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THE GEOLOGY OF SOUTH GEORGIA:
IV. BARFF PENINSULA AND ROYAL BAY AREAS

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ABSTRACT

THE history of the geological exploration of South Georgia is briefly outlined, with special reference to the controversy surrounding the relationship between the two main lithostratigraphic units. These two units, the one composed of volcaniclastic greywackes and the other of quartzose greywackes, are now considered to be facies variants within a single turbidite sequence deposited during the Upper Jurassic and Lower Cretaceous. The names *Sandebugten Formation* and *Cumberland Bay Formation* are proposed for the quartzose and volcaniclastic greywackes, respectively. The most distal part of the Cumberland Bay Formation is described as the *Barff Point Member*. A continuous lateral variation in the composition of the detrital components of the greywackes has been established and it is likely that the two formations were derived from opposite sides of the depositional basin; the volcaniclastic greywackes from an active volcanic island arc, and the quartzose greywackes from a continental landmass. The sedimentology of the Cumberland Bay Formation suggests a lateral variation in proximality compatible with this theory which is also supported by the sparse palaeocurrent data obtained.

Deep burial of the turbidite sequence resulted in extensive prehnitization, and during polyphase deformation the metamorphic grade was locally elevated to the lower greenschist facies. The earliest folds recognized are tight to isoclinal, similar or sometimes chevron in style with north-westerly trending hinges. They have been re-folded by major overturned folds which have hinge surfaces gently inclined to the north in the Sandebugten Formation and moderately inclined to the south-west in the Cumberland Bay Formation. Post-overfolding minor fabrics are widely developed. At a late stage in orogenesis, the volcaniclastic greywackes were thrust towards the north-east over the quartzose greywackes so that the two formations are now separated by a major thrust plane. The regional metamorphic peak was also post-overfolding and caused the growth of biotite in many of the Sandebugten Formation quartzose greywackes.

A number of dolerite sheets were intruded early in the structural history of the area and these have been subsequently metamorphosed to epidiorites.

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I. INTRODUCTION

1. *Location and scope of the study*

THE island of South Georgia is one of the fragments of the isthmus of continental crust which once joined southern South America and the Antarctic Peninsula. All of the fragments have subsequently drifted eastward during the development of the Scotia Sea (Barth and Holmsen, 1939, p. 62; Hawkes, 1962) and South Georgia is now situated approximately 2,000 km. east of Cape Horn in the South Atlantic Ocean (Fig. 1). Tightly folded Mesozoic sedimentary rocks form most of the island, which measures 160 km. by 5–30 km., with a central mountain range, rising to almost 3,000 m., deeply dissected by glaciers (Plate Ia). Inland the exposure is fairly good, often as steep cliffs with extensive screes at their bases (Plate Ib) but around the coast, although the exposure may be very good locally, it can rarely be followed for any great distance (Plate Ic).

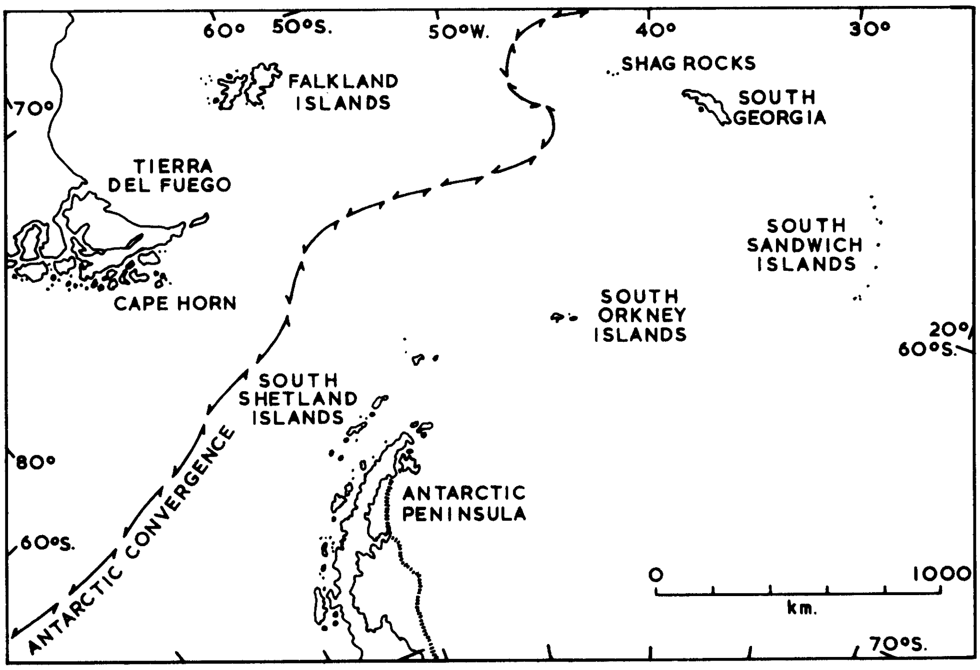

FIGURE 1

Sketch map of part of the South Atlantic Ocean, showing the geographical relationship of South Georgia to South America and the Antarctic Peninsula.

During the three austral summer field seasons of 1970–71, 1971–72 and 1973–74 the deeply embayed north-east coast of South Georgia was mapped geologically from Barff Point (lat. 54° 14′ S., long. 36° 24′ W.) to Iris Bay (lat. 54° 42′ S., long. 35° 56′ W.) (Fig. 2). The main geological results are shown on the maps of Barff Peninsula (Figs. 3 and 4) and the Royal Bay area (Figs. 5 and 6), and they are discussed in this report. Aspects of the physiography and glaciology of this area have already been published elsewhere (Clapperton, 1971; Stone, 1974, 1975).

The base maps used during the geological field work were compiled at a scale of 1 : 25,000 from a number of sources. Their accuracy therefore varies and the reliability diagram (Fig. 2) illustrates this variation. Four grades of confidence are indicated:

A. Based on the map of the Royal Bay area surveyed by the Combined Services Expedition, 1964–65, and produced at a scale of 1 : 25,000 by 42 Survey Engineer Regiment.

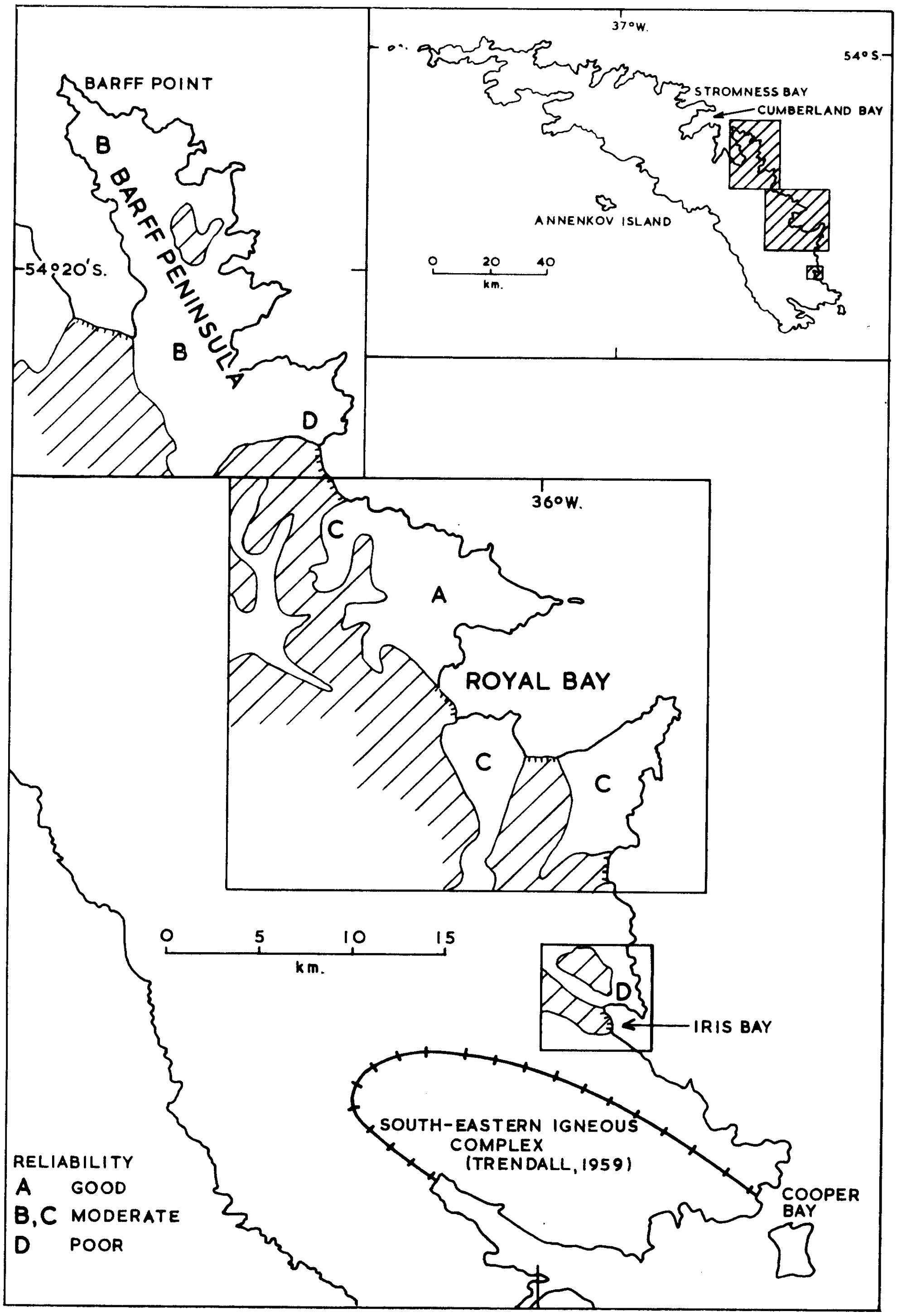

FIGURE 2

Sketch map of the north-east coast of South Georgia, showing the topographical reliability and location of the geologica maps of Barff Peninsula (Figs. 3 and 4) and the Royal Bay area (Figs. 5 and 6).

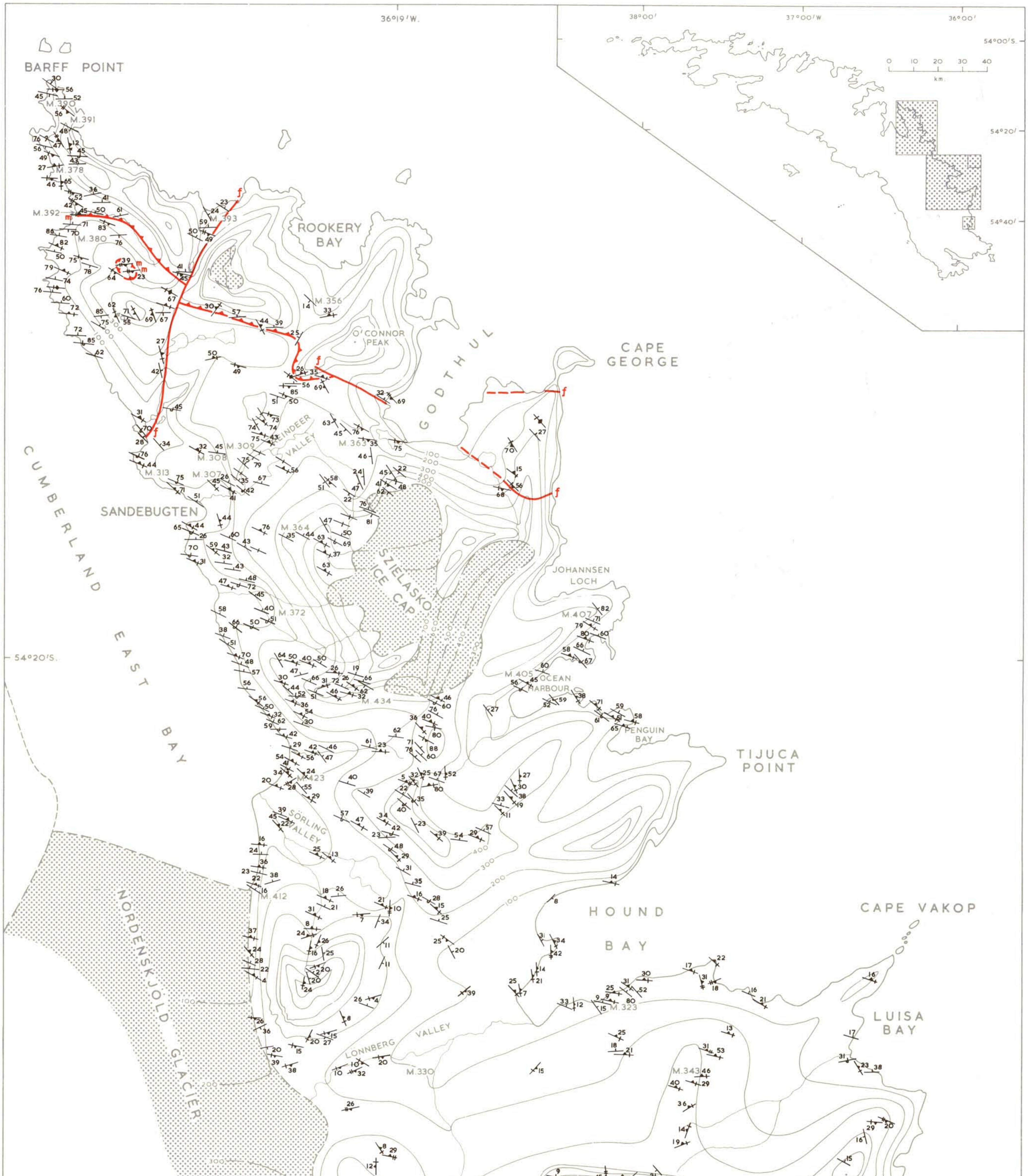

FIGURE 3

Sketch geological map of Barff Peninsula showing planar structures.

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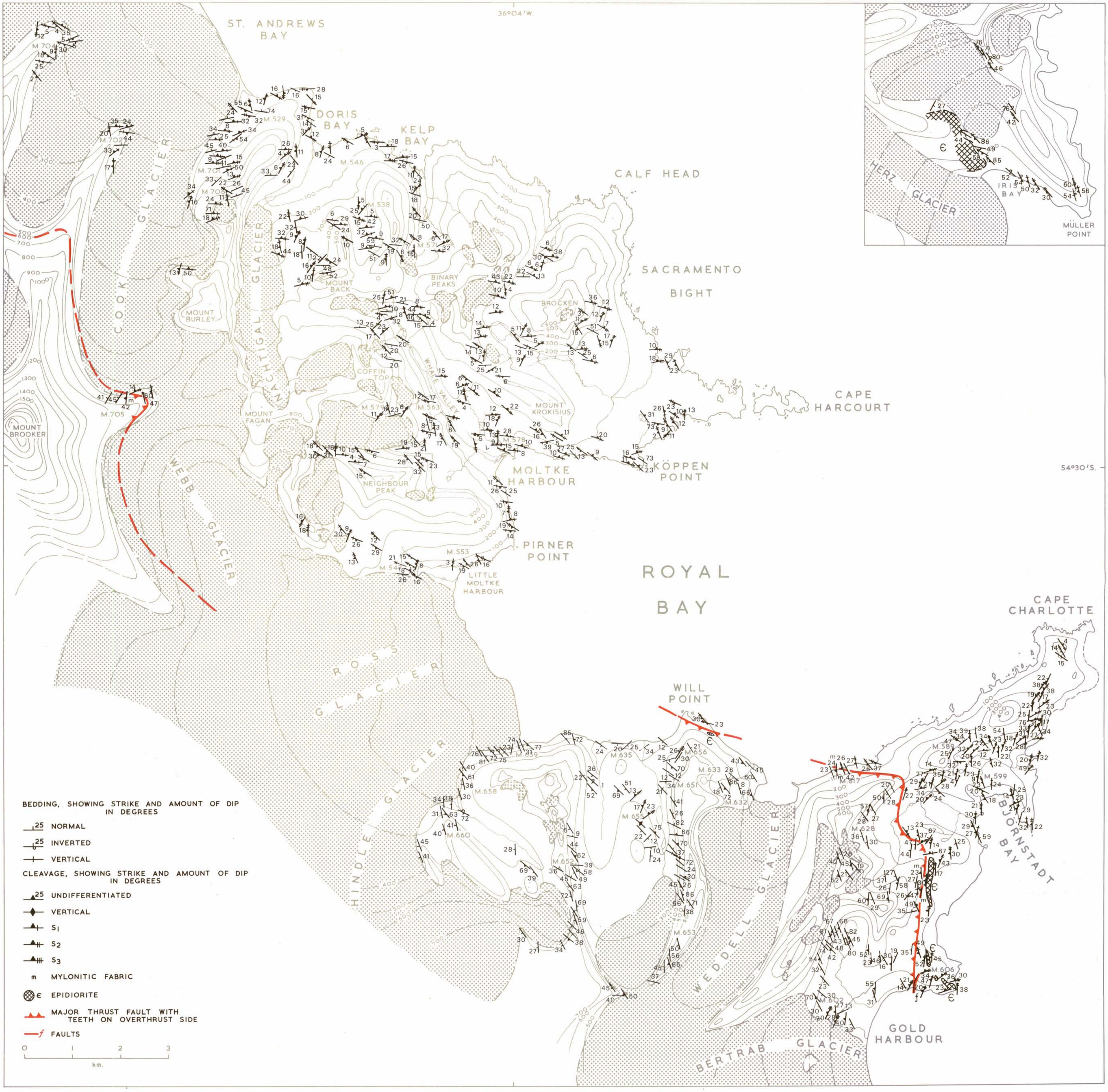

FIGURE 5
Sketch geological map of Royal Bay area showing planar structures.

