedimentology and dispersal pattern of a Cretaceous flysch sequence, Patagonian Andes, southern Chile. *Bull. Am. Ass. Petrol. Geol.*, **50**, No. 1, 72–107.

SIMPSON, S. 1957. On the trace-fossil *Chrondrites. Q. Jl geol. Soc. Lond.*, **112** (for 1956), Pt. 4, No. 448, 475–96.

SMITH, J. 1960. Glacier problems in South Georgia. *J. Glaciol.*, **3**, No. 28, 705–14.

STANLEY, D. J. *and* A. H. BOUMA. 1964. Methodology and palaeogeographic interpretation of flysch formations: a summary of studies in the Maritime Alps. (*In* BOUMA, A. H. *and* A. BROUWER, *ed. Developments in sedimentology. Vol. 3. Turbidites.* Amsterdam, London, New York, Elsevier Publishing Company, 34–64.)

TAYLOR, B. J. 1967. Trace fossils from the Fossil Bluff Series of Alexander Island. *British Antarctic Survey Bulletin*, No. 13, 1–30.

TEN HAAF, E. 1956. Significance of convolute lamination. *Geologie Mijnb.*, **18**, No. 6, 188–94.

THOMSON, M. R. A. 1967. A probable Cretaceous invertebrate fauna from Crabeater Point, Bowman Coast, Graham Land. *British Antarctic Survey Bulletin*, No. 14, 1–14.

TRENDALL, A. F. 1953. The geology of South Georgia: I. *Falkland Islands Dependencies Survey Scientific Reports*, No. 7, 26 pp.

———. 1959. The geology of South Georgia: II. *Falkland Islands Dependencies Survey Scientific Reports*, No. 19, 48 pp.

TYRRELL, G. W. 1930. The petrography and geology of South Georgia. (*In Report on the geological collections made during the voyage of the "Quest" on the Shackleton–Rowett Expedition to the South Atlantic and Weddell Sea in 1921–1922*. London, Trustees of the British Museum, 28–54.)

VANCE, J. A. 1968. Metamorphic aragonite in the prehnite-pumpellyite facies, northwest Washington. *Am. J. Sci.*, **266**, No. 4, 299–315.

WALKER, R. G. 1965. The origin and significance of the internal sedimentary structures of turbidites. *Proc. Yorks. geol. Soc.*, **35**, Pt. 1, No. 1, 1–32.

WEEKS, L. G. 1963. Environment and mode of origin and facies relationships of carbonate concretions in shales. *J. sedim. Petrol.*, **23**, No. 3, 162–73.

WILCKENS, O. 1937. Geologische Ergebnisse der Deutschen Süd-Georgien Expedition Dr. Kohl-Larsen, 1928–29. *Geol. Rdsch.*, **28**, 127–28.

———. 1947. Paläontologische und geologische Ergebnisse der Reise von Kohl-Larsen (1928–29) nach Süd-Georgien. *Abh. senckenb. naturforsch. Ges.*, No. 474, 66 pp.

WILLIAMS, H., TURNER, F. J. *and* C. M. GILBERT. 1954. *Petrography: an introduction to the study of rocks in thin sections.* San Francisco, W. H. Freeman and Co.

WINKLER, H. G. F. 1965. *Petrogenesis of metamorphic rocks.* Berlin, Heidelberg, New York, Springer-Verlag.

ZEUNER, F. E. 1945. *The Pleistocene period: its climate, chronology and faunal succession.* London, Ray Society.

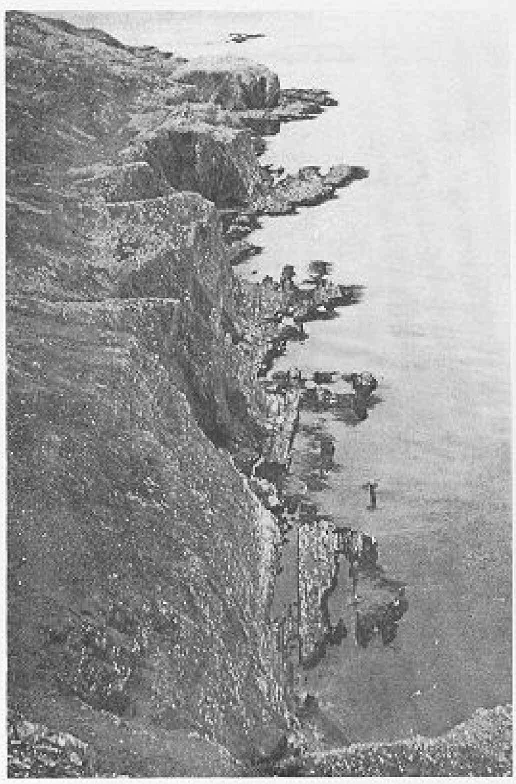
PLATE I

a. Southerly view from Coronda Peak, Stromness Bay. Headland development between the bays is due to the resistance of vertical strata to marine erosion with the preservation of the old smooth concave foreland. Olsen Valley (centre background) is low-lying and glacier-free. The glacierized Allardyce Range comprises Mount Sugartop (2,324 m.; left), Marikoppa (1,841 m.; centre) and Three Brothers (2,040 m.; extreme right).

b. Overfolded strata marking the northern side of Lighthouse Bay, Prince Olav Harbour. Wave-cut offshore rock platforms have formed at the base of the 30–35 m. cliffs in the old foreland level. The extent of the platforms in the vertical strata marks the hinge of the overfold to the south of which marine erosion has destroyed flat-lying strata.

c. Smooth concave hillside and low flat-lying foreland at Bellingshausen Point, Beckmann Fjord. Comparison with Holtedahl's (1929, pl. XXVII, fig. 2) photograph shows a recession of the hanging glacier from the lip of the cirque in the past 40 yr. The firn line is at about 340 m. Summit levels of a similar altitude occur on the islands of the Bay of Isles, indicating the past extent of foreland development due to piedmont glacierization of the South Georgia coastline.

a



b

c

PLATE II

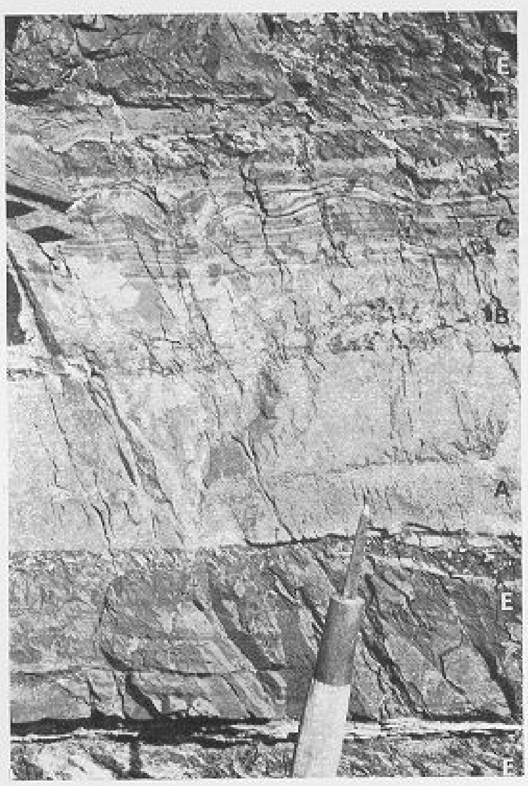
a. Photograph showing the extent of raised beaches at Elephant Lagoon and Sheep Point, Prince Olav Harbour.

b. Flute casts on slightly overfolded strata at Point Abrahamsen, Prince Olav Harbour. The cliff is 15 m. high and the current direction is from east to west.

c. Part of an "idealized" turbidite sequence at Cape Saunders, Stromness Bay. The parts are explained in Fig. 12.

a

b



c

PLATE III

a. A partly weathered out "cannon-ball" concretion 50 cm. wide in massive greywacke; East Bay, Prince Olav Harbour.

b. Westerly dipping fracture cleavage cutting earlier *en échelon* tension gashes in a vertical pelitic stratum. The competence of the diagenetically formed "cannon-ball" concretion is comparable with that of the matrix rock since the quartz-filled *en échelon* tension gashes cut both the concretion and the matrix rock without discontinuity.

c. A small thrust plane sub-parallel to the axial-plane cleavage and which disappears into a bedding plane after cutting a small parasitic fold at Lighthouse Bay, Prince Olav Harbour.

d. Convolute lamination resembling deformed current-ripple lamination; Prince Olav Harbour. The upper unit of parallel lamination is absent.

a

b

c

d

PLATE III

PLATE IV

a. Pseudo-nodules in the hand specimen (× 1).