[face Fig 4

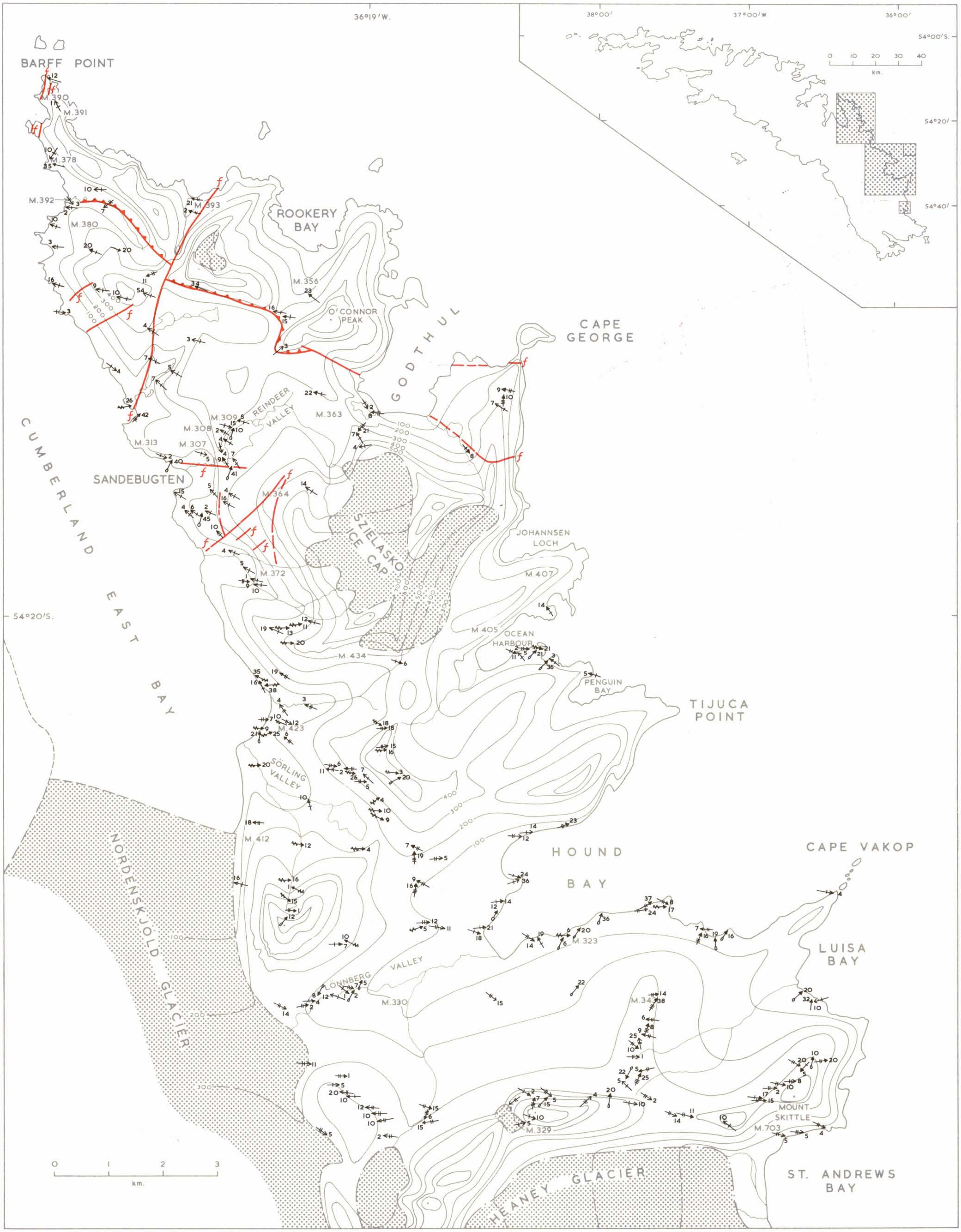

FIGURE 4
Sketch geological map of Barff Peninsula showing linear structures.

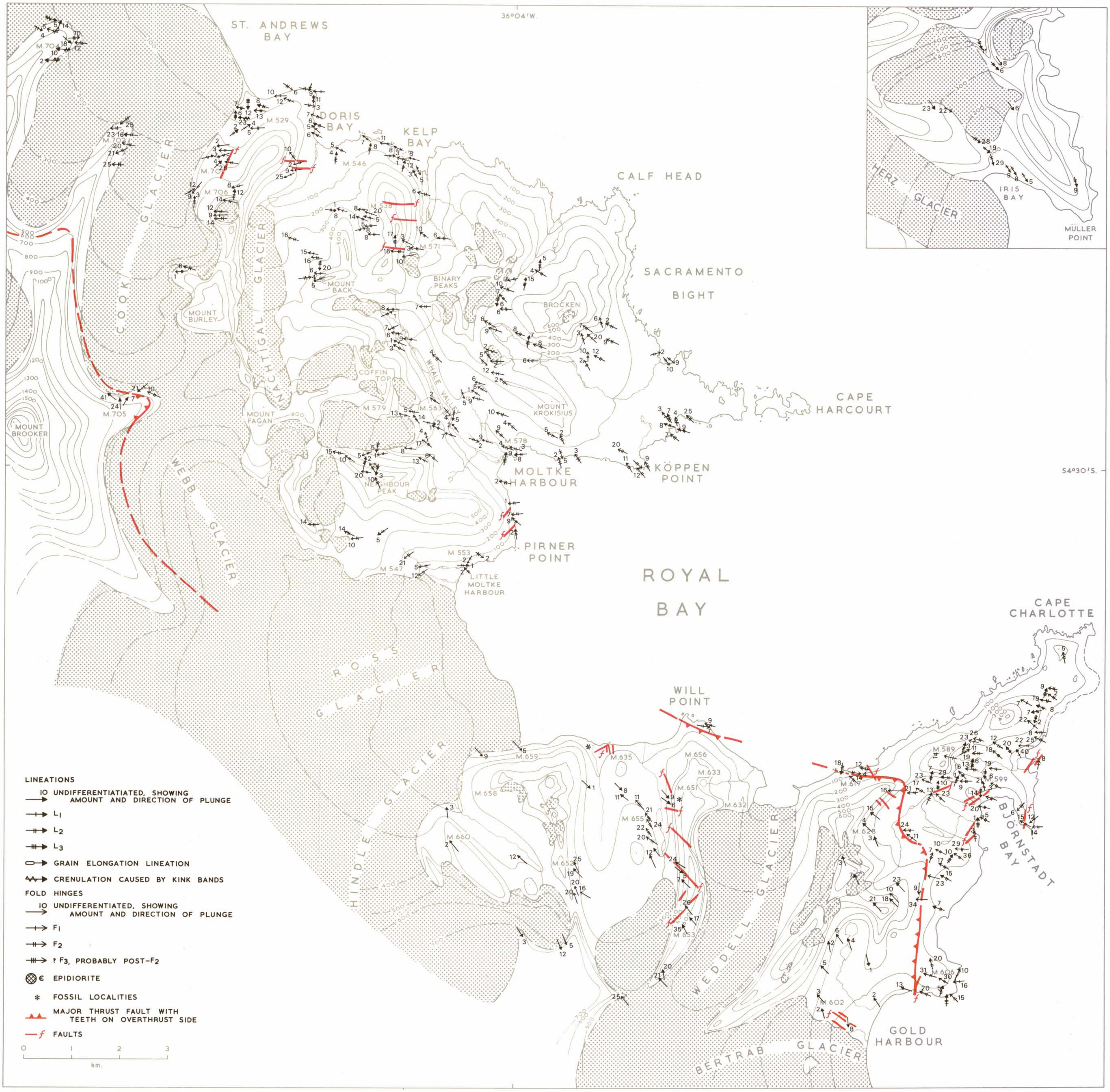

Figure 6
Sketch geological map of Royal Bay area showing linear structures.

B. Based on an unpublished map compiled by A. G. Bomford in December 1959 at a scale of 1 : 50,000. Enlarged and amended in the field.

C. Compiled from field plane-table and sketch maps, and related to the enlarged triangulation system from the map of South Georgia published by the Directorate of Overseas Surveys at a scale of 1 : 200,000 (D.O.S. 610, first edition, 1958).

D. Based on a direct enlargement of map sheet D.O.S. 610.

During compilation difficulty was encountered in matching the Royal Bay map of the Combined Services Expedition to the D.O.S. 1: 200,000 triangulation system. Two common triangulation stations were used but when these were superimposed there was an approximate 5° discrepancy between true north on the two maps. For this compilation, true north was taken from the D.O.S. 1 : 200,000 sheet and the Combined Services Expedition map was rotated accordingly. A magnetic variation of 7° W. was allowed for during field work and all bearings given in the text are true.

2. *History of geological exploration*

After the discovery of South Georgia in 1775 by James Cook geological knowledge of the island grew very slowly, mainly through the observations of scientists accompanying passing expeditions bound for the Antarctic proper (summarized by Trendall (1953, p. 1–4)). In fact, it was not until the South Georgia Survey Expeditions between 1951 and 1957 that an attempt at a comprehensive reconnaissance was made; the surveyors were accompanied for two seasons by a geologist, A. F. Trendall, whose work was published by the Falkland Islands Dependencies Survey (Trendall, 1953, 1959) and this has been summarized by Skidmore (1972, p. 3). In recent years the British Antarctic Survey has followed up the work of Trendall with detailed mapping programmes in several areas of the island; one of these has given rise to the present account. Other parts of South Georgia thus covered include the Cumberland Bay area (Aitkenhead and Nelson, 1962), the Stromness Bay and Prince Olav Harbour areas (Skidmore, 1972), Annenkov Island (Pettigrew, in press), the Cooper Bay area (Stone, in press) and parts of north-western South Georgia (Clayton, in press; Mortimore, 1979).

It is now established that the sandstones and shales of South Georgia form part of a thick Mesozoic turbidite sequence which is generally deformed and has in places suffered polyphase deformation. The folding was accompanied by lower greenschist-facies regional metamorphism and in the extreme south-east of the island part of the succession has been intruded by a syn-tectonic igneous complex. At a late stage in orogenesis major thrust movements occurred.

II. STRATIGRAPHY

THE first systematic stratigraphy for South Georgia was proposed by Ferguson (Ferguson and others, 1914; Ferguson, 1915), who recognized two separate sequences in an undistinctive succession of tuff, greywackes, mudstone, shale and phyllite. Ferguson considered the younger "Cumberland Bay Series" to be at least 5,700 ft. [1,800 m.] thick and to unconformably overlie 500 ft. [150 m.] of siliceous slates which formed the older "Cape George Harbour Series". Subsequent workers (Wordie, 1921; Holtedahl, 1929; Douglas, 1930) all disputed this stratigraphical sequence. They explained the apparent angular unconformities recognized by Ferguson as being the result of overfolding, and preferred to include all the rocks of South Georgia in a single sedimentary succession. However, from the specimens collected by Douglas, Tyrrell (1930) was able to distinguish petrologically between a tuff sequence over most of the island and a group of more siliceous siltstones and greywackes from the Barff Peninsula area. Tyrrell restricted the name "Cumberland Bay Series" to the tuffs and he suggested that the underlying siliceous rocks be called the "Godthul Harbour Series". The relationship between these two sequences remained uncertain.

Most of the fossils collected from South Georgia during this early period of investigation (Trendall, 1953, p. 22) indicated a Mesozoic age and all were found in the tuffs of the "Cumberland Bay Series". The most precise age, Upper Aptian, was obtained from the fauna collected on Annenkov Island from rocks regarded as being the youngest beds of the "Cumberland Bay Series" (Wilckens, 1947).

The first geological report arising from the work of the South Georgia Survey Expeditions (Trendall, 1953) divided the rocks into two groups on much the same criteria as those used by Tyrrell (1930). The well-cleaved siliceous grits and shales between Barff Peninsula and Royal Bay were given the name "Sande bugten Series", whereas the name "Cumberland Bay Series" was applied to the tuffs and volcaniclasti greywackes. The contact between the two sequences was described as probably tectonic, with the Mesozoi "Cumberland Bay Series" originally unconformably overlying the possibly Palaeozoic "Sandebugte Series". In his second report, Trendall (1959, p. 44) moved away from the concept of two separate se quences and described a single Mesozoic succession of turbidites, at least 10 km. thick divided by " . . a major, regional palaeogeographic change . . . " into two disticnt lithofacies. For this reason, he suggeste that the term "series" should be abandoned and that the two lithofacies of the geosynclinal sedimentar succession should be referred to as the "Sandebugten type" and the "Cumberland Bay type". However Trendall (1959, p. 42) considered that a Palaeozoic age was still possible for the Sandebugten-type rock and Adie (1964, p. 122) thought that, in the light of unpublished British Antarctic Survey mapping dat (Aitkenhead and Nelson, 1962), this was probably the case. Adie emphasized the petrological similarit between the resurrected "Sandebugten Series" and the (?) Carboniferous Trinity Peninsula Series o Graham Land. More recently, a correlation of the "Sandebugten Series" with the Permo-Carboniferou sediments of the Madre de Dios basin in southern Chile has been suggested (Dalziel and Elliot, 1973).

The idea of facies variation within a single sedimentary succession and a Mesozoic age for the Sande bugten-type rocks has re-gained support during the recent investigations and, after field work in th Cumberland Bay area in early 1973, Dalziel and Dott (1973) concluded that " . . . the Sandebugten sequenc is merely a facies of the early Cretaceous Cumberland Bay rocks . . . ".

A. Revision of Stratigraphical Nomenclature

The terms "Sandebugten type" and "Cumberland Bay type", introduced by Trendall (1959, p. 4) hav proved very useful in descriptions of the two major greywacke types of South Georgia. Since they have n stratigraphical implications, the use of these terms has avoided considerable confusion during the contro versy concerning stratigraphical relationships within South Georgia. However, now that sufficient fiel work has been carried out to clarify the situation, it seems appropriate to formalize the stratigraphy withi the accepted code of stratigraphical nomenclature (American Commission on Stratigraphic Nomencla ture, 1961).

Two major lithostratigraphic units can be recognized along the north-east coast of South Georgia Both were deposited by turbidity currents and consist of a vertical alternation of greywacke and shale but the greywackes of one (Sandebugten type) are highly quartzose whereas the greywackes of the othe (Cumberland Bay type) are dominantly volcaniclastic. The contact between the two is tectonic but the are now considered to be facies variants deposited in the same basin during the Upper Jurassic and Lowe Cretaceous (Dalziel and others, 1975; this report, p. 42).

For the quartzose greywackes the name *Sandebugten Formation* is proposed, since this has the dua advantage of continuity with the previous casual usage and the use of a geographical name close to a formally described section (Table I). This section at station M.313, measured in sea cliffs 0·5 km north-west of Sandebugten itself, should in future be regarded as the type section of the Sandebugte Formation. A reasonable degree of homogeneity is shown by the greywackes of the Sandebugten Forma tion (analyses 1–10; p. 19) across their area of outcrop which stretches for 50 km. along the north-eas coast of South Georgia from Barff Peninsula to Gold Harbour and extends inland for up to 10 km.

Correspondingly, the name *Cumberland Bay Formation* would be convenient for the volcaniclasti greywackes, but the formal proposal of this name will hopefully be accompanied in the future by th description of a type section in the Cumberland Bay area. However, in the vicinity of Barff Point a smal klippe-like "outlier" of the Cumberland Bay Formation overlies a thrust plane above the Sandebugte Formation. The rocks forming this "outlier" are atypical in that they represent a mixed unit of greywacke ranging in composition from volcanic greywacke to greywacke very much richer in quartzose detritu (analyses 11–15; p. 22). These are considered to be the most distal rocks of the Cumberland Bay Formation deposited in the transition zone to the Sandebugten Formation. Their unusual composition and physica isolation is emphasized by referring to them as the *Barff Point Member* of the Cumberland Bay Formation.

Recent fossil discoveries in the Cumberland Bay Formation confirm the Upper Mesozoic age. Gastro pods from Prince Olav Harbour (Skidmore, 1972) have a probable range of Lower Triassic–Lower Cre taceous. Belemnite fragments from the Royal Bay area have an age range of Upper Jurassic–lowest

Cretaceous (Stone and Willey, 1973) and belemnites from Annenkov Island are considered to be probably Albian (Pettigrew and Willey, 1975). Several of the ammonites from Annenkov Island described by Wilckens (1947) as Aptian have been re-examined by Casey (1961, p. 56), who considered that they more closely resemble Neocomian forms.

B. Sandebugten Formation

1. *Lithology*

The rocks of the Sandebugten Formation cropping out along the north-east coast of South Georgia (Fig. 7) vary in texture from gravel-conglomerate, containing grains up to 5 mm. in diameter, to dark

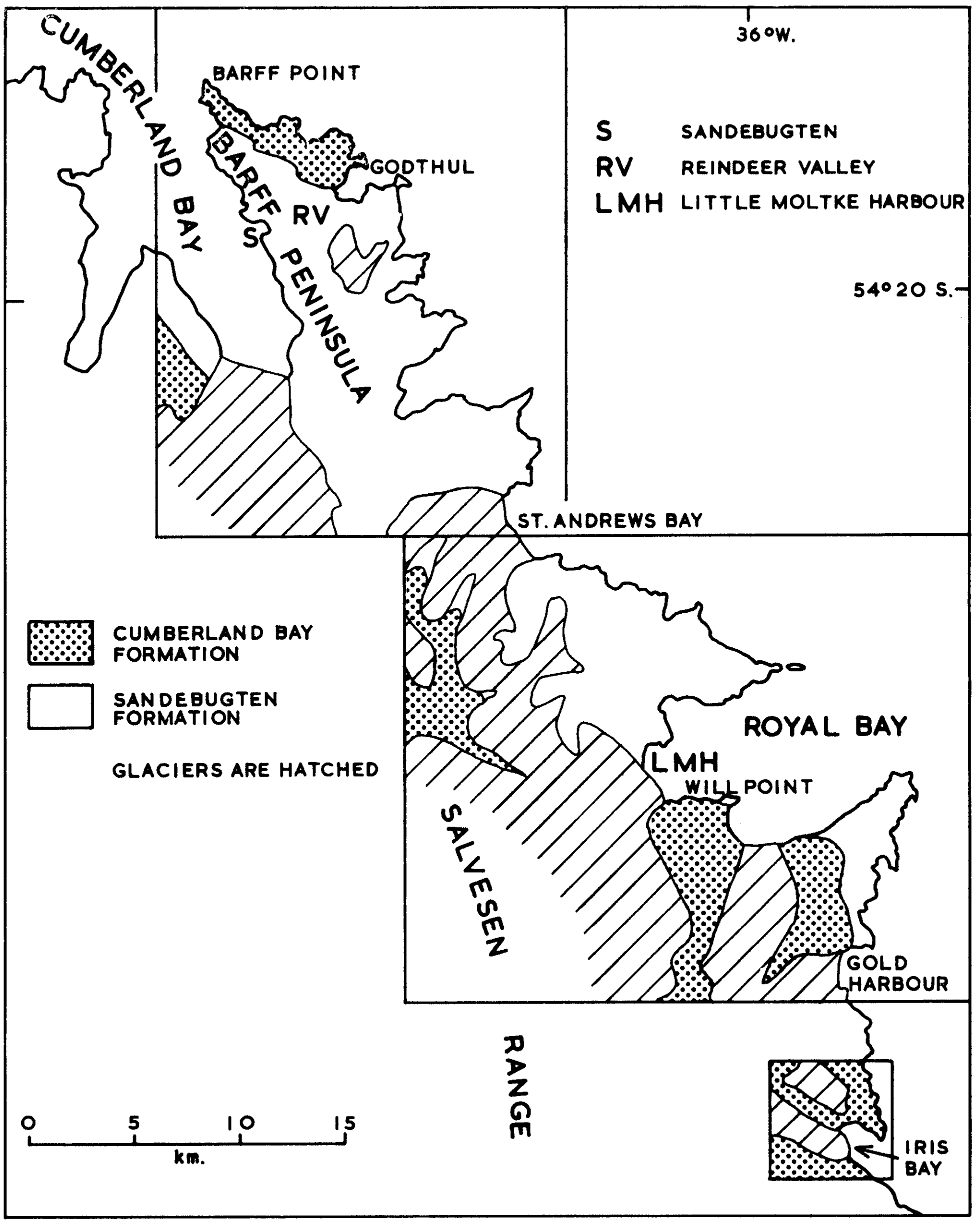

FIGURE 7

Sketch map of part of the north-east coast of South Georgia, showing the distribution of the two formations in the areas studied and some key stratigraphical locations.

fine-grained shale. Where individual grains can be distinguished, they are usually sub-rounded or sub-angular, and large flattened mud pellets are fairly common inclusions in the coarser sandstones. The pellets are frequently surrounded by a pale bleached halo, probably caused by the weathering of secondary minerals such as prehnite which seem to form preferentially in the vicinity of the very fine-grained inclusions and layers. Most of the rocks are dark in appearance, slightly indurated and were referred to in the field as greywackes. A fuller macroscopic description of the lithologies within the Sandebugten Formation has been given by Trendall (1953, p. 5–8) and showed that the succession was essentially formed of graded turbidite units ranging in thickness from a few centimetres up to 6 or 7 m. A typical section of the Sandebugten Formation was measured on sea cliffs approximately 0·5 km. north-west of Sandebugten and is summarized in Table I. The turbidite divisions recognized are related to Bouma's (1962) ideal sequence by the letters A–E immediately to the right of the pictorial column.