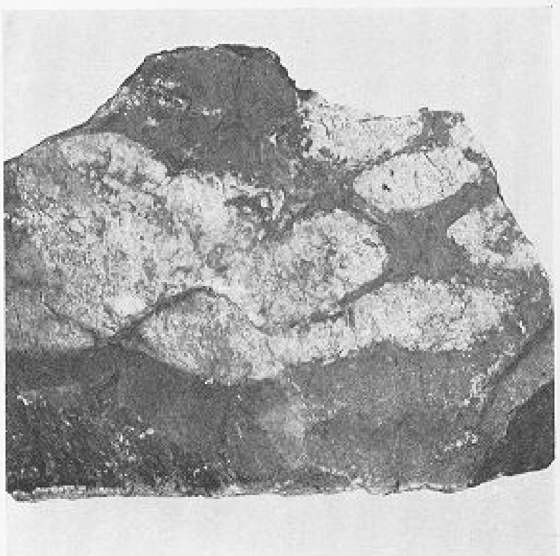
b. A narrowly turriculate gastropod with possible affinities to *Rhabdocolpus* (× 10).

c. A contact print made from a peel of a section cut through a "cannon-ball" concretion. The organism, possibly the shell of a lamellibranch, rests in the slightly coarser stratum and is completely recrystallized. A calcite-filled veinlet crosses the concretion diagonally, and the face is cut by later parallel-trending fracture cleavage.

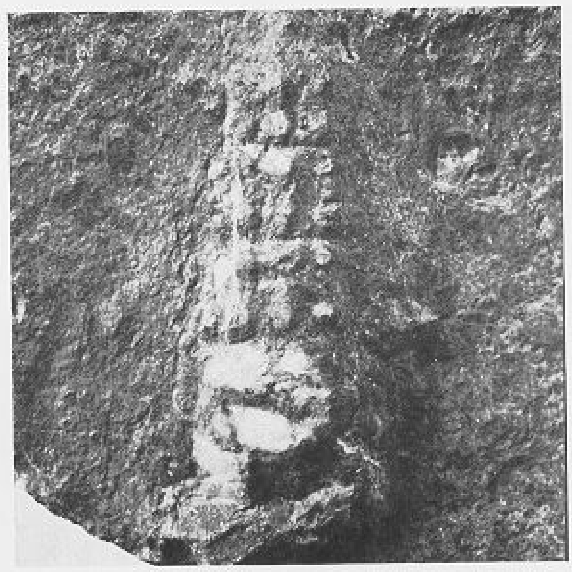
d. A discrete exotic burrowed mudstone surrounded by a prehnitized aureole and enclosed in compacted mudstone with prehnitized banding. The burrows (arrowed) are similar to those in Plate IVe.

e. A perpendicular section through the upper part of a bioturbated mudstone, showing the irregular shape of the burrows (now completely prehnitized) and the distortion (mainly down-warping) of the bedding.

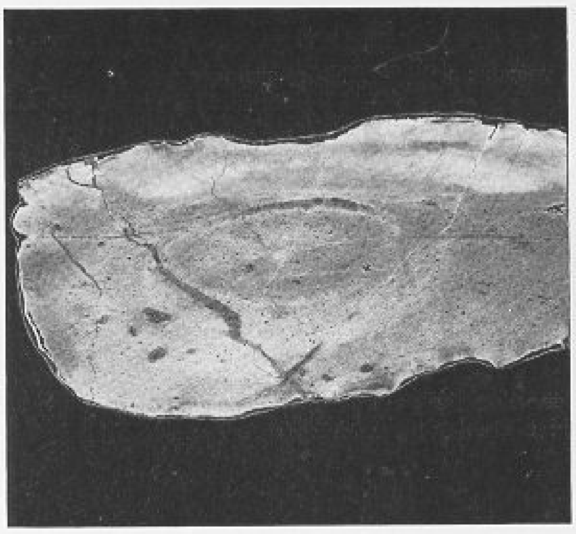
f. A discrete reddish translucent spherical and unornamented (?) algal body (15–20 μm. in diameter) common in slates.



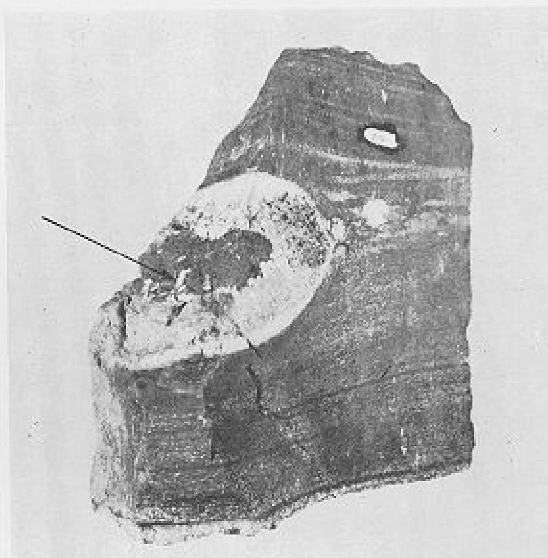
a



b

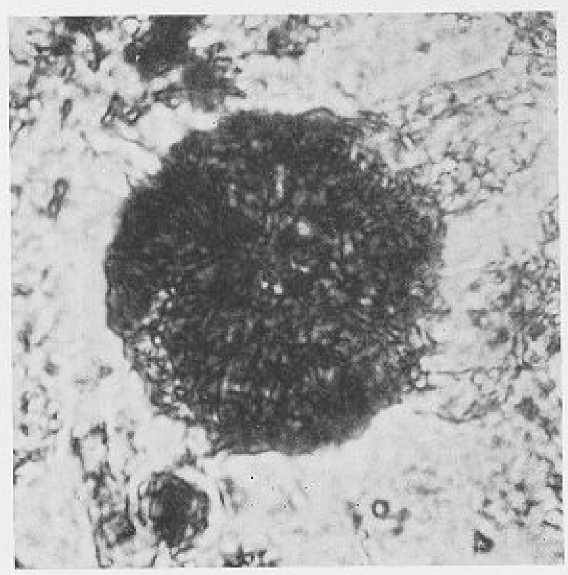


c



d

e



f

PLATE V

a. Chloritized matrix to a microlitic groundmass of a volcanic clast (M.225.4b; ordinary light; ×155).

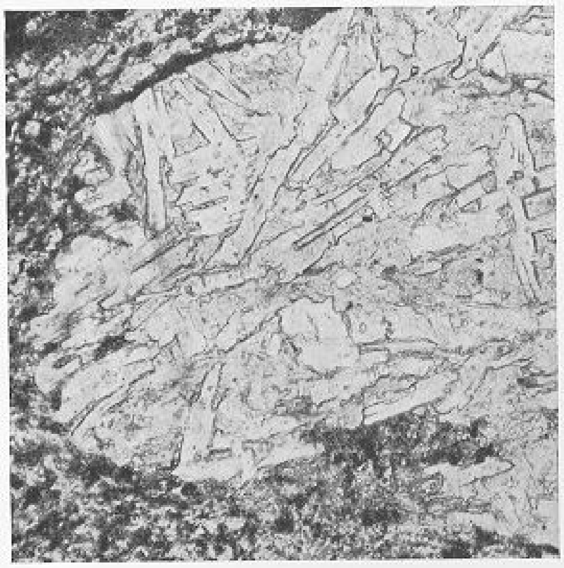
b. Prehnite development parallel to the twin plane of albitized plagioclase (M.247.2; X-nicols; ×65).

c. Aggregates of authigenic quartz in highly birefringent prehnite which has pseudomorphed plagioclase (M.213.1; X-nicols; ×130).