The varying proportions of the turbidite lithologies comprising the measured section can be summarized as follows:

Total thickness 35·05 m.

		m.	per cent
Division A	Sandstone, graded or ungraded	20·15	61·9
BCD	Laminated sandstone, siltstone and shale	9·9	30·4
E	Shale	2·5	7·7
		32·55	
	Exposure gap	2·5	
		35·05	

Laterally, the beds vary very little and within the confines of most exposures the bedding and bed thickness are very regular. The exceptions are lenses of coarse sand and gravel at the base of some of the A divisions, occasional thinning of sandstone beds and very rarely the lateral fading of current-ripple laminations into parallel laminations.

2. *Sedimentology*

In all of the Sandebugten Formation outcrops examined the majority of the turbidite units seen were either top- or middle-absent. Complete ABCDE sequences were also fairly common but base-absent units were very rare. This relationship is also shown in the measured section (Table I), where units corresponding to at least 21 turbidity flows were recognized in 30·45 m. of succession. This gives a maximum average thickness of 1·45 m. for each turbidite unit. The relative proportions of the various groupings of turbidite divisions in relation to the total thickness and to the number of flows present are summarized in Table II. The uncertainty in determining the number of turbidity flows present in any section is governed by two main factors: the repetitive grading in many of the A divisions and the thick B division in which the finely laminated sandstones may also be graded. Difficulties in field interpretation of both may possibly have resulted in the underestimation of the number of flows present, especially in the A, AB and AE categories. This would increase the already marked tendency towards top- and middle-absent turbidite units and, although reducing the average thickness of the units, would increase the overall proximality of the succession.

a. *Internal structures.* In the sandstone divisions (A), variation in the nature of the grading allows five distinct styles to be identified:

i. Ungraded.
ii. Normal size graded.
iii. Repeated size graded.
iv. Reverse graded.
v. Content graded, with the mean grain-size decreasing upwards whilst the maximum grain-size remains approximately constant.

TABLE I

DIAGRAMMATIC REPRESENTATION OF A CLIFF SECTION OF SANDEBUGTEN-TYPE ROCKS 0.5 km. NORTH-WEST OF SANDEBUGTEN

Top not seen

Bouma division	Thickness in metres	Cumulative	Comments
A	0.70	0.70	
A	2.00	2.70	Reverse grading
A	0.60	3.30	
A	0.30	3.60	
D C B	1.05	4.65	No cross lamination but open ripples have wave-length up to 10 cm.
A	0.65	5.30	Content grading Lens of gravel at base
E	0.20	5.50	*Chondrites*
DCB	0.30	5.80	Shale in hollows between ripple crests
A	0.25	6.05	
E	0.20	6.25	
B	0.20	6.45	
A	0.45	6.90	Calcareous concretions
B	2.00	8.90	
A	0.50	9.40	
B A	0.30	9.70	
E	0.10	9.80	
A	0.90	10.70	Reverse grading
A	0.45	11.15	
C B	0.90	12.05	
A	0.95	13.00	
A	0.50	13.50	
B A	1.05	14.55	Repeated grading
A	0.50	15.05	
2.5 m. gap in exposure		17.55	
B	1.00	18.55	
E	0.10	18.65	
B A	0.75	19.40	
E	0.15	19.55	
A	0.75	20.30	
E	0.40	20.70	
B	0.75	21.45	
E	0.20	21.65	*Chondrites*
A	2.00	23.65	Repeated grading
E	0.45	24.10	
A	1.85	25.95	Repeated grading
E	0.15	26.10	
DCB	0.30	26.40	
A	3.50	29.90	Groove casts at base
E	0.25	30.15	
D C B	3.00	33.15	
A	1.50	34.65	
E	0.40	35.05	*Chondrites*

Base not seen

TABLE II

SUMMARY OF THE RELATIVE PROPORTIONS OF THE VARIOUS TURBIDITE UNITS IN THE SECTION SHOWN IN TABLE I

Turbidite units		*Number of flows identified*	*As a percentage of the total succession in terms of thickness*		*As a percentage of the number of flows*	
Complete	ABCDE	3	31·0	31·0	14·3	14·3
Top-absent	ABCD	1	5·6	38·5	4·8	52·4
	ABC	1	6·0		4·8	
	AB	3	12·6		14·3	
	A	6	14·3		28·5	
Middle-absent	ABE	2	5·6	26·6	9·5	28·5
	AE	4	21·0		19·0	
Base-absent	BE	1	3·8	3·8	4·8	4·8

The ungraded sandstones (e.g. 3·30, 3·60, 9·70, 11·15, 13·50, 15·05 and 20·30 m. from the top of the section in Table I) are generally poorly sorted but they do not contain the coarsest sand or gravel fractions found at the base of graded sandstone beds. If the decreasing velocity of a turbidity current allows the shear responsible for the movement of an underlying traction carpet to fall below a critical level (Walker, 1965), the traction carpet may suddenly "freeze", resulting in the deposition of unsorted sands. A relatively immature turbidity current may also be responsible for such a feature, with deposition occurring as the velocity of the current was suddenly reduced, possibly at the first major break in the palaeoslope.

The majority of sandstones seen in the Sandebugten Formation are graded normally according to size (e.g. 5·30, 6·90, 9·40, 13·00, 19·40, 29·90 and 34·65 m. from the top of the section in Table I). However, in several other A divisions the grading is repeatedly interrupted by a sudden return to a coarser grain-size (e.g. 0·70, 14·55, 23·65 and 29·95 m. from the top of the section in Table I). This phenomenon was first noted on South Georgia by Trendall (1953, p. 7, 16, fig. 14), who referred to the repeated coarse horizons as "intra-grades". This amalgamation of graded sandstones could have been caused by a series of turbidity current flows following each other closely (Kuenen, 1953). In each case, the dense swiftly moving nose would dive beneath the more dilute tail of its predecessor and interrupt the depositional cycle with the coarse base of another A division. If a series of separate flows is not responsible for repeated graded bedding, a "pulse" of some sort within one flow might provide an alternative mechanism (Walker, 1965). This theory has similarities with the suggestion of Walton (1967) that a complex immature current may deposit a number of graded sub-units from successive coarse-grained pockets to give an A division with repeated or multiple grading. The small lenses of gravel occasionally observed at the base of sandstones (e.g. 5·30 m. from the top of the section in Table I) certainly imply deposition from an immature current (Walker, 1965).

In the A divisions of the Sandebugten Formation, reverse grading, though very much less common than normal grading, was fairly widely observed (e.g. 2·70 and 10·70 m. from the top of the section in Table I). The grain-size distributions in these cases usually result in fining in both directions away from a coarse horizon in the centre of the division. This reversal of grading must reflect a rather unusual grain distribution in the depositing current and the most likely explanation lies in the "inertia-flow" process described by Sanders (1965), who determined that when grains of mixed sizes are sheared together the larger size fraction tends to drift towards the zone of least shear strain. Since this zone lies at the top of the current, the coarse grains migrate upwards. Sanders described a waning current deposit laid down on top of the "inertia-flow" layer, resulting in a bed which is inversely graded in the lower part and normally graded in the upper part. This is precisely the situation which occurs in some of the A divisions of the Sandebugten Formation.

In relatively rare cases, the grading in the sandstones was such that, whilst the mean grain-size decreased upwards, the maximum grain-size remained constant throughout the division (e.g. 5·30 m. from the top of the section in Table I). This was referred to originally as content grading, although some authors (e.g. Walker, 1965) have used this term to describe an upward increase in the percentage of mud. This form of grading probably originated by deposition from a moderately mature current in which some degree of sorting had been achieved. A current of this type may still retain some immature characteristics and, significantly, small pockets of gravel occur at the base of the example in Table I, suggesting deposition from an immature turbidity flow.

Of the laminated divisions, only the lower parallel laminations are relatively common and, even then, there is occasional overall grading of the sandstone despite the fine intercalations of shale. In other instances, the fine-grained sandstone between the shale laminae is graded in horizons no more than 3 or 4 mm. thick. In either case, it is difficult to determine whether primary deposition or re-working of the underlying sediments was the dominant agent. In the majority of B divisions there is no sign of any grading and very fine-grained alternations of silt and clay are commoner. Where the lower parallel laminations grade up into the divisions of current-ripple lamination (C), the cross lamination seen was always on a very small scale ($\lambda < 5$ cm.) and usually indistinct. Between some of the ripple-like features, the presence of small shale lenses in the hollows may indicate accumulation of mud in sheltered positions.

Most of the black shale horizons in the Sandebugten Formation are less than 50 cm. thick, and it is impossible to determine which is the pelitic residue from the turbidity current (division E) and which is the pelagic shale resulting from normal marine sedimentation. Exceptionally, the shale thickness exceeds 3 m. and in these horizons the bulk of the sediment must have been deposited under normal marine conditions.

Most of the turbidite units in the Sandebugten Formation are either top- or middle-absent, the implication being that the tail of the turbidity current was powerful enough to sweep away much of the finer-grained material. This suggests that deposition occurred fairly close to source in a proximal environment. Walker (1967) devised a parameter (P_1), which has subsequently become known as the proximality index, based on the assumption that, in more distal turbidites, progressively higher Bouma divisions form the base of the unit. The parameter is calculated, in terms of percentages, as:

$$P_1 = A - (A \longrightarrow E) - \tfrac{1}{2}B.$$

TABLE III

A QUALITATIVE ASSESSMENT OF PROXIMALITY INDICATORS FOR THE SANDEBUGTEN FORMATION

Characteristics of proximality (Walker, 1967)	*Evidence*	*Inference*
1. Thick beds	Maximum average thickness for turbidite units is 1·45 m. thick compared to most turbidites	Proximal
2. Coarse-grained beds	Coarse sandstones fairly common	Proximal
3. Amalgamation of sandstones	Amalgamation common	Proximal
4. Beds irregular in thickness	Bedding very regular	Distal
5. Scours, wash-outs and channels common	Scours, wash-outs and channels are very rare	Distal
6. Mudstone layers poorly developed	Half of the units are top-absent	Intermediate
7. Beds ungraded or poorly graded	Most sandstones show some grading	Intermediate
8. Many complete A–E sequences	Only 14 per cent of units are complete	Distal
9. Laminations and ripples occur infrequently	Laminations common but ripples relatively rare	Possibly distal
10. Scour marks more common than tool marks	Scour marks absent, tool marks rare	Possibly distal

The A—→E sequence described by Walker is a unit in which the grading is perfect from sandstone to shale without the transition through the laminated divisions and which is less than 3 cm. thick. Turbidite sequences of this sort were grouped by Walker with the C division but, although such A—→E units exist in the Sandebugten Formation, they are all very much thicker than 3 cm. If the measured section (Table I) is at all typical, the proportion of units starting with the A division is in excess of 90 per cent. Possibly 5 per cent commence with the B division and, if these values are substituted into Walker's equation, the Sandebugten Formation rocks have a proximality index of approximately 95.

Several qualitative proximality indicators have also been suggested (Walker, 1967) and these are summarized in Table III. The evidence from these suggests a relatively distal depositional facies which is rather at variance with the high proximality index. Lovell (1970) suggested that the sandstone : shale ratio gave a better gauge of the relative proximality within a turbidite body and for the Sandebugten Formation rocks this relationship is about 4 : 1 (approximately 80 per cent sandstone). As with Walker's proximality index, the sandstone : shale ratio gives a comparative rather than an absolute value, but a ratio of 4 : 1 in the Sandebugten Formation is more compatible with a relatively distal depositional environment than a proximality index of 95. However, a considerable number of the Sandebugten Formation turbidite flows must have been fairly immature and reverse grading may indicate a proximal environment at the first major flattening of the slope (Walker, 1965). Overall, therefore, the available proximality evidence is rather contradictory and an intermediate facies may be the best compromise.

b. *External structures*. At the base of the sandstone divisions the effects of differential loading have frequently caused the development of small flame structures. Seen in cross-section, they have no dominant sense of overturning and, where a plan view was also possible, they were invariably associated with small linguoid load casts. The lack of a preferred orientation in the flame structures probably means that the palaeoslope was fairly gentle.

Tool marks were rarely observed but four measurable grooves with possible palaeocurrent significance were noted (Fig. 8) and corrected stereographically for fold-axis plunge and bedding attitude. The grooves

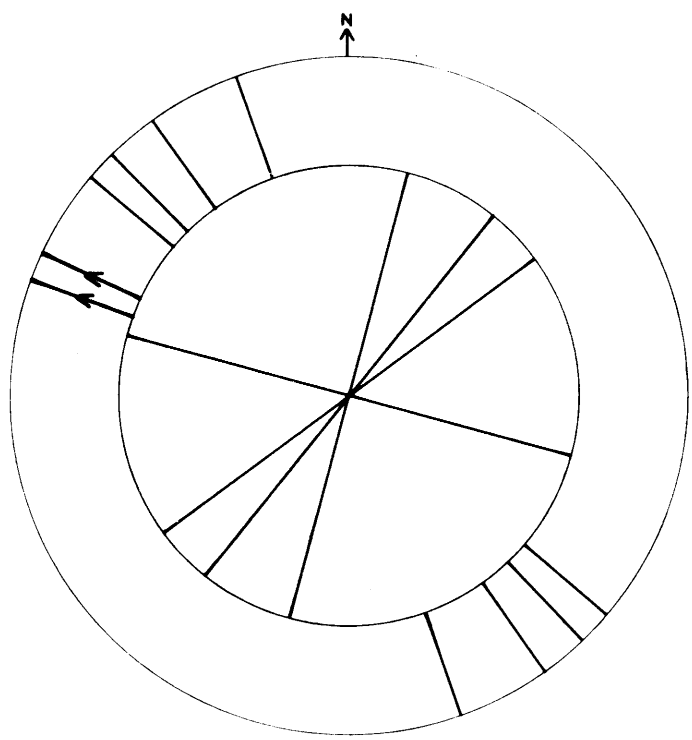

FIGURE 8

Summary of current directions indicated by groove casts (———) and flute casts (—→—).
Inner circle, Sandebugten Formation.
Outer circle, Cumberland Bay Formation south of Royal Bay.

themselves do not provide evidence for determining the direction of current flow, and associated scour features are absent. It proved very difficult to deduce palaeocurrent directions from the small-scale cross bedding in the ripple-lamination division, and frequently two cross sets in very close proximity appeared to be contradictory. However, more detailed recent work on cross laminae (Dott, 1974; Dalziel and others, 1975) has shown that currents from both the north-north-east and the south-south-west were active during the deposition of the Sandebugten Formation.

Sandstone dykes are a rare sedimentary feature, usually developed as straight-sided intrusions 1–10 cm. wide. They cut across the bedding at a high angle and show a fairly wide variety of strikes within the north-east quadrant, but their relationship to the S1 cleavage was not established.

The occurrence of calcareous concretions in the greywackes of South Georgia was commented on and discussed in some detail by Trendall (1959, p. 14–16). They are pre-tectonic syn-compaction features similar to those described from Cretaceous shales in Colombia (Weeks, 1957) as having nucleated around organic remains, but none of the examples examined in the Sandebugten Formation rocks contained obvious organic nuclei. However, in one concretion from the Sandebugten Formation west of St. Andrews Bay the nucleus consisted of a series of thin concentric discs (Plate IVc), the outer of which was about 7 cm. in diameter. Despite the initial similarity of this to some kind of nummulite, the most likely explanation is that the concretion originally built up as a series of concentric layers each of a slightly varying chemical composition. Flattening during the later stages of compaction or during orogenesis would have produced the disc-like shape and differential weathering of the layers would give the concretion its present appearance. When the specimen was removed from *in situ*, no trace of the concentric layers could be seen on fresh surfaces.

3. *Palaeontology*

The Sandebugten Formation is almost completely unfossiliferous and the only macro-fossils recovered were rare fragments of carbonized wood. In the shale divisions, numerous small clusters of radiating burrows form a *Chondrites*-like trace fossil (Simpson, 1957), which ranges from 1 to 3·5 cm. in diameter. The individual burrows are approximately 1 mm. in diameter and occasionally crescentic cross laminations can be distinguished. A few circular Radiolaria are present in most thin sections of siltstone or shale.

C. Cumberland Bay Formation

The Cumberland Bay Formation of South Georgia was previously described (Trendall, 1953, p. 5, 1959, p. 4; Skidmore, 1972, p. 14) as a thick sequence of turbidites rich in epiclastic volcanic debris. The total thickness of the greywackes and shales comprising the formation has been estimated as at least 10 km. (Trendall, 1959, p. 33). During orogenesis this succession was thrust north-eastward over the Sandebugten Formation, and subsequent erosion has isolated a small part of the thrust sheet so that the Barff Point Member of the Cumberland Bay Formation crops out between Barff Point and Godthul (Fig. 7). The main outcrop of the Cumberland Bay Formation, to the west and south of the Sandebugten Formation, covers most of South Georgia, and a limited area of this was examined south of Royal Bay between Will Point and Gold Harbour. Farther south in Iris Bay, a brief reconnaissance revealed rocks with affinities to the Cumberland Bay Formation but with a more penetrative fabric beginning to mask the original sedimentary features.