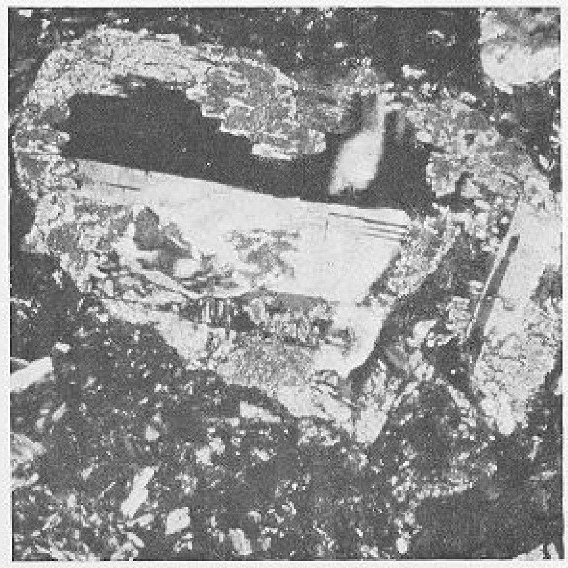
d. Granular amygdales of authigenic quartz with penninite inclusions in a volcanic clast (M.215.1; X-nicols; ×137).

e. Amygdaloidal spherulitic chlorite and granular authigenic quartz in a volcanic clast; Q, quartz (M.215.1; ordinary light; ×52).

f. A section of a nodular "cannon-ball" concretion showing recrystallized platy calcite with dark margins of leucoxene in a penninite matrix. a, apatite; p, penninite (M.220.1; ordinary light; ×53).

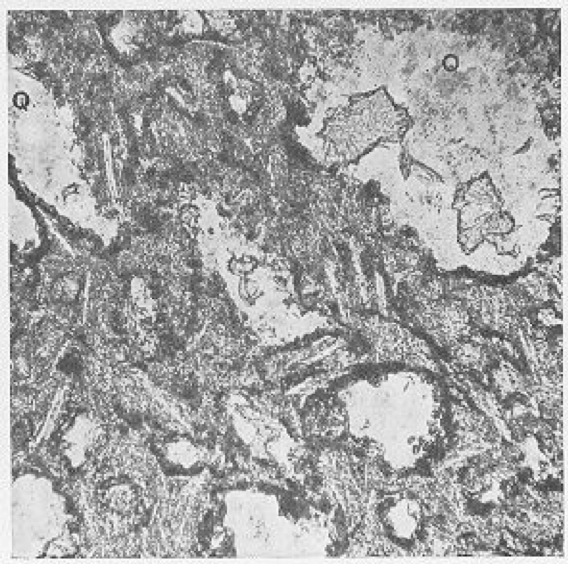


a

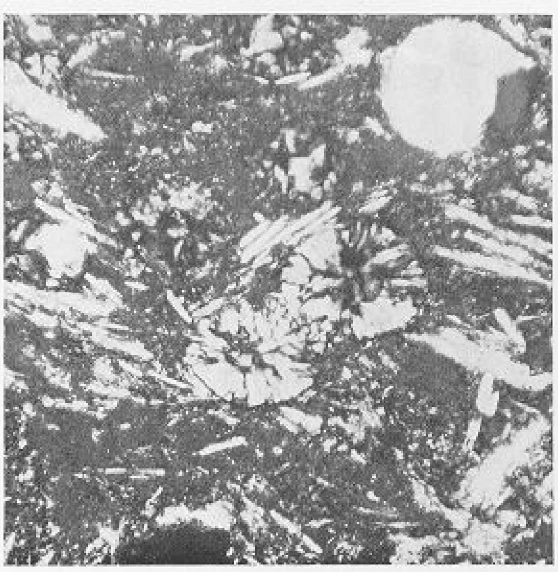


b

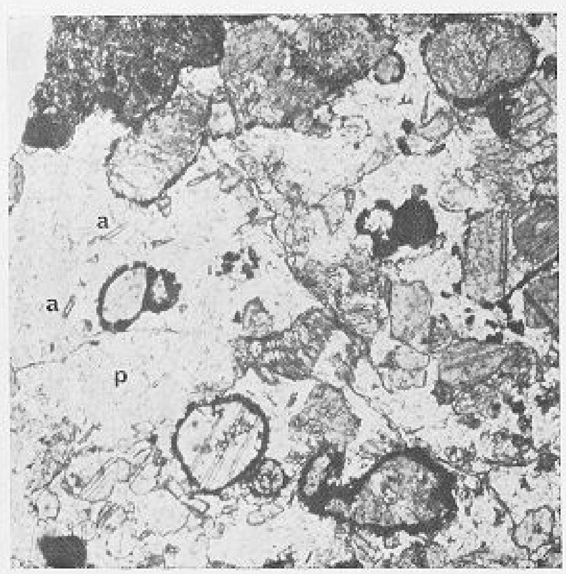
c



d



e



f

PLATE VI

a. Prehnite of high relief and birefringence with authigenic quartz in a fine-grained quartzite (M.235.3; ordinary light; ×48).

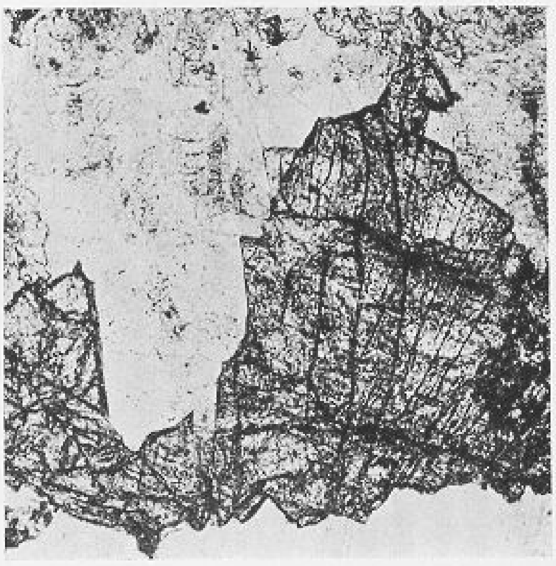
b. Prehnite development as globular to reniform masses approaching spherulites occurring interstitially in fine-grained quartzite; 0·1 mm. diameter (M.235.1; X-nicols; ×330).

c. An almost complete pseudomorph of prehnite developing in the core of an albitized plagioclase lath in an argillaceous greywacke (M.225.4b; X-nicols; ×175).

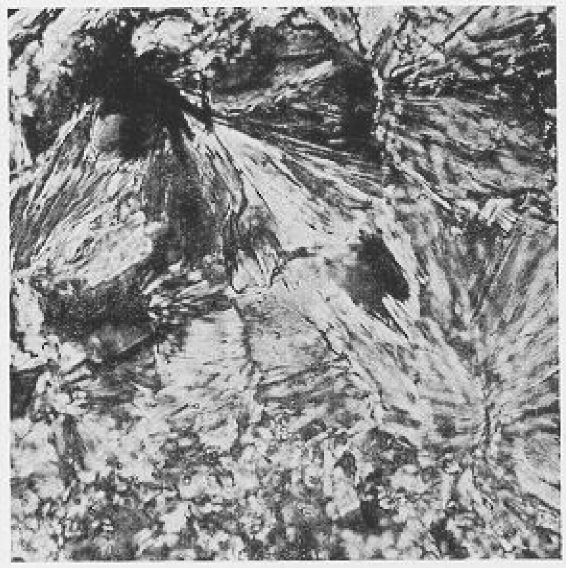
d. A Radiolaria completely replaced by optically discontinuous low-birefringent prehnite which suggests successive stages of replacement (M.248.3; X-nicols; ×160).

e. Typical prehnite development in a quartz veinlet (M.222.7; ordinary light; ×54).