1. *Lithology*

The complete range of sandstone, siltstone and shale associated with turbidity current deposition is represented in both the Barff Point and south Royal Bay areas. The main differences between these two areas are the larger maximum grain-size and the greater thickness of the turbidite units south of Royal Bay. In this area, pebble-conglomerates contain clasts up to 3 cm. in diameter, whereas at Barff Point the maximum grain-size observed was 5 mm. diameter. Variation in the thickness of the turbidite units is due mainly to differences in the thickness of the A divisions. At Barff Point, units very rarely exceed 1·5 m. in thickness but south of Royal Bay some massive-bedded sandstones occur as units approximately

10 m. thick. In all probability these thick sandstone beds resulted from the amalgamation of several ungraded sandstones. The clasts themselves are usually sub-rounded or sub-angular but in the pebble-conglomerates there is a tendency for the larger fraction to be more rounded. Some of the pebbles can be readily identified as lava fragments packed with tiny feldspar laths. Common inclusions in the sandstones of the Cumberland Bay Formation south of Royal Bay are large pebbles of dark siltstone which are invariably surrounded by a pale-weathering halo or bleached aureole (cf. Trendall, 1953, p. 8, fig. 4B), but these were only rarely seen in the Barff Point Member. Some of the siltstone inclusions are flattened but others maintain their shape (Plate IVd), especially within the more massive sandstones where the diameter of the inclusions ranges up to 50 cm., and in a few instances the bedding drapes over them suggesting that they acted as rigid bodies during compaction and folding (cf. Trendall, 1953, pl. I, fig. 2). Occasionally a larger number of more irregular siltstone or shale flakes, each with a pale halo, forms a definite horizon within the coarser sandstones. This may well indicate brecciation of an original thin shale bed. The pale secondary halo is not restricted to inclusions and frequently the contact between shale and sandstone is marked by a pale rim within the sandstone. At one locality immediately south of Barff Point, pale patches were nucleated on the extreme tips of small flame structures.

South of Royal Bay, there seems to be an alternation of several hundred metres in which sandstone is dominant, forming as much as 90 per cent of the succession, with a much thinner sequence in which the sandstones and shales are more equally represented. These two lithological associations are very similar to the sandy and normal flysch sub-facies described by Dzulynski and Walton (1965). The varying proportions of the turbidite Bouma divisions comprising each of these sub-facies are estimated as follows:

		Sandy sub-facies (per cent)	*Normal sub-facies* (per cent)
Division A	Sandstone, graded or ungraded	80	50
BCD	Laminated sandstone, siltstone and shale	15	30
E	Shale	5	20

In total thickness the sandy sub-facies forms about five or six times as much of the succession as does the normal sub-facies. The thickness of the turbidite units ranges from 0·2 to 10 m. in the sandy sub-facies and from 0·1 to 3 m. in the normal sub-facies.

Lateral variation in bed thickness is very rare and the only change in texture seen in exposures is caused by lenses of gravel and occasionally pebbles at the base of coarse sandstones. On a much larger scale, there is a tendency for the normal sub-facies to be less well represented farther inland to the south and south-west. It seems likely that the normal sub-facies becomes more sandy in that direction, and an examination through binoculars of the crags rising to the main Salvesen Range suggests that there the sandy sub-facies forms the entire succession. Glaciers flowing from cirques at the foot of these crags bring down morainic boulders of conglomerate very much coarser than anything seen *in situ*.

2. *Sedimentology*

In the Barff Point Member of the Cumberland Bay Formation exposed between Barff Point and Godthul a large proportion of the turbidite units is middle-absent ABE sequences. Where the C division is also developed, it is invariably less than 10 cm. thick with the ripple laminations appearing as very small-scale cross sets ($\lambda < 5$ cm.). One rather unusual feature observed several times is the apparent repetition of the current-ripple and parallel laminations, so that each occurs several times in alternating divisions less than 3 cm. thick. This alternation is difficult to explain in terms of turbidity flow, especially if an alternation between the B and C divisions is involved since this would require a fluctuation of current strength between the upper and lower flow regimes. Normal oceanic currents are therefore more likely to have been involved in the deposition of these units. Amalgamation of the sandstones in the A division was only very rarely observed.

South of Royal Bay, complete ABCDE units are fairly common in the sandy sub-facies but much less so in the normal sub-facies, where middle-absent ABE units are in the majority. The massive-bedded sandstones of the sandy sub-facies are often amalgamated so that top-absent units are very common, many showing poor or no grading. Occasionally the ungraded amalgamated sandstones are interbedde with thin shale horizons to form AE units. Rarely, a perfect grading from sandstone to shale was observe with no intervening laminations, forming units similar to the A⟶E units described by Walker (1967 However, those observed were invariably at least 15 cm. thick, and Walker restricted his definition to maximum thickness of 3 cm. when used to calculate P_1. Where the laminated divisions are present, th units are usually ABCE (Plate V) or complete ABCDE but, since the D division was always very indistinct it was possibly overlooked in many exposures. Base-absent units commencing with the B division an usually formed by BCE were a rare feature of the normal sub-facies.

a. *Internal structures*. Grading of the A divisions at Barff Point was usually normal with only very rar repeated grading caused by the amalgamation of the sandstones. In contrast, south of Royal Bay, amalga mation of sandstones to give thick repeated graded beds was very common, as were thick sandstone bed with no signs of grading. Reversed grading was very rare but a number of beds show the same style c content grading as do some of the A divisions within the Sandebugten Formation.

The laminated divisions are well developed in the sandy sub-facies south of Royal Bay, and in particula the frequency of occurrence of the C division is much higher there than in either the Barff Point area or i the normal sub-facies. Good ripples are often developed without any signs of cross bedding and they ar rather similar to convolute laminations. However, the ripples frequently grow upwards into either loa casts along the base of the E division (Plate V) or, more rarely, highly contorted laminations.

The shale division (E) is well represented between Barff Point and Godthul, and in both of the sub-facie south of Royal Bay; it is only absent in those turbidite units which consisted solely of the A division an formed part of a thick amalgamated sandstone bed. In the normal sub-facies, a large proportion of th thick shale beds must have been the result of pelagic sedimentation rather than settling of the peliti residue of the turbidite.

Within the Cumberland Bay Formation south of Royal Bay the alternation of sandy and normal sub facies suggests that at a given place there was marked variation in the relative proximality of the turbidit deposition from successive flows. There is no evidence to indicate that each of the sub-facies is associate with a different source area, and the overlapping of differently orientated lobate turbidite fans from on source is unlikely to produce the marked alternation between the two sub-facies. The most likely explana tion therefore lies in variation in the strength and size of the turbidity flows. Thus, a period during whic large turbidity flows followed each other rapidly and deposited the sandy sub-facies was followed by period of relative quiescence during which deposition in the area studied was from the more distal part of smaller flows. This alternation of conditions could have been caused either by a variation in the rate o supply of sediment to the source area of the turbidites or by a variation in the intensity of the seismi activity which may have triggered off each flow. If the source area for the Cumberland Bay Formatio was an active volcanic archipelago (Trendall, 1959), both of these conditions would be satisfied, since th eruptions which produced the material for re-sedimentation would also have been accompanied b seismicity. A similar vertical alternation of proximal and more distal turbidites has been reported in muc greater detail from the western part of South Georgia (Mortimore, 1979).

Lateral variations in proximality can be best illustrated by the comparison of the proximality indicator (Walker, 1967) for each of the sub-facies south of Royal Bay with those of the succession at Barff Poir (Table IV). Assuming that the Barff Point Member and that part of the Cumberland Bay Formation expos ed south of Royal Bay represent the same stratigraphical level, there is a considerable southward increas in proximality. This trend is continued by the general observation that the sandy sub-facies forms more c the succession farther inland south of Royal Bay. Turbidity current flow has generally been from th south-east quadrant (Fig. 8), longitudinal to the depositional basin envisaged by Trendall (1959). Thu palaeocurrent and proximality indicators are in general agreement. One final piece of evidence is th distribution of calcareous concretions. Lovell (1969) found that concretions increased in more proxima turbidite deposits and, whereas they are quite rare in the Barff Point Member, calcareous concretion are large and numerous in the sandy sub-facies of the Cumberland Bay Formation immediately south c Royal Bay.

An increase in proximality towards the south would probably mean a thickening of the succession in tha direction. Thus, that part of the Cumberland Bay Formation exposed south of Royal Bay may well b

TABLE IV
A COMPARISON OF PROXIMALITY INDICATORS FOR CUMBERLAND BAY FORMATION SUB-FACIES OF SANDY AND NORMAL TYPE SOUTH OF ROYAL BAY AND THE CUMBERLAND BAY SUCCESSION OF THE BARFF POINT MEMBER

Characteristics of proximality (Walker, 1967)	*Sandy sub-facies (Royal Bay)*		*Normal sub-facies (Royal Bay)*		*Barff Point area*	
1. Thick beds	Thick beds common, some are massive	P*	Thick compared to most turbidites	P*	Thick compared to most turbidites	P*
2. Coarse-grained beds	Some pebble-conglomerates	P	Coarse sandstones rare	D	No conglomerates but some coarse sandstones	P
3. Amalgamation of sandstones	Amalgamation common	P	Amalgamation rare	D	Amalgamation rare	D
4. Beds irregular in thickness	Only local irregularities	I	Bedding very regular	D	Bedding very regular	D
5. Scours, wash-outs and channels common	Very few scours or channels	D	No scours or channels seen	D	No scours or channels seen	D
6. Mudstone layers poorly developed, indicated quantitatively by the approximate sandstone : shale ratio (Lovell, 1969)	9:1	P	3:1	I	4:1	I
7. Beds ungraded or poorly graded	Thick ungraded sandstones	P	Most sandstones show some grading	D	Most sandstones show some grading	D
8. Many complete A–E sequences	Complete units fairly common	P	Only a small minority of complete units	I	Complete units rare	D
9. Laminations and ripples occur infrequently	Laminations and ripples moderately common	I	Laminations and ripples fairly common	D	Laminations and ripples fairly common	D
10. Scour marks more common than tool marks	Scour marks and tool marks probably about equally abundant	I	No evidence		No evidence	

*Inference in terms of proximal (P), intermediate (I) or distal (D) depositional environments.

very much thicker than the more distal, chronologically equivalent, Barff Point Member. Both successions were deposited contemporaneously during the Upper Jurassic–Lower Cretaceous.

b. *External structures.* Load casts and associated flame structures are especially common in the sandy sub-facies south of Royal Bay. In these rocks the load casts are rather irregular in shape, with approximate diameters ranging up to 25 cm., and at their edges large flame structures may penetrate as far as 30 cm. into the overlying sandstone or more rarely shale. Locally, the flame structures are overturned consistently in one direction but overall there is no dominant trend, suggesting that the overturning was the result of local slope conditions rather than an indication of the more general palaeoslope or current direction. Differential loading was probably also in part responsible for the pseudo-nodules which were seen in several outcrops of the Cumberland Bay Formation (Plate VIa). These structures are always associated with well-laminated sandstones and siltstones in the B and C divisions, and may originally have formed from an organic shale horizon, since they are now preferentially prehnitized. As a result, they weather tc grey-white colour on exposed surfaces.

No tool or scour marks were observed in the Barff Point Member but south of Royal Bay a large numb of sole marks were seen, including several localized sets of grooves and two sets of small elongate flu casts. These were recorded in the sandy sub-facies and the details are summarized in Fig. 8. All of t beds concerned were folded about sub-horizontal axes and so the correction applied involved only t restoration of the bedding to the horizontal. The grooves all suggest that north-west- or south-east-direct currents were active during deposition and the flute casts confirm flow towards the north-west quadra This is in general agreement with the palaeocurrent data from other areas of the Cumberland Bay Form tion in South Georgia (Trendall, 1959; Dalziel and others, 1975) all of which have suggested a source ar to the south or south-east.

Large-scale slump structures were not seen in the Cumberland Bay Formation but locally well-bedd turbidite units have foundered. The movement is restricted to thicknesses of less than 1 m.; the contortio only continue along the bedding for 2 or 3 m. and these were probably caused by local water saturation small areas of sediment. Other irregular structures have been produced by the injection of mobile coa material into more consolidated fine-grained sandstone; straight-sided sandstone dykes, ranging fro small intrusions less than 1 cm. thick up to more massive structures which may reach thicknesses of 2 r are quite common. The vertical extent of these dykes is considerable and source beds were never see There is no evidence to indicate in which direction the intrusive material moved but their formation pr bably pre-dated the main phase of folding since some are offset very slightly along the major lithologic boundaries by bedding-plane slip. However, there has also been fault movement along some of the plan of intrusion, with relative displacement of up to 5 cm.; it is difficult to determine whether the sediment w intruded into the fault zone or whether faulting followed the dyke as a plane of weakness. In some thi amalgamated sandstones enclosing thin shale horizons, fine-grained siltstone or shale dykes cut diagona across considerable thicknesses of sandstone. These dykes thin upwards and are essentially very extend flame structures. It is interesting to note that quartz veins are preferentially developed in the fine-grain dykes, possibly indicating that they were more susceptible to later tensional stresses than were t enclosing sandstones.

Calcareous concretions are a very common feature of the sandy sub-facies south of Royal Bay but th were only very rarely observed in the normal sub-facies or in the Barff Point Member. They are particular abundant in the thick amalgamated sandstone divisions, where flattening is at a minimum and large ov concretions may measure as much as 2 m. by 1 m. Occasionally, the concretions seem to be nucleated siliceous fragments, some of which may originally have been hollow spheres up to 1·5 cm. in diamete It is just possible that these may be the recrystallized skeletal remains of an original organic nucleu Alternatively, a variation in the chemical composition of the concretion, similar to that described for t example in Plate IVc may have been responsible. In one specimen (M.660.4), the concretion had form around a fragment of siltstone containing traces of burrows, and elsewhere a close association was observ between calcareous concretions and the pale-weathering halo around siltstone and shale inclusions. T concretions and the pale haloes both partly surround the same inclusion in a few cases, indicating th the origins of both phenomena are very closely related. A few branched concretions were observed ar these may have been caused either by the merging of several adjacent concretions or by nucleation arour a large branched burrow (Horne and Taylor, 1969).

3. *Palaeontology*

Two belemnite fragments recovered from Little Moltke Harbour have been described (Stone and Wille 1973) as *Belemnopsis*-like and they were considered to be Upper Jurassic–lowest Cretaceous in age. Durir subsequent field work, three more belemnite fragments were recorded from the Will Point area, one fro a loose boulder (M.659.3) and two *in situ*, one of which was collected (M.635.5). These were confirmed *Belemnopsis*-like by L. E. Willey and this supports the previously suggested age range.

Rare chips of flattened carbonized wood were seen in the Barff Point Member but they were very muc more common south of Royal Bay, where the largest piece recorded measured approximately 12 cm. b 2·5 cm. Where the fragments were long in relation to their width, the long axes were usually orientat approximately parallel to the strike of the bedding planes. This is in approximate agreement with t general current direction towards the north-west (Fig. 8) and suggests that the pieces of wood were originally deposited parallel to the direction of current flow.

Radiolaria were seen in many thin sections of shale and siltstone from the Cumberland Bay Formation. Two forms are common (seen in cross-section as a disc and an elongated "boat shape"), which may represent two distinct varieties of Radiolaria or be due to different angles of section through an organism shaped like a rugby ball. Generally, the tests are completely replaced by prehnite or quartz which may be zoned into a discrete core and rim. Fine ornamentation is rarely preserved but occasionally the remains of radial ribs can be distinguished (Plate VIb).

Bioturbation is fairly common in the shales and siltstones of the Barff Point Member, usually associated with small *Chondrites*-like trace fossils or with small vermicular structures approximately perpendicular to the bedding. South of Royal Bay, trace fossils are abundant in the fine-grained rocks of the Cumberland Bay Formation. *Chondrites*-like structures are common, forming radiating clusters of branching burrows up to 11 cm. in diameter, but even more abundant are masses of unbranched burrows affecting up to 20 cm. thicknesses of siltstone and extending along the bedding for up to 50 cm. The individual tunnels range from 0·5 to 4 mm. in diameter and are segmented by fine crescentic lamination (Plate VIc). In thin section, the unbioturbated siltstone between the burrows is usually seen to be rich in Radiolaria and this trace fossil was undoubtedly made by a burrowing deposit feeder. Surface trace fossils were much rarer than burrows but occasional meandering trails were seen (Plate VId), reflecting the grazing activities of bottom-living organisms.

III. SEDIMENTARY PETROLOGY

A PETROGRAPHIC distinction between the quartzose greywackes from the Barff Peninsula area and the volcanic greywackes from the remainder of South Georgia was first made by Tyrrell (1930). His descriptions were supplemented by Trendall (1953), who later referred to the two lithologies as the "Sandebugten type" and "Cumberland Bay type" (Trendall, 1959, p. 4). Other petrographic descriptions (Barth and Holmsen, 1939, p. 48–52; Skidmore, 1972, p. 25–37) have concentrated on the Cumberland Bay Formation and, in particular, the authigenic and secondary effects have been dealt with in some detail. Despite the compositional variations between the Cumberland Bay and Sandebugten Formations, it is impossible to differentiate between hand specimens of each type; in the field they appear as a monotonous succession of dark, grey or greenish blue sandstones and black shales.

A. SANDEBUGTEN FORMATION

Southward from Barff Peninsula, deformation of the Sandebugten Formation greywackes becomes progressively more intense and a penetrative schistose fabric appears in the coarse-grained rocks. Recrystallization of grain boundaries (Plate VIIa) reduces the average grain-size and increases the proportion of matrix present (Cummins, 1962). Towards Royal Bay the increasing dominance of a later crenulation cleavage destroys any relict sedimentary textures (Plate VIIb) and south of Royal Bay the only surviving detrital grains, such as the more robust plagioclase crystals, have suffered cataclastic shattering in the vicinity of minor intrusions and the main thrust contact (Plate VIIc).

The lithologies of the Sandebugten Formation in the Barff Peninsula area range from fine black shale to gravel-conglomerate containing grains up to 5 mm. in diameter. The larger grains are usually sub-angular or sub-rounded, but in thin section many smaller grains are seen to be angular.