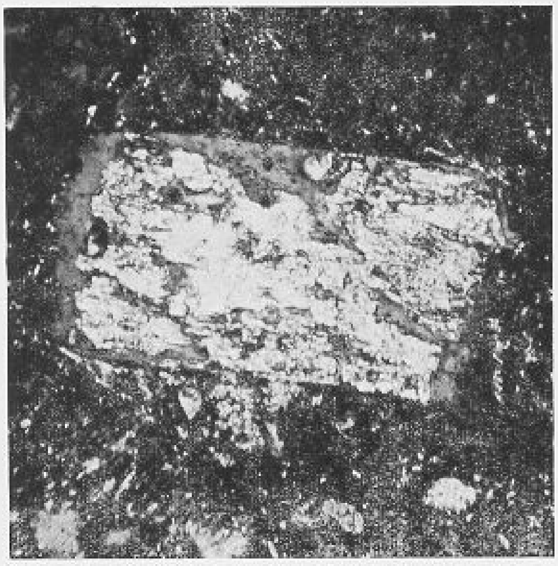
f. Partial "bow-tie" structure of exsolved prehnite and quartz infilling the bioturbate structures in the upper parts of a pelitic unit. Secondary quartz veinlets cut the radiate structures, suggesting pre-tectonic authigenic development of the quartz-prehnite facies of burial metamorphism (M.223.1; X-nicols; ×55).



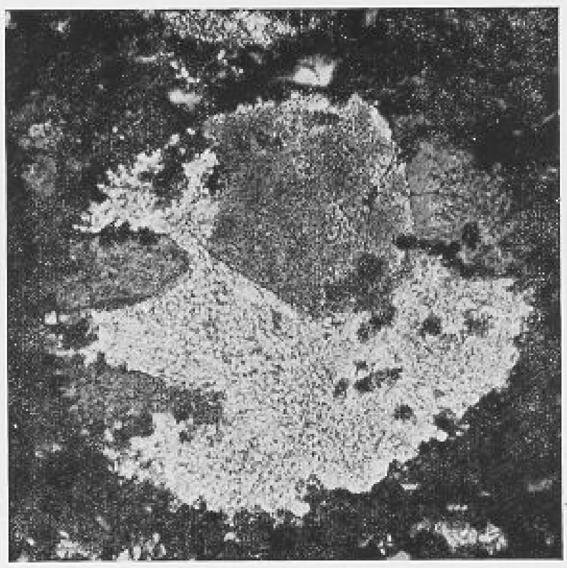
a



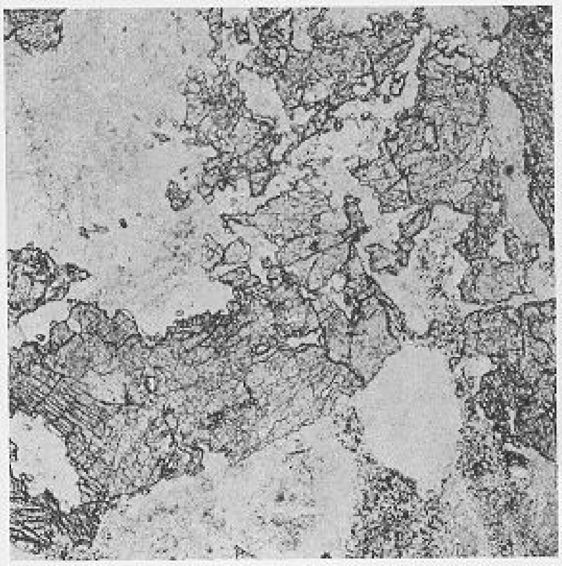
b



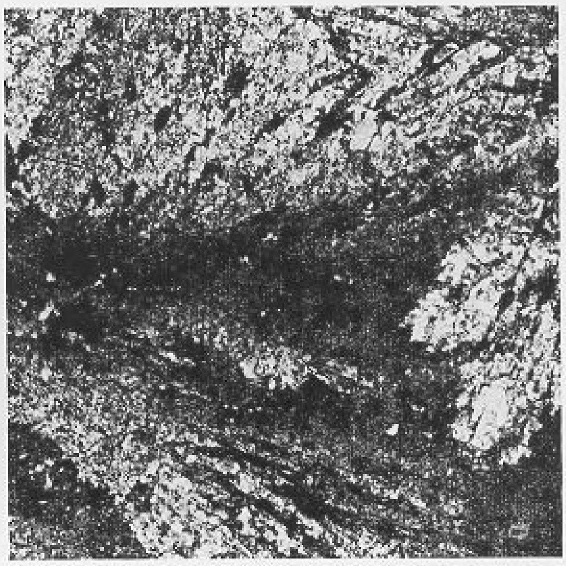
c



d



e



f