1. *Detrital components*

Approximately half of the detrital grains in the Sandebugten Formation rocks are composed of quartz, which may be mono- or polycrystalline. Broken or euhedral quartz crystals are usually angular or sub-angular and the majority have an undulose extinction due to strain. This is probably an original effect, since strained and unstrained quartz grains exist side by side in the same section. The clear unstrained quartz, which is probably volcanic in origin, occasionally includes small penninite-filled amygdales, which may represent the alteration products of original inclusions of volcanic glass (Plate VIId). The texture of t polycrystalline quartz grains ranges from very fine-grained chert, which sometimes forms areas of pseuc matrix, through quartzites with highly sutured internal boundaries, to granoblastic quartzite. The lat is fairly rare and the development of a true polygonal fabric is usually incomplete (Plate VIIe) but th grains were probably derived from quartzites of a higher metamorphic grade than those grains with sutur internal boundaries (Wilson, 1973). Of the latter, the commonest form observed showed relics of old gra surrounded by smaller new ones. In some polycrystalline grains, the internal micro-fabric can be relat to the comb structure of vein quartz, and occasionally grains show a well-developed ribbon structu Rarely, the composition of the ribbons alternates irregularly between quartz and orthoclase and th grains may have been derived from a high-grade gneiss.

Fragments of igneous rocks form about a quarter of the detrital grains and by far the most abunda igneous component is felsitic acid volcanic material. It is sometimes very difficult to distinguish t felsitic grains from detrital chert but usually tiny feldspar laths, and more rarely larger euhedral plagiocla phenocrysts (usually oligoclase or albite) can be discerned in the cryptocrystalline felsic groundma (Plate VIIf). Some grains consist of a mass of tiny feldspar laths with a trachytic texture enclosing larg phenocrysts of albite, oligoclase and orthoclase and, more rarely, small ferromagnesian minerals no partly altered to chlorite. The feldspar laths are very small and a positive identification is often difficu but albite and oligoclase are both present. These trachytic grains may originally have been derived fro andesite, trachyandesite or sodic trachyte lava. A minority of the trachytic grains contain accessory qua and are therefore more dacitic in composition. The smallest detrital igneous group consists of grains deriv from granite. Quartz, plagioclase and alkali-feldspar are all present among these grains, the latter microcline (Plate VIIIa) or orthoclase which may form a distinctive graphic intergrowth with the quar

Feldspars form the third major detrital category and the majority of the grains are broken or subhedr crystals of plagioclase, usually angular or sub-angular. The plagioclase, which is in the albite-oligocla range with some rare andesine, is twinned on the Carlsbad and albite laws, and occasionally the cryst are zoned. Some orthoclase is present in accessory amounts, often twinned on the Carlsbad and sometim on the Baveno laws. A few small angular grains of microcline were also noted. Some of the feldspars m have been derived from the same source rock as the trachytic fragments, some from the felsitic mater and some may have come from the granitic terrain.

The rare detrital grains of slate present are usually deformed and recrystallized so that they are on distinguished from the matrix with difficulty. A few grains have a strong penetrative fabric involvi chlorite and quartz, and these may have been derived from a schistose rock type. Detrital ferromagnesi or heavy minerals are present in most thin sections, the commonest being a pale green pyroxene, but various thin sections detrital grains of biotite, amphibole, sphene, zircon and rutile were all observed.

2. *Secondary minerals*

Albite, replacing more intermediate plagioclase, quartz, chlorite (often as the penninite variety with an malous blue interference colours), sericite and epidote (at least some of which is clinozoisite) are the mo important secondary minerals. Calcite is locally abundant, possibly released by the albitization of mo calcic intermediate plagioclase, and occasionally the plagioclase shows patchy prehnitization. The seco dary chlorite and white mica define the schistosity but in many thin sections radial clusters of acicul biotite have grown across the locally dominant fabric (Plate VIIIb) with no preferred orientation. Th indicates two phases of secondary mineral growth: the formation of a lower greenschist-facies assembla during deformation, preceding the regional metamorphic peak which produced the radial clusters of bi tite. Most of the original ore minerals have been altered almost completely to leucoxene and this, togeth with the relict skeletal form, suggests that ilmenite was originally present. However, haematite veins a fairly common and many of the finer-grained lithologies in the Cape Charlotte area contain much pyri and possibly some chalcopyrite. The abundance of the latter seems to increase in the vicinity of min epidiorite sheets.

3. *Modal analyses of Sandebugten Formation sandstones*

Ten specimens of coarse Sandebugten Formation sandstones were modally analysed by point countin and the results are given in Table V. The statistical basis of the point-counting technique has been extensive

TABLE V

MODAL ANALYSES OF SANDEBUGTEN FORMATION SANDSTONES FROM THE BARFF PENINSULA AREA

Analysis number *Specimen number*		1 M.307.1	2 M.307.2A	3 M.308.1	4 M.309.5	5 M.313.3	6 M.343.2	7 M.363.1	8 M.372.2	9 M.380.2	10 M.434.2	*Arithmetic mean*	*Standard deviation* ±
Matrix		18·8*	18·1	18·4	18·6	19·2	20·5	19·9	21·5	20·3	19·0	19·4	1·05
Unstrained quartz		7·2	6·9	6·8	6·8	5·1	4·9	3·0	4·7	4·6	2·9	5·3	1·48
Strained quartz		9·6	10·5	10·5	8·8	8·6	8·6	7·7	7·1	12·0	7·7	9·1	1·45
Polycrystalline quartz		31·0	28·8	29·8	30·9	30·5	31·0	32·7	30·2	31·0	29·7	30·6	0·99
Igneous rock fragments	granitic	1·2	0·7	3·4	0·8	2·4	1·8	2·3	1·8	1·3	2·7	1·8	0·82
	felsitic	13·8	15·7	15·8	19·3	16·4	15·5	19·1	18·3	14·6	19·5	16·8	1·76
	trachytic	1·3	1·3	3·6	1·6	4·8	4·8	2·6	3·7	1·4	4·6	3·0	1·43
Feldspar		15·1	16·4	10·6	12·0	12·0	11·5	11·1	11·5	13·9	11·6	12·6	1·81
Schist, slate, etc.		1·5	1·2	0·6	0·7	0·6	0·9	1·3	0·7	0·3	1·7	0·9	0·43
Detrital minerals		0·5	0·4	0·5	0·5	0·4	0·5	0·3	0·5	0·6	0·6	0·5	0·11
	Q	47·8	46·2	47·1	46·5	44·2	44·5	43·4	42·0	47·6	40·3		
	L	33·4	35·7	34·5	34·9	36·6	35·0	36·7	36·5	32·1	40·7		
	M	18·8	18·1	18·4	18·6	19·2	20·5	19·9	21·5	20·3	19·0		
	Q	58·9	56·4	57·7	57·1	54·7	56·0	54·2	53·5	59·7	49·8		
	R	22·5	23·6	29·3	28·1	30·5	29·6	32·0	31·8	22·8	35·9		
	F	18·6	20·0	13·0	14·8	14·8	14·4	13·8	14·7	17·5	14·3		

*All figures are given as percentages.

discussed by Chayes (1956) and, in the light of his recommendations, between 1,000 and 2,000 points we counted for each section analysed, based on a rectangular grid extended across the complete thin sectio These were cut perpendicular to any planar fabric visible in the hand specimen. Any error introduced b an incipient schistosity was therefore minimized but, since the specimens selected for analysis were a from the Barff Peninsula area, the secondary mineral growth and development of tectonic fabrics were n extensive enough to pose any great difficulty.

The quartzose material was counted in terms of strained and unstrained single quartz crystals, a distin tion which is probably original since both types of grain occur in the same section, and polycrystalli quartz grains. The latter were not subdivided on internal micro-fabric because a continuous variatio was observed and, similarly, it was not practical to differentiate between chert and the finer polycrystalli grains. The igneous components were divided into granitic, felsitic and trachytic categories, and the ra gneissose fragments consisting of quartz and orthoclase were included with the granitic rocks. Some diff culty was occasionally encountered when trying to distinguish between chert and non-porphyritic felsit but the trachytic grains formed a very distinctive and easily identifiable group. Many of the smaller fel spar grains were very difficult to determine and so plagioclase and potash feldspar were counted togethe However, where large feldspar phenocrysts occurred in any of the igneous rock fragments, the feldspar w counted as part of the appropriate igneous grain.

The greatest problem experienced during counting lay in defining the grain/matrix boundary. On textur grounds, all of the sandstones analysed are greywackes, the matrix content ranging from 18·1 to 21· per cent, but secondary matrix has certainly formed by the deformation of weak detrital grains and th recrystallization of grain boundaries. It proved impossible to distinguish between primary and secondar matrix, which were therefore counted together but, where a detrital grain was partly overgrown by secondary mineral (for example, calcite on plagioclase) the detrital grain was counted. In this way th variation in the proportion of the detrital components should more accurately reflect possible difference in the provenance.

The standard deviation (S.D.) for each of the detrital components was calculated using the formul

$$\text{S.D.} = (\Sigma d^2/N)^{\frac{1}{2}},$$

where d is the difference between the figure for each specimen and the arithmetic mean, and N is the tota number of specimens used to determine that mean. The maximum value obtained for the standard devia tion of the major components was 1·81 which indicates that the specimens analysed formed a fairly homo geneous group. Since the ten specimens were selected on a random geographical basis within Barff Penin sula, it seems likely that the original Sandebugten Formation sandstones also formed a well-defined com positional group. However, the more highly deformed representatives of the Sandebugten Formation i the Royal Bay area are now richer in secondary matrix and relatively more quartz-rich than the less meta morphosed rocks of Barff Peninsula. In the first area, the secondary matrix has probably grown preferen tially at the expense of the unstable rock fragments.

B. Cumberland Bay Formation South of Royal Bay

A range of lithologies from fine-grained shale to coarse gravel-conglomerate is exposed in this area o South Georgia. The fine-grained rock types have generally been converted into slates but a clastic textur has been retained by the sandstones and conglomerates. In the coarser-grained rocks, individual detrit grains may reach 3 cm. in diameter, the larger ones often being well rounded. Frequently, these pebble are packed with aligned feldspar laths and are clearly derived from a lava.

1. *Detrital components*

In thin section, the rocks consist of a poorly sorted selection of angular to sub-rounded rock fragment and euhedral feldspar crystals set in a matrix-rich groundmass. The volcanic origin of the majority of th rock fragments is clear. Some of them are felsitic, with only a few small feldspar phenocrysts set in cryptocrystalline quartzo-feldspathic groundmass (Plate VIIIc), but the majority consist of a microliti mass of feldspar laths. The laths surround phenocrysts of albite, oligoclase, occasionally orthoclase an rare mafic minerals, whilst some grains contain a high proportion of brown devitrified volcanic glass.

Many of the feldspar-rich grains have a strong alignment of the individual laths forming a well-developed trachytic texture (Plate VIIId), and, since albite and some subsidiary orthoclase are both present in a few grains, the rock type represented is a sodic trachyte. However, in the majority of grains orthoclase was absent, and the plagioclase present was in the albite-oligoclase range with very rare andesine. In all probability this assemblage resulted from the albitization of intermediate plagioclase, and these trachytic grains were probably derived originally from trachyandesite and andesite lavas. A trachytic texture was not always obvious and in some grains the random orientation of the feldspar laths produced a felted texture. The overall variation in composition of the felted grains is much the same as that of the trachytic grains, but in addition some specimens contain accessory quartz which, together with plagioclase very much in excess of potash feldspar, gives them a dacitic composition. The groundmass of many of the lava grains is dark brown and cloudy, and probably consists in the main of devitrified glass. The proportion of glass sometimes increases to give a truly hyalopilitic texture. Original mafic minerals are rare in all of the lava grains but a pale green pyroxene, extensively altered to chlorite and epidote, is sometimes present.

A few thin sections contain grains of ophitic dolerite (Plate VIIIe), suggesting that coarser-grained rocks were associated with the lava possibly as intrusive bodies feeding the lava flows. There was certainly active volcanicity contemporaneous with the deposition of the sediments, since a number of thin sections contain devitrified glass shards (Plate VIIIf) which are truly pyroclastic in contrast to the epiclastic nature of the majority of the volcanic detritus.

The detrital feldspar is usually sodic plagioclase in the albite-oligoclase range or more rarely orthoclase. The plagioclase is frequently twinned but it is rarely zoned, whilst the orthoclase is usually untwinned. Small chlorite-filled amygdales occur in both the plagioclase and orthoclase, probably through the alteration of original glassy inclusions, indicating that at least some of them were derived from eruptive rocks. Similar amygdales were noted in the feldspar phenocrysts of the trachytic grains.

Apart from the felsites, siliceous resistates are comparatively rare in the Cumberland Bay Formation south of Royal Bay. The few single crystals of quartz nearly all show undulose strain extinction and the rare polycrystalline grains commonly have highly sutured internal boundaries. Two polycrystalline quartz grains showing comb structure were noted and this suggested derivation from vein quartz.

Minor detrital components include dark siliceous slate fragments and occasionally cloudy brown apparently vesicular fragments, now extensively chloritized but which may originally have been a form of pumice. Detrital heavy minerals are rare but pale green pyroxene partly altered to chlorite was observed in several thin sections, whilst occasional grains of detrital sphene were also noted. Some iron ore may also be detrital and, since this has usually been altered to leucoxene, ilmenite was probably present originally.

2. *Secondary minerals*

The matrix of the Cumberland Bay Formation greywackes is now almost entirely composed of secondary minerals including quartz, penninitic chlorite, calcite, sericite and epidote. Prehnite is also of major importance and was first recognized by Tyrrell (1930, p. 38), who descriptively observed that "... prehnitization spreads like a disease through the affected rocks ...". Subsequently, descriptions of the secondary minerals of the Cumberland Bay Formation rocks, especially the prehnite, were given by Barth and Holmsen (1939, p. 48–52), Trendall (1959, p. 11–14) and Skidmore (1972, p. 37–40). Recent studies have added nothing of significance to these accounts.

3. *Modal analyses of Cumberland Bay Formation sandstones*

Five specimens of coarse Cumberland Bay Formation sandstone from the south side of Royal Bay were modally analysed by point counting 1,000 points for each thin section. The results are given in Table VI. The same allowances were made for fabric as were described for the Sandebugten Formation modal analyses.

The volcanic components were separated on textural criteria into felsitic, trachytic, felted and hyalopilitic categories, since much of the finer-grained detritus could not be ascribed to a definite compositional group. The pyroclastic glass shards were generally very difficult to distinguish and so no attempt was made to separate them during counting. They will probably have been included with the matrix, because many are represented only by shadowy outlines in areas of matrix and all show varying degrees of alteration to quartz, chlorite and occasionally prehnite. Quartz was separated simply on single or polycrystalline internal

TABLE VI

MODAL ANALYSES OF SANDSTONES FROM THE BARFF POINT MEMBER AND CUMBERLAND BAY FORMATION SANDSTONES FROM SOUTH OF ROYAL BAY

	Barff Point area (analyses 11–15)					*Cumberland Bay Formation south of Royal Bay (analyses 16–20)*					*Arithmetic mean of Sandebugten Formation*
Analysis number	11	12	13	14	15	16	17	18	19	20	
Specimen number	M.356.2	M.378.1	M.390.1	M.391.2	M.392.6A	M.602.1	M.628.1	M.633.1	M.635.1	M.659.1	
Matrix	20·1*	20·3	22·6	16·9	21·7	19·7	21·1	19·6	20·2	21·2	19·4
Monocrystalline quartz	12·3	11·7	9·3	1·3	16·1	1·6	2·3	0·5	2·9	2·7	14·4
Polycrystalline quartz	20·8	18·3	7·2	5·9	16·8	3·2	7·6	3·7	6·8	5·1	30·6
Igneous rock fragments: felsitic	22·7	18·7	14·7	14·0	18·4	12·5	13·3	11·1	9·7	10·8	16·8
Igneous rock fragments: felted	1·5	0·2	2·1	13·7	2·1	15·7	5·0	7·6	10·1	9·1	—
Igneous rock fragments: hyalopilitic	0·4	3·9	8·1	8·7	1·6	9·7	4·1	15·0	13·1	13·9	—
Igneous rock fragments: trachytic	6·3	4·1	7·8	23·8	5·5	24·2	20·0	26·0	21·3	20·1	3·0
Igneous rock fragments: dolerite	—	—	—	—	—	—	—	0·8	—	—	—
Feldspar	14·4	21·9	25·9	14·9	16·4	12·7	25·8	14·6	14·7	15·4	12·6
Slate, pumice, etc.	1·4	1·6	1·9	0·6	1·1	0·2	0·6	0·7	0·8	1·1	0·9
Detrital minerals	0·1	0·3	0·4	0·2	0·3	0·5	0·2	0·4	0·4	0·6	0·5
											1·8 granitic
Q	33·1	30·0	16·5	7·2	32·9	4·8	9·9	4·2	9·7	7·8	
L	46·8	49·7	60·9	75·9	45·4	75·5	69·0	76·2	70·1	71·0	
M	20·1	20·3	22·6	16·9	21·7	19·7	21·1	19·6	20·2	21·2	
Q	41·1	37·6	21·3	8·7	42·1	6·0	12·5	5·2	12·2	9·9	
R	40·6	36·2	45·2	73·4	37·0	78·2	54·8	76·7	69·4	70·6	
F	18·0	26·2	33·5	17·9	20·9	15·8	32·7	18·1	18·4	19·5	

*All figures are given as percentages.

fabric, and all detrital feldspars were counted as a single group. Phenocrysts of feldspar, and rarely of quartz, within the lava fragments were counted into the appropriate volcanic textural group.

All of the sandstones analysed are greywackes with a matrix content ranging from 19·6 to 21·2 per cent; again some difficulty was posed by recrystallized and indistinct grain boundaries. However, the Cumberland Bay Formation rocks chosen for analysis were generally less cleaved than the Sandebugten Formation rocks and the modal analysis of the Cumberland Bay Formation volcanic greywackes was an easier task.

C. Rocks of the Barff Point Member (Cumberland Bay Formation)

Despite their initial description as "Cumberland Bay type" (Aitkenhead and Nelson, 1962), the rocks exposed between Barff Point and Godthul range in composition from rocks typical of the Cumberland Bay Formation to those typical of the Sandebugten Formation. The rocks of mixed composition are markedly richer in basic and intermediate volcanic detritus than the Sandebugten Formation rocks and they contain much more quartzose material than the Cumberland Bay Formation rocks. This overall variation is illustrated by the five modal analyses in Table VI (analysis numbers 16–20).

The rocks in the Barff Point area have clearly been formed of detritus derived from the source areas of both of the major rock types. However, the presence of devitrified glass shards in several of the Cumberland Bay Formation sandstones (Plate VIIIf) shows that they were laid down within range of the pyroclastic fall-out from the Cumberland Bay Formation's active volcanic source. Also of significance is the increase in relative importance of detrital feldspars and felsite in comparison with both of the main rock types. This is probably due to the presence of these components in both of the source areas and their corresponding build-up in the mixed lithologies represented between Barff Point and Godthul.

D. Compositional Variation and its Implications

Compositional variation can best be illustrated by plotting the modal analysis data in terms of QLM and QRF (Tables V and VI) on triangular diagrams (Fig. 9). In these the distribution of the components between the three parameters is important and for Fig. 9a and b Q represents the total mono- and polycrystalline quartz and chert, M represents the total matrix, F represents total feldspar, R represents rock fragments including all of the volcanic detritus whether andesitic, trachytic or felsitic and the minor com-

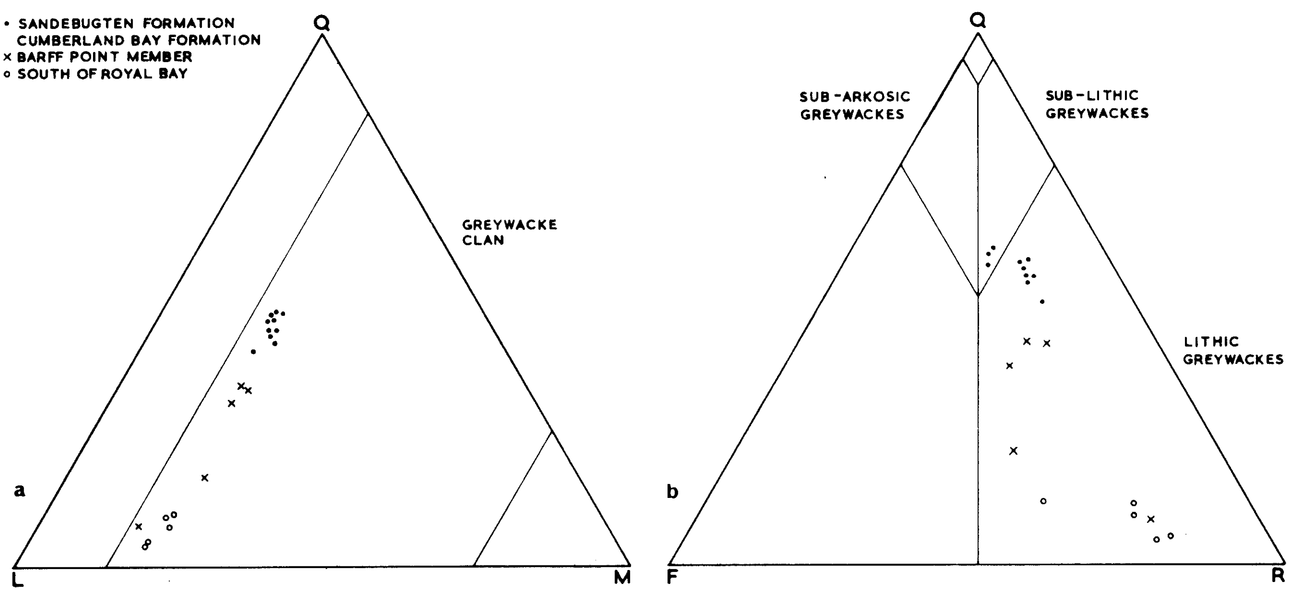

FIGURE 9

Modal triangles based on the sandstone analyses given in Tables V and VI.
a. Quartz : matrix : labiles (Q : M : L).
b. Quartz : rock fragments : feldspar (Q : R : F).

ponents such as granite and dolerite, and L represents the sum of rock fragments and feldspar, the so-called "labile" components. In a previously published modal diagram (Stone and Willey, 1973, fig. 1), the siliceous felsite grains were included with quartz as the total siliceous resistates, whilst only the andesitic and trachytic grains were counted as unstable rock fragments.

1. *Nomenclature*

A nomenclatural system based on Dott (1964) and Pettijohn and others (1972, p. 158) is shown superimposed on the basic triangles in Fig. 9. All of the sandstones analysed contain more than 15 per cent matrix (Fig. 9a) and so on textural criteria they are greywackes. All of the Cumberland Bay Formation and the majority of the Sandebugten Formation greywackes fall into the lithic class, with a few of the Sandebugten Formation rocks overlapping as sub-lithic greywackes (Fig. 9b). However, within the lithic

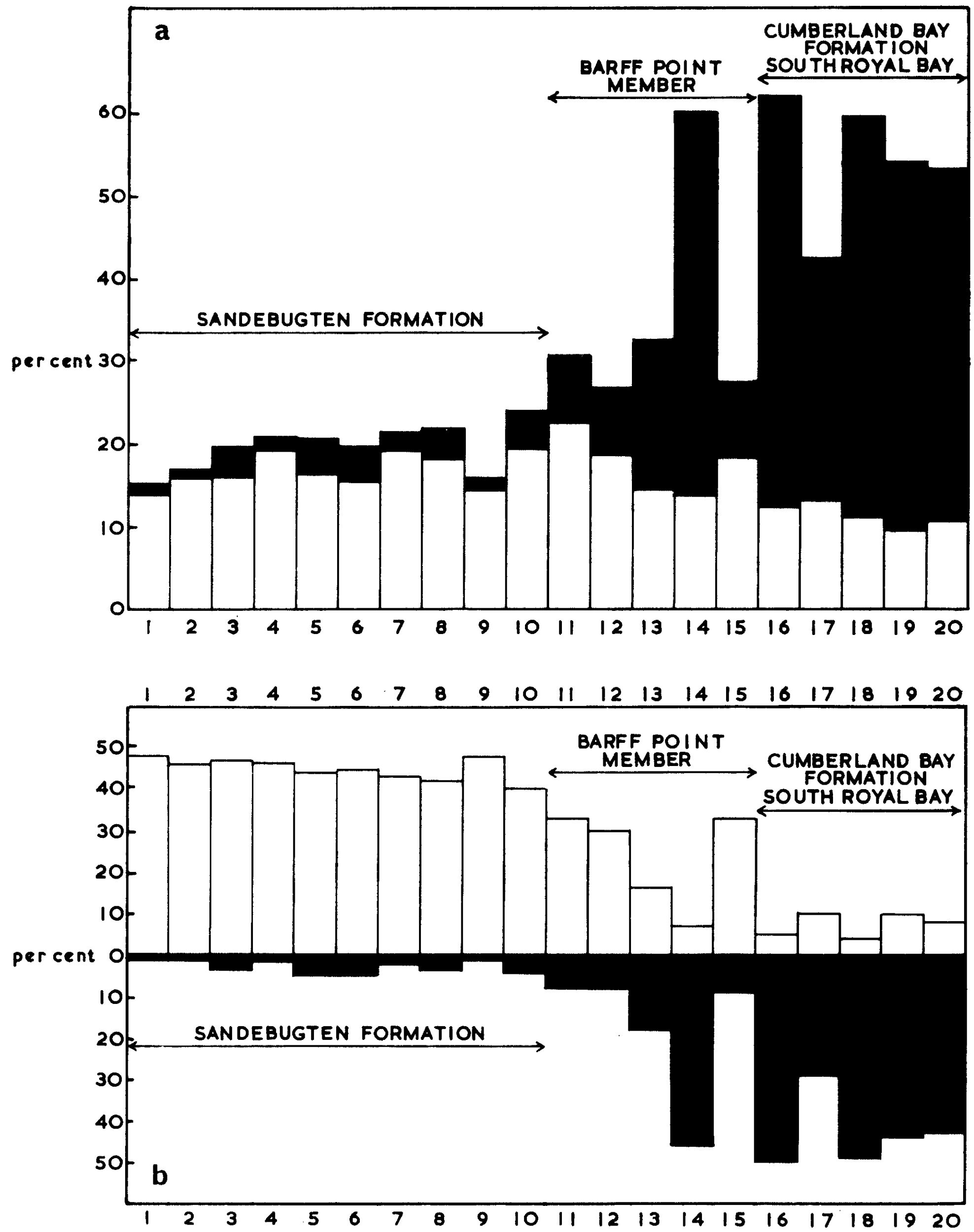

FIGURE 10

Some aspects of the compositional variations within the South Georgia greywackes.
a. The varying proportion of felsite (unshaded) to basic volcanic debris (cross-hatched) in the rock-fragment category.
b. The varying proportion of total detrital quartz (unshaded) to basic volcanic debris (cross-hatched).

field there is a clear distinction between the two major greywacke types, with several mixed lithologies from the Barff Point area spanning the gap between them.

Most of the rocks analysed contained between 10 and 20 per cent felsite (Tables V and VI) and the large increase in the proportion of rock fragments in the Cumberland Bay Formation greywackes is due entirely to a considerable influx of andesitic and trachytic volcanic detritus. This is clearly shown in the compositional histogram in Fig. 10a. The other major variable among the detrital components is quartz, and the inverse relationship between detrital quartz and the basic to intermediate volcanic material is illustrated in Fig. 10b. Both of the histograms in Fig. 10 emphasize the intermediate composition of rocks from the Barff Point Member. On the basis of Figs. 9b and 10b, the lithic greywackes of the Cumberland Bay and Sandebugten Formations could best be distinguished as volcanic or volcaniclastic greywackes and quartzose greywackes, respectively. The term volcanic greywacke was first applied to the Cumberland Bay Formation rocks by Tyrrell (1930, p. 35) and has since been adopted by Skidmore (1972).

2. *Provenance*

Markedly dissimilar provenances are indicated for each of the main rock types by the array of different detrital components. Debris for the Sandebugten Formation was derived from a terrain which included quartzites, acid volcanic rocks, granite and perhaps some outcrops of gneiss and schist. The Cumberland Bay Formation was, in contrast, derived from an active volcanic source of basic and intermediate lavas. Some more acidic lavas may also have been produced. This area was described by Trendall (1959, p. 44) as a "volcanic archipelago" and by more recent authors (e.g. Dalziel and others, 1974, 1975) as an island arc bordering a marginal basin.

A more quantitative indication of the provenance of the Cumberland Bay and Sandebugten Formations can be obtained by applying the detrital mode parameters of Dickinson (1970) which are summarized in Table VII.

TABLE VII

A QUANTITATIVE ASSESSMENT OF PETROLOGICAL PROVENANCE INDICATORS FOR THE SANDEBUGTEN AND CUMBERLAND BAY FORMATIONS (AFTER DICKINSON, 1970)

Parameter	*Sandebugten Formation*		*Cumberland Bay Formation*	
	Value	*Inferred provenance**	*Value*	*Inferred provenance**
Quartz (Q)	Moderate–high, 50–60 per cent	T–P	Low, about 10 per cent	V
Feldspar (F)	Low, 10–20 per cent	T	Moderate, 20–30 per cent	V–T
Rock fragments (RF)	Moderate, about 30 per cent	T	High, about 70 per cent	V
Chert : total Q	Low, rarely >0·1	V–P	Very low	V–P
Plagioclase : total F	Variable	T–P	High	V
Volcanic (V) : total RF	High	V	Very high	V
It would be useful here to introduce a new parameter, felsite : total volcanic rocks (V), to differentiate between acid and basic volcanic provenances				
Felsite : total V	High	Acid V	Low	Basic V

* Provenance defined in terms of volcanic (V), tectonic (T) and plutonic (P) terrains.

Coupled with the sedimentological evidence, the data provided by petrological examination support a depositional basin bounded on one side by an active volcanic island arc and on the other by a continental landmass. Such a model has recently been proposed by Dalziel and others (1974, 1975). The mixed lithologies exposed between Barff Point and Godthul were deposited in a part of this basin where turbidity currents flowing from each of the provenances alternated and intermingled.

3. *Comparison with previously published results*

Modal analyses of greywackes from South Georgia have been previously plotted in terms of QRF by Skidmore (1972) and Dalziel and others (1975). Their results are superimposed on the data from Fig. 9b in the composite triangular diagram in Fig. 11.

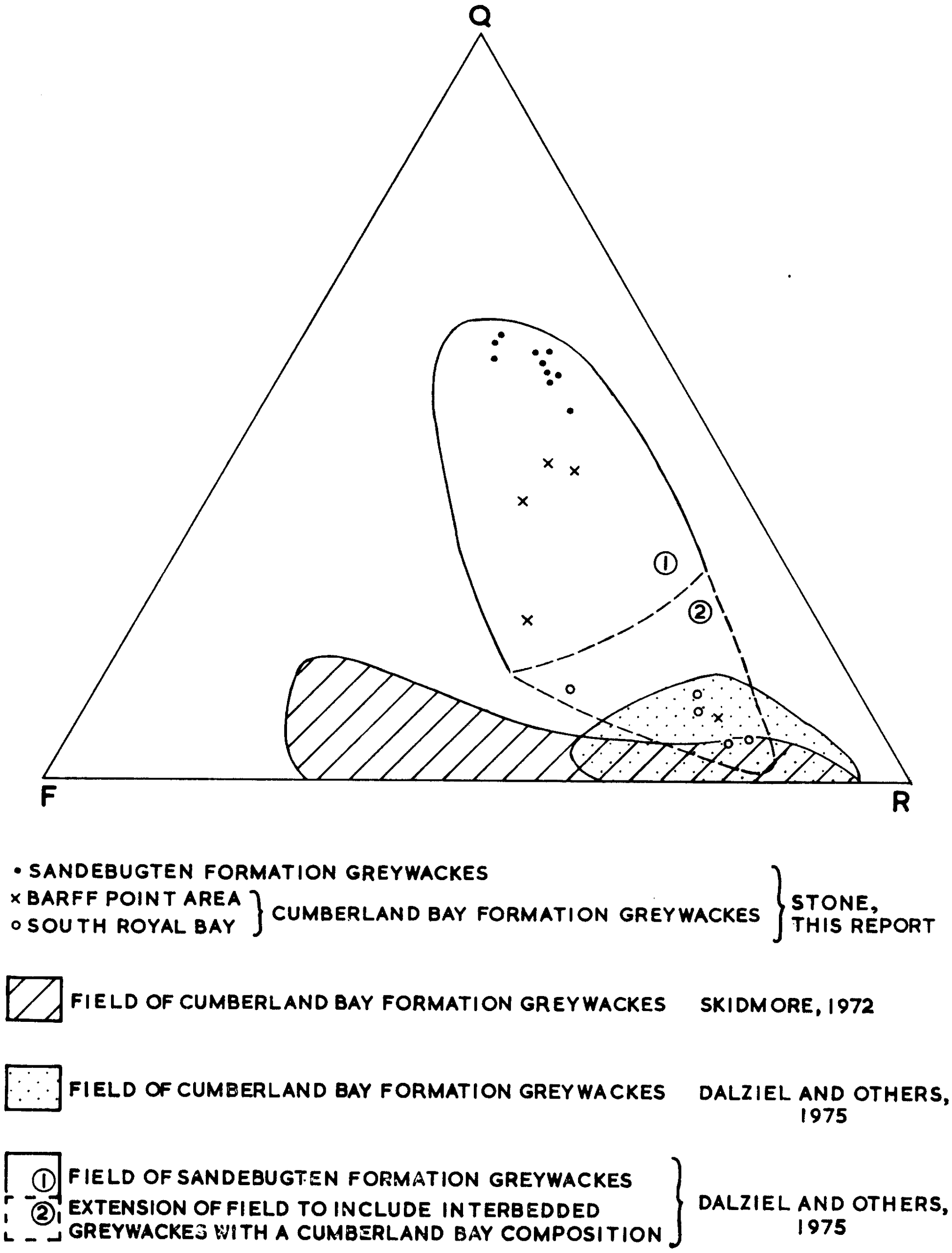

FIGURE 11

A comparison of modal analyses in this report with previously published results.

The results for the Cumberland Bay Formation from all three sources are fairly consistent, but Dalziel and others extended the field of the Sandebugten Formation to overlap the Cumberland Bay Formation. However, the results given in this report show that the Sandebugten Formation greywackes form a distinct fairly homogeneous group. The difference has probably arisen because Dalziel and others included all of the rocks exposed on Barff Peninsula with the Sandebugten Formation, whereas the rocks above the thrust plane, which are exposed between Barff Point and Godthul, form a group intermediate in composition between the two main types. This tendency, and the resultant extension of the Sandebugten Formation field as figured by Dalziel and others, is illustrated by Fig. 11.

E. Metamorphic Grade

In terms of textural evolution, reflecting increasing intensity of deformation, the Sandebugten Formation metagreywackes range up to the Chlorite 2 or very rarely the Chlorite 3 sub-zone of the greenschist facies (Turner, 1968, p. 31). Turner described the rocks of the Chlorite 2 sub-zone as "foliated metagreywackes or *semischists*". Chlorite and sericite grow parallel to the S1 and the S2 planar fabrics and so both fold episodes were probably accompanied by low-grade regional metamorphism. However, a number of specimens contain radial clusters of acicular biotite which grow across the local fabrics and this was probably produced by post-F2 metamorphism.

The most diagnostic of the secondary minerals present in the Cumberland Bay Formation is prehnite, but zeolites characteristic of the burial metamorphism of thick sedimentary sequences (Hay, 1966) are absent. A prehnite–pumpellyite metagreywacke facies was defined by Coombs (1960) to bridge the gap between the zeolite and greenschist facies, and it is into this gap that the South Georgia examples fall. Pumpellyite was not observed in any of the thin sections examined and it has only once been reported from South Georgia by Dalziel and others (1975), who referred to quartz-prehnite-pumpellyite layers in the Cumberland Bay Formation. The scarcity of pumpellyite may indicate metamorphism only to the lowest part of the prehnite–pumpellyite facies (Coombs, 1960) or it may have been caused by an original richness in calcite (Surdam, 1973). The latter factor may well have been important in South Georgia, since prehnitization with very little development of pumpellyite seems to have been similarly favoured by an original richness in calcite in a similar epiclastic volcanic sequence in Tierra del Fuego (Watters, 1965). The implications of the prehnitization of the Cumberland Bay Formation sediments in terms of metamorphic conditions have been discussed by Skidmore (1972, p. 40–42), who concluded that the greywackes had been buried to a depth of about 10 km. with a geothermal gradient between 40° and 50° C/km. This is in general agreement with the conclusions of Hay (1966) that prehnite reached its maximum development in marine tuffs at burial depths of about 9·5 km. Recent experimental results show that the prehnite–pumpellyite metagreywacke facies is stable at pressures exceeding 2 kbar in a temperature range of 250–380° C (Liou, 1971). The assemblage prehnite–epidote–chlorite–quartz, which is characteristic of many of the South Georgia greywackes, is stable at pressures below 2·5 kbar in the temperature range 320–360° C (Nitsch, 1971), the high-temperature–low-pressure zone of the prehnite–pumpellyite facies. This relatively restricted field of stability requires a geothermal gradient in excess of 40° C/km., assuming a normal pressure gradient of 300 bar/km., and supports the conclusions of Skidmore for these rocks. The obvious reason for the poor development of prehnite in the Sandebugten Formation greywackes is their quartzose composition with a relative lack of unstable components. By contrast, the Cumberland Bay Formation rocks contain large quantities of volcaniclastic material eminently suitable for prehnitization.

Overall, the metamorphism of the greywackes of the north-east coast of South Georgia indicates burial of the sediments to a depth of at least 9 km. in an area with a geothermal gradient in excess of 40° C/km. Subsequent intense polyphase deformation of part of the greywacke sequence was accompanied by low-grade regional metamorphism to the lower greenschist facies. The growth of biotite across the tectonic fabrics in some Sandebugten Formation metagreywackes indicates that the local metamorphic peak was post-F2.

IV. STRUCTURAL GEOLOGY

A. Major Structural Relationships

The structural relationship between the Cumberland Bay Formation and the Sandebugten Formation of South Georgia has been the subject of some controversy in the past. The "Cape George Harbour Series" (Ferguson, 1915) and the "Godthul Harbour Series" (Tyrrell, 1930) were names applied to a basal group of quartzose sediments considered to underlie the tuffaceous "Cumberland Bay Series". The nature of the contact between them was uncertain. Trendall (1953) described the "Cumberland Bay Series" as tectonically overlying an older succession of quartz-rich greywackes for which he proposed the name "Sandebugten Series". Overturned anticlines in the "Sandebugten Series" were described as closing to the south-west, whereas in the overlying "Cumberland Bay Series" overturned anticlines consistently close towards the north-east. Further field work led to a re-appraisal of this situation and recognition of a single sedimentary succession divided into two by "a major, regional palaeogeographic change" (Trendall, 1959, p. 42). For this reason, Trendall suggested the two "series" be re-named the "Sandebugten type" and "Cumberland Bay type".

During a later reconnaissance survey by Aitkenhead and Nelson (1962), a discordant contact between tightly folded "Sandebugten-type" rocks and overlying rocks akin to "Cumberland Bay-type" greywackes was located at the northern end of Barff Peninsula. The structural style on either side of the contact was markedly dissimilar. Aitkenhead and Nelson came to no firm conclusion as to the nature of this contact but they favoured an unconformity, possibly modified by thrusting. This evidence was used by Adie (1964) to re-emphasize an unconformable relationship between the "Sandebugten-type" and the "Cumberland Bay-type" rocks and to re-introduce the idea that there was a considerable age difference between them.

The Barff Peninsula and Dartmouth Point areas (Fig. 12) were examined in early 1973 by Dalziel and others (1975), who concluded that on Dartmouth Point the "Cumberland Bay-type" rocks had been thrust north-eastward over the "Sandebugten type". They did not recognize a tectonic contact on Barff Peninsula and related the change in structural style to the variation in the attitude of the folds across the peninsula. This variation was first commented on by Aitkenhead and Nelson (1962), who referred to an "anticlinorium" with the north-easterly dip of the S1 axial-plane cleavage in the "Sandebugten-type" rocks steepening, passing through the vertical and finally assuming a south-westerly dip, progressively north-eastward across Barff Peninsula (Figs. 3 and 12). Despite this variation in fold attitude across the area of "Sandebugten-type" outcrop, there is still a considerable difference in both fold style and attitude on either side of the contact on Barff Peninsula (Fig. 13a).

The contact exposed 2·4 km. south of Barff Point, on the west coast of Barff Peninsula (Aitkenhead and Nelson, 1962), was re-examined and mapped in early 1971 (p. 31). The Sandebugten Formation rocks below the thrust plane are folded into upright chevron folds which are sharply truncated along a plane which dips at 45° in a direction 352°. There are no signs of a weathering zone or a basal conglomerate at the contact and the zone above the thrust plane is marked by an undulating mylonitic fabric. The contact was traced south-eastward towards Godthul, where it is cut by two faults which bring down the Cumberland Bay Formation to crop out on Cape George and to the north of Godthul (Figs. 12 and 13b).

On the Dartmouth Point promontory, bedding and cleavage in the Sandebugten Formation are also sharply truncated by a thrust plane (Dalziel and others, 1975) and a mylonitic foliation is developed in the lowest few centimetres of the overlying Cumberland Bay Formation.

Farther south-east, a very limited exposure of the thrust contact was discovered on the eastern spur of Mount Brooker at the col between Cook and Webb Glaciers (Fig. 12). Again, a weak mylonitic fabric has developed in the lowest few centimetres of the adjacent Cumberland Bay Formation rocks, but at this locality there is a breccia zone in the underlying Sandebugten Formation which ranges up to 3 m. in thickness. Below this breccia zone the Sandebugten Formation has a dominant cleavage sub-parallel to the thrust plane.

On the south coast of Royal Bay the contact was located at Will Point and approximately 0·5 km. east of Weddell Glacier (Fig. 12). From there it was traced more or less continuously through the main col in the Cape Charlotte ridge and down into Gold Harbour. The best exposure is on the south coast of Royal Bay east of Weddell Glacier (Fig. 12; Plate IIa), where the thrust plane dips at 21° to 266°. Other outcrops were visited at the main col in the central Cape Charlotte ridge and at Gold Harbour, and two apparent

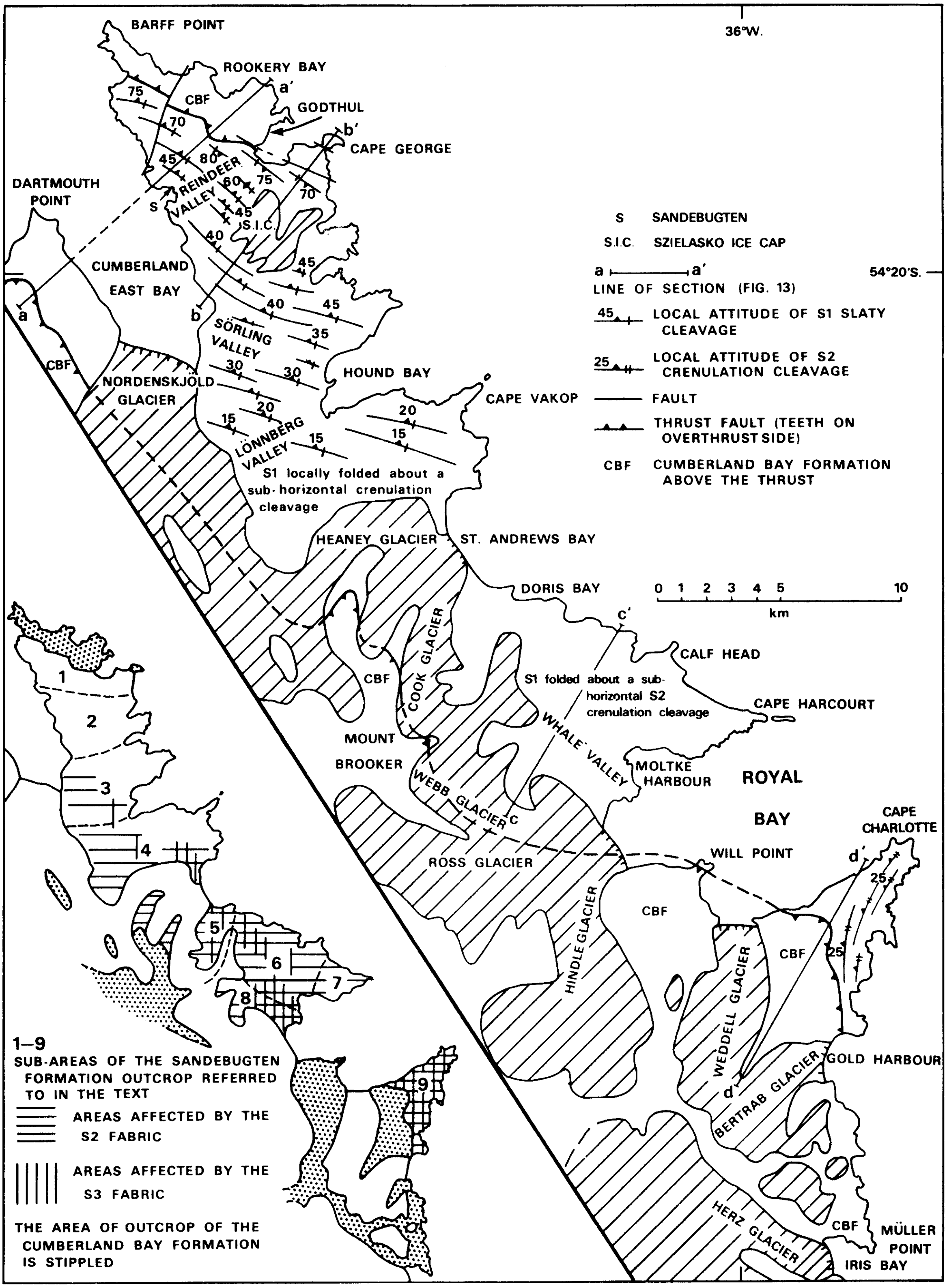

FIGURE 12

Geological sketch maps of part of the north-east coast of South Georgia. The main structural trends in the Sandebugten Formation are shown. Glaciers ase hatched.

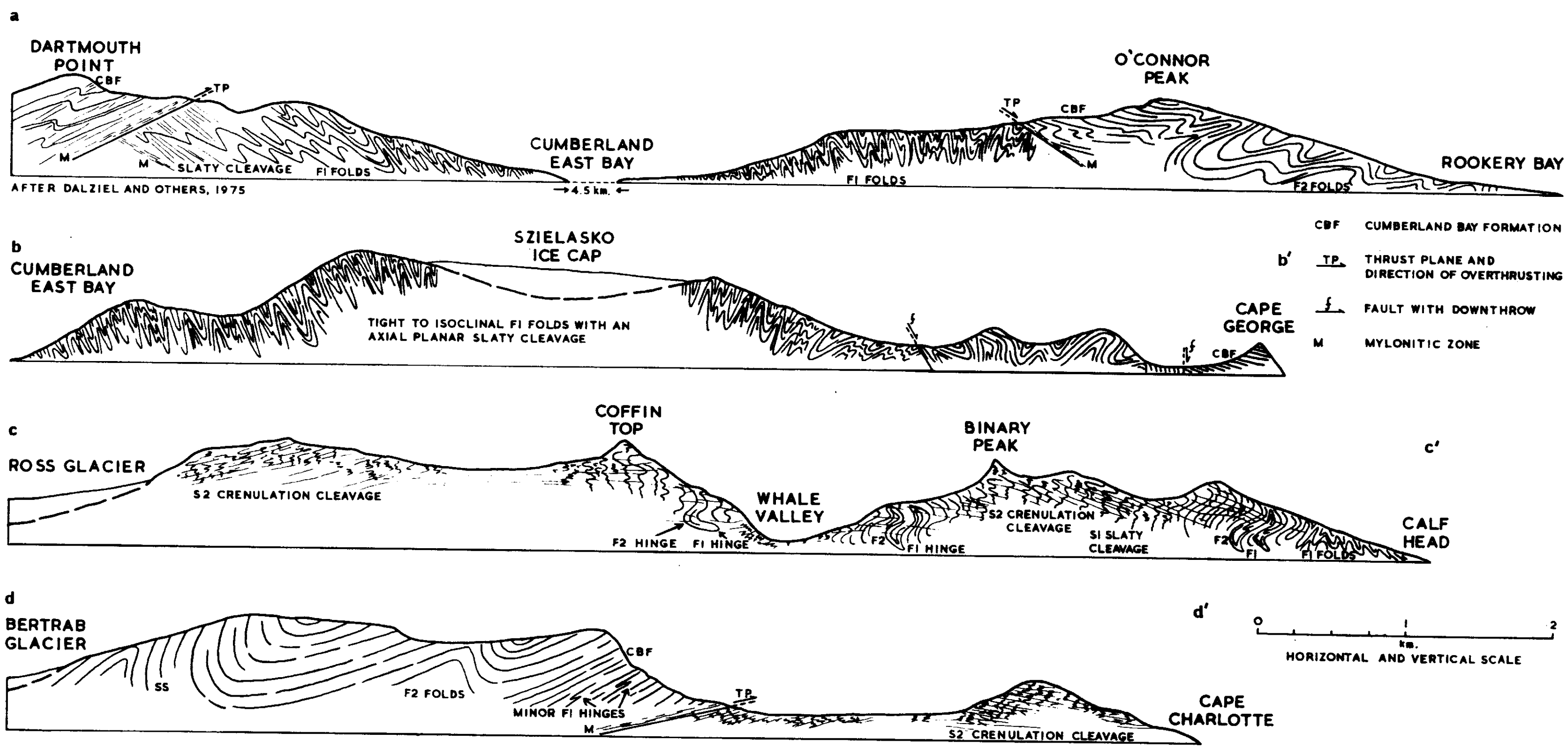

FIGURE 13

Diagrammatic geological sketch cross-sections:

a—a′ Dartmouth Point to Rookery Bay.
b—b′ Cumberland East Bay to Cape George.
c—c′ Ross Glacier to Calf Head.
d—d′ Bertrab Glacier to Cape Charlotte.

dips of the plane passing through all of these outcrops (col to Weddell Glacier and col to Gold Harbour) both lie on a plane dipping at 11° to 251°. Immediately above the thrust plane a weak mylonitic fabric has developed in the lowest few centimetres of the Cumberland Bay Formation, and several other thin mylonite zones less than 2 cm. thick occur within 30 m. of the contact.

The sense of movement at all of these localities, deduced from slickensides and local drag effects, indicates that the Cumberland Bay Formation has been thrust towards the north-east, over-riding the Sandebugten Formation. Subsequent erosion has exposed the latter and isolated a small area of the Cumberland Bay Formation between Barff Point and Godthul (the Barff Point Member). This situation was in fact implied by Tyrrell (1930, p. 46), who described quartzose greywackes from Barff Peninsula, but commented on a bedded tuff found *in situ* at Barff Point which he considered was identical to many of the rock types within the Cumberland Bay Formation.

If all of the Cumberland Bay Formation, including the Barff Point Member, was originally to the south-west of the area of outcrop of the Sandebugten Formation, a minimum translation of 12 km. to the north-east has occurred along the thrust plane.

Thus, along the north-east coast of South Georgia three tectonostratigraphic units can be recognized: the Sandebugten Formation cropping out over most of Barff Peninsula and the Royal Bay area; the Barff Point Member of the Cumberland Bay Formation exposed in the extreme north of Barff Peninsula; and the Cumberland Bay Formation exposed south of Royal Bay (Fig. 12). The fold structures and associated fabrics found within each of these units are now described separately. The nomenclature used is that proposed by Fleuty (1964) and Ramsay (1967). All stereograms figured are lower hemisphere, equal area projections.

B. Folding of the Sandebugten Formation

The structural style and degree of deformation of the Sandebugten Formation vary considerably throughout the length of its outcrop on the north-east coast of South Georgia.

Over most of Barff Peninsula the rocks are folded into tight, inclined or upright folds with hinges trending approximately north-west. These folds, which resulted from the earliest phase of deformation recognized (F1), have been affected by later folding and probably lie on the lower limb of a later, large recumbent antiform closing to the south. The intensity of this second phase of folding (F2) increases southward so that the weak, irregularly spaced sub-horizontal S2 crenulation cleavage, first observed in Sörling and Lönnberg Valleys, becomes the dominant cleavage farther south towards Royal Bay. In the St. Andrews Bay area, the S2 crenulation cleavage is cut by very weak sub-vertical crenulation planes (S3) which strike north-north-east. The resultant crenulation lineation produced on S2 becomes stronger to the south and is probably parallel to the axis of a major upright synform. The Cape Charlotte promontory forms part of the eastern limb of this synform and the S2 crenulation cleavage planes there are moderately inclined towards the west in contrast to the sub-horizontal attitude of S2 elsewhere. All of the planar fabrics in the Sörling Valley–St. Andrews Bay area are cut by a late pair of conjugate kink bands. The progressive southward appearance and intensification of the three main phases of folding are shown diagrammatically on the inset to Fig. 12; the detailed information is given in Figs. 3–6.

To facilitate future structural correlations between structures found in different parts of South Georgia, it may well be valuable to refer to the various fold phases recognized above by geographical names. This should reduce the confusion which may arise, for example, if F2 folds from one area prove to be contemporaneous with the F3 structures elsewhere. The following proposed names are used in the discussion below:

F1 Reindeer Valley phase,
F2 Whale Valley phase,
F3 Cape Charlotte phase.

1. *Reindeer Valley phase (F1) folding in Barff Peninsula*

In this area F1 structures are tight to isoclinal, chevron and similar folds (Plates IIb, IIIa and b). The amplitude of the folds ranges up to several metres but the axial-plane separation ($\lambda/2$) is rarely in excess of 50 m. A slaty cleavage has developed parallel to the hinge surfaces of these folds in the finer-grained rocks and is continuous with planes of grain flattening within the coarser sandstones. Many of the sandstone horizons are slightly boudinaged with the long axis of each boudin approximately parallel to the local F hinge trend. Minor thrusting in the hinge zones of the folds parallel to the hinge surface is fairly commor

Variations in bed thickness frequently cause bulbous hinge structures (Plate IIIb) and dilation in th fold hinge zone may result in quartz-filled tension gashes or hinge collapse (Ramsay, 1974). These tensio gashes are often slightly sigmoidal but are usually approximately perpendicular to the local beddin Sometimes there is strong lithological control so that quartz-filled tension gashes in the shale terminat abruptly against the coarser sandstones.

The F1 fold hinges* and axes generally trend north-west or south-east (Fig. 4) and the overall orientatio (Fig. 14a) is a plunge of a few degrees towards the north-west. The same orientation is shown by the bec ding/cleavage intersection lineations (Fig. 14b) but over much of Barff Peninsula there is also a well-develop ed grain-elongation lineation trending approximately perpendicular to the local F1 axial direction (Fi 14b). This elongation lineation is contained within the planes of grain flattening which are continuous wit the slaty cleavage.

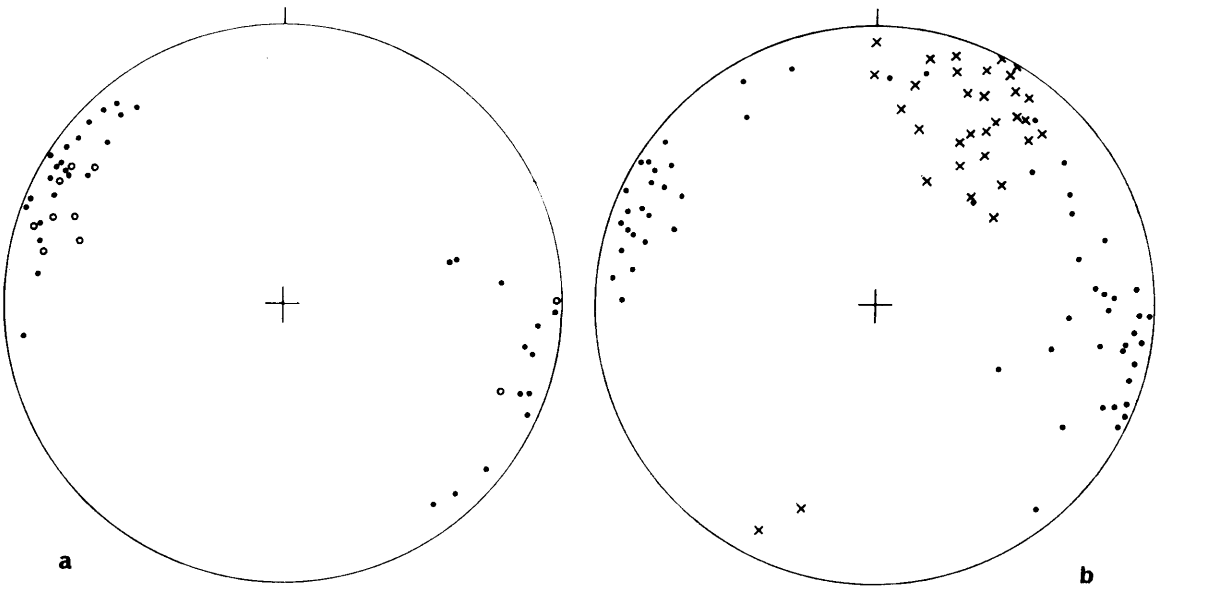

FIGURE 14

Stereograms illustrating early linear fabrics for Barff Peninsula, sub-areas 1–3.
a. F1 fold hinges (●) and axes (○).
b. Bedding-cleavage intersection lineations (●) and grain-elongation lineations (×).

The variation in the attitude of the S1 cleavage across Barff Peninsula (Figs. 3 and 12) to form th "anticlinorium" of Aitkenhead and Nelson (1962) is clearly illustrated when poles to the S1 plane are plot ted on a stereogram (Fig. 15a). Total bedding variation across the same area (Fig. 15b) shows a simila trend because of the tight to isoclinal style of the F1 folds. The folds change in attitude from tight uprigh similar folds in central Reindeer Valley (Plate IIIa) to steeply inclined chevron folds west of the Szielask Ice Cap (Plate IIb) to tight gently inclined F1 anticlines (Plate IIIb) which close towards the south an south-west in the Lönnberg Valley area.

Apart from the variation in fold attitude across Barff Peninsula, there is also a difference in the attitud of S1 planes with increased structural depth. Overall, the planes are distorted sigmoidally such that gentl "S" folds, with a wave-length of about 500 m. and a gently inclined hinge surface, are seen when lookin along the strike towards the south-east. This re-folding and the variation in the F1 fold attitude can be mos simply explained by the superposition of a large F2 structure with minor congruous folds. The distributio of poles to S1 from Barff Peninsula (Fig. 15a) suggests that the axis of the F2 re-folding plunged a fev degrees to the east-south-east.

* A fold hinge is an observed feature, whereas an axis is calculated from other data (Fleuty, 1964, p. 466).

FIGURE 15

Stereograms illustrating early planar fabrics for Barff Peninsula.
a. Poles to S1 cleavage, sub-areas 1 (●, 44 poles), 2 (×, 56 poles) and 3 (○, 97 poles).
b. Total poles to bedding, sub-areas 1–3, contoured in percentages (346 poles).

2. *Whale Valley phase (F2) fold fabrics south of Barff Peninsula*

Over most of the Barff Peninsula area there is no S2 planar fabric parallel to the inferred axial surface of the F2 re-folding. An S2 crenulation cleavage in conjunction with minor F2 folds appears for the first time in the Sörling Valley area and from there southward into the St. Andrews Bay area the F2 fabric is seen as a sub-horizontal crenulation cleavage (Figs. 3 and 16a) parallel to the hinge surface of minor folds. The folds have mainly east–west trending hinges (Fig. 16a) and are generally tight, similar or more rarely concentric structures with an amplitude and axial-plane separation ranging up to 3 m. As the F2 fabrics become increasingly well developed, the earlier structural elements show a much wider range of orientation. In the St. Andrews Bay area both bedding and S1 cleavage (Fig. 16b) show the effects of F2 folding about an east–west axis, whilst F1 fold hinges (Fig. 16b) have apparently been re-orientated to an east–west trend.

North of St. Andrews Bay the direction of overturning of the F2 folds is not clear but southward the re-folding of the F1 structures (Plate IIIc) suggests that the area forms part of the lower limb of a major antiform whose axial surface is gently inclined towards the north or north-east. The similar style of the minor F2 folds becomes increasingly well developed southward and the more competent horizons, which may have initially deformed in a concentric style, have suffered increased buckling and shearing in the Royal Bay area (Plate IIId).

The S2 cleavage becomes stronger towards the south but as far south as St. Andrews Bay the earlier planar fabrics are still clearly recognizable. There, the S2 cleavage is typically formed either as a fine micro-crenulation cutting the earlier S1 slaty cleavage or as a coarser crenulation cleavage with movement concentrated along more widely spaced planes (Plate IVa). Southward into the Royal Bay area the S2 fabric is progressively more dominant with a true slaty cleavage developing in the finer-grained lithologies and the total destruction of the earlier fabrics by transposition along S2. The S2 slaty cleavage thus formed is often continuous with a crenulation cleavage in adjacent coarser lithologies.

The sub-horizontal attitude of the S2 crenulation cleavage varies very little from the Lönnberg Valley area down to Royal Bay with only a slight increase in the westerly dip in the Neighbour Peak and Cape Charlotte areas. However, the orientation of the F2 fold hinges, though regularly east–west in the St. Andrews Bay area (Fig. 16a), shows no such regularity around Royal Bay (Fig. 17a–c). The F2 fold hinges in the Cape Charlotte promontory show the greatest local variation (Fig. 17d), which suggests that the

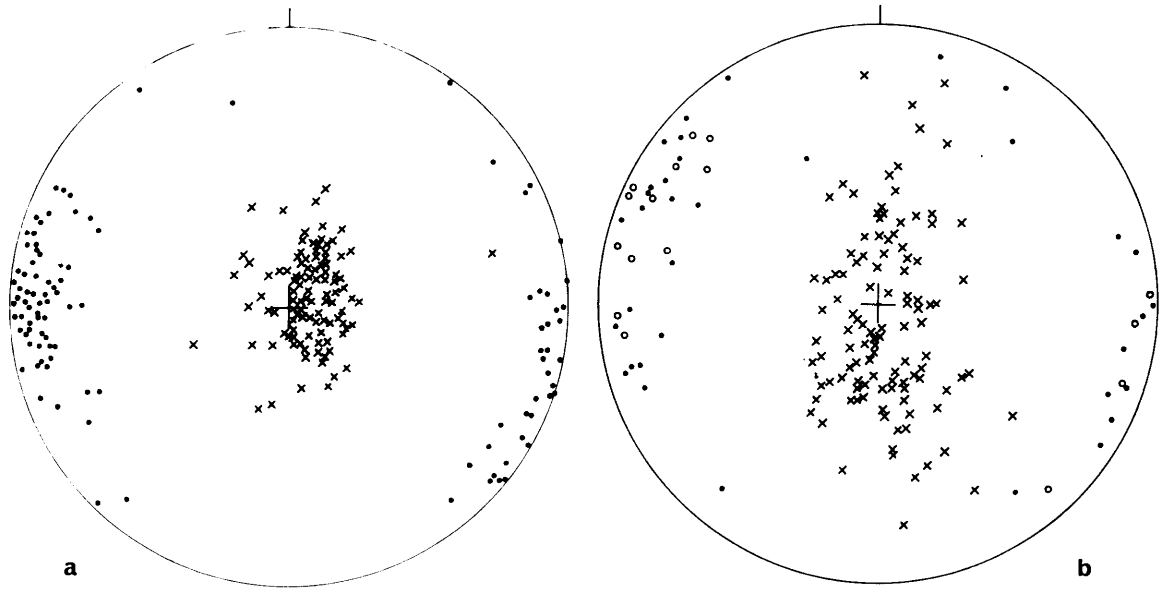

FIGURE 16

Stereograms illustrating structural data from St. Andrews Bay, sub-areas 4 and 5.
a. F2 fold hinges (●) and poles to the S2 cleavage (×).
b. F1 fold hinges (●) and axes (○), and poles to the S1 cleavage (×).

F2 folding was increasingly heterogeneous towards the south. Alternatively, the situation illustrated l the stereograms in Fig. 17, where the poles to an axial-plane cleavage fall at a point maximum whilst tl fold axes themselves are arranged on a great circle, may indicate that the folding was superimposed on a initially variable surface (Ramsay, 1960). If this were the case, post-F1 but pre-F2 structures should l seen in the field, and none was in fact noted. It therefore seems most likely that the trend of the F2 mino fold hinges becomes increasingly random with the southward increase in the intensity of the F2 deformatio

3. *Minor post-F2 structural effects*

a. *S3 crenulation cleavage* (*Cape Charlotte phase*). A very fine crenulation cleavage cuts the S2 plane at few localities in the Lönnberg Valley area and this is increasingly important southward towards Roy Bay (Fig. 12). The cleavage is sub-vertical and, by intersection with the earlier S planes, produces a crem lation which plunges a few degrees to the north-north-east or south-south-west. These lineations form distinctive group when plotted on a stereogram (Fig. 18), in contrast to the L2 crenulation lineations whic have a similar distribution to the F2 fold hinges (Figs. 16a and 17). If the S3 crenulation cleavage is axi planar to a third fold episode, the structures produced must have been open and on a large scale, since n F3 folds were identified in the field. However, in the Cape Charlotte promontory area, the S2 crenulatic cleavage has a steeper westerly dip than the S2 planes on the north-west side of Royal Bay (Fig. 12 This difference in attitude may be the result of F3 folding, in which case the whole Royal Bay area may l part of the south-east limb of a large-scale open and upright synform with an axis trending north-north-ea parallel to the L3 crenulation.

b. *Late kink bands.* Probably the youngest of the structures affecting the Sandebugten Formation are pai of conjugate reverse kink bands. These are widely developed, especially between Sörling Valley and S Andrews Bay, and they were first noted by Trendall (1953, p. 13), who referred to them as "anastomosin planes of puckering". These kink bands frequently bifurcate but generally the fold hinges associated wit each of the bands trend west-north-west to east-south-east.

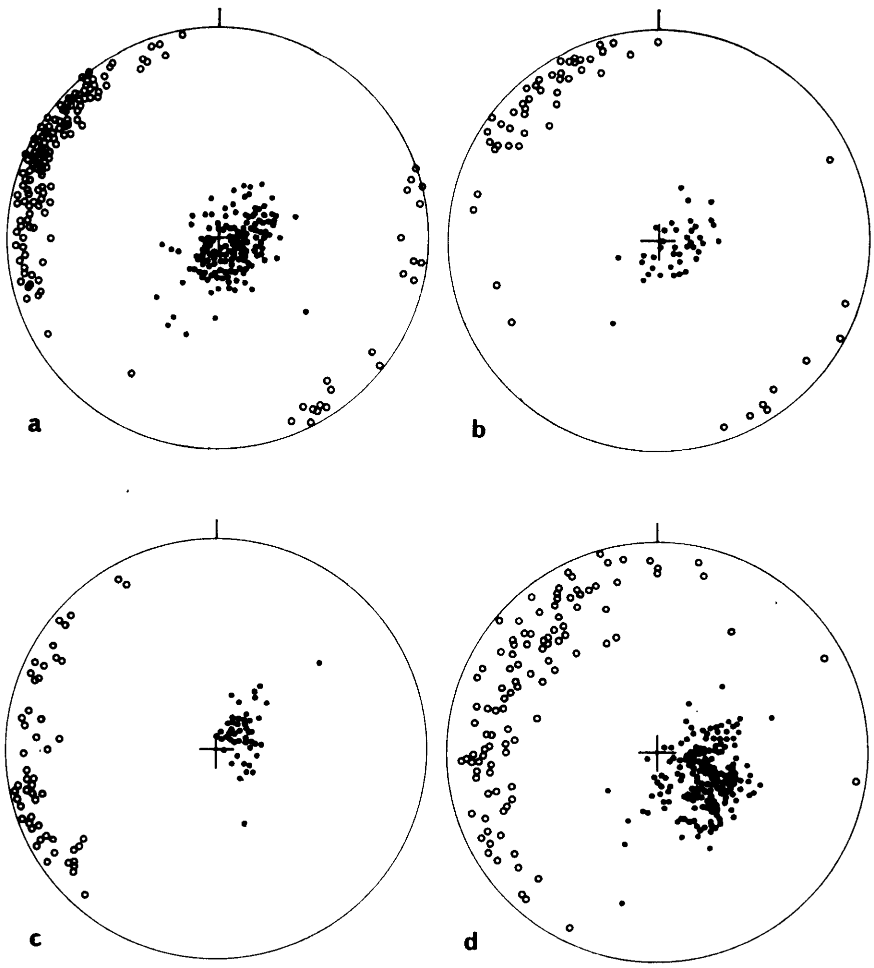

FIGURE 17

Stereograms illustrating F2 fabrics of the Royal Bay area; F2 fold hinges (○) and poles to the S2 crenulation cleavage (●).
a. Sub-area 6, Moltke Harbour–Kelp Bay.
b. Sub-area 7, Cape Harcourt.
c. Sub-area 8, Mount Pirner area.
d. Sub-area 9, Cape Charlotte.

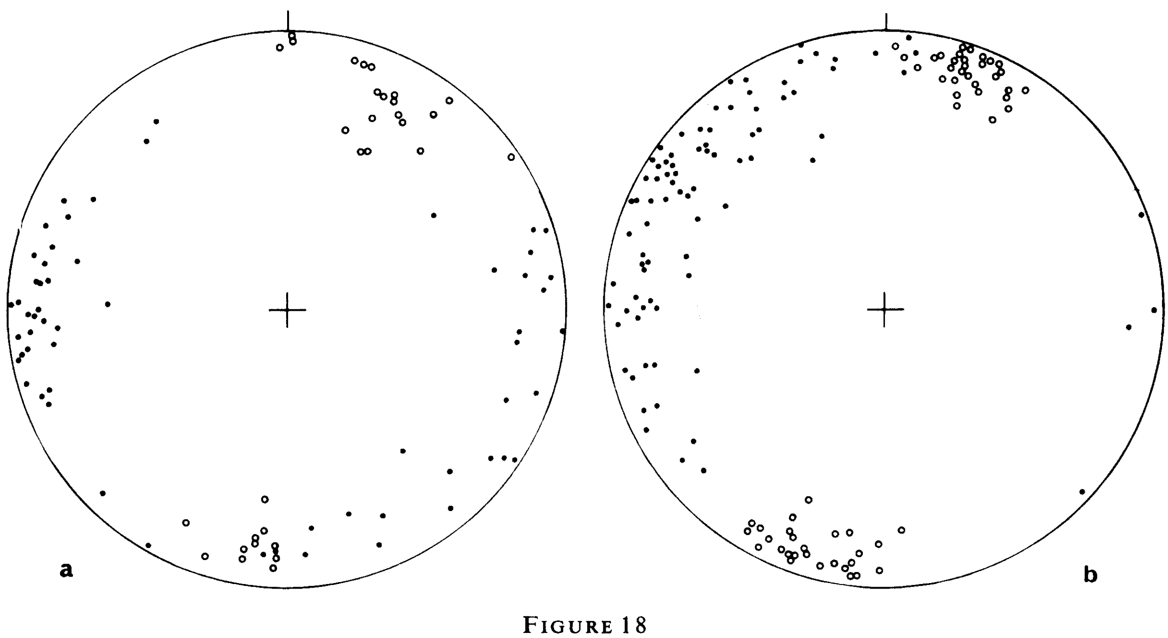

FIGURE 18

Stereograms illustrating late linear fabrics, L2 (●) and L3 (○).
a. Sub-areas 4 and 5, St. Andrews Bay area.
b. Sub-areas 6–9, Royal Bay area.

4. *Summary of the structural history*

The deformation history of the Sandebugten Formation may be summarized as follows:

i. F1; Reindeer Valley phase. Tight similar and chevron folding on axes now trending north-west t south-east with the development of an axial-plane slaty cleavage.

ii. F2; Whale Valley phase. Formation of a crenulation cleavage axial planar to tight, inclined o rarely recumbent overturned folds. All of the folds recognized could be minor congruous structure in the lower limb of a very large recumbent or gently inclined antiform closing south with its axi probably trending east–west. The orientation of the minor fold hinges becomes increasingl diverse towards the south.

iii. F3; Cape Charlotte phase. Formation of a fine sub-vertical crenulation cleavage trending north north-east. The cleavage is possibly axial planar to a large open and upright synform, but no mino folds associated with this phase have been recognized.

iv. Formation of conjugate kink bands with fold hinges trending west-north-west to east-south-east.

It is generally true that all of the deformation phases increase in intensity towards the south with th exception of the final episode of kink-band formation.

C. Folding of the Cumberland Bay Formation

The Cumberland Bay Formation has been thrust north-eastward over the Sandebugten Formation and i now exposed as an isolated, klippe-like outlier in the Barff Point area (the Barff Point Member) and ove most of South Georgia to the west and south of the Sandebugten Formation outcrop (Fig. 12). Fiel work was carried out in the limited area of exposure around Barff Point and to the south of Royal Bay o the Will Point and Cape Charlotte promontories. A brief reconnaissance was also possible farther sout in the Iris Bay area but the coastline between Gold Harbour and Müller Point was not visited.

In all of the areas studied the main folds are large structures with an amplitude and wave-length generall in excess of 250 m., and hinge surfaces moderately inclined towards the south-south-west. They have re- folded an earlier set of minor tight to isoclinal folds.

The various fold phases may be conveniently referred to as follows:

	Barff Point area	*South Royal Bay–Iris Bay area*
F1	Rookery Bay	Iris Bay
F2	O'Connor Peak	Weddell Glacier

1. *The Barff Point area*

The main phase (F2; O'Connor Peak) folds in the Barff Point Member are large asymmetric structures folding bedding and a sub-parallel slaty cleavage (see the cross-section through O'Connor Peak (Fig. 13a)) with hinge surfaces moderately inclined towards the south-south-west. The antiforms are tight in contras to the more open synforms; in the former a fine crenulation cleavage has usually formed parallel to th hinge surfaces but this becomes progressively weaker towards the hinge zones of the synforms.

Locally, the slaty cleavage is very well developed and in several cases it was observed to be parallel to th hinge surfaces of small tight or isoclinal folds with an amplitude ranging from 1 to 3 m. These minor fold and the slaty cleavage are probably the result of an earlier (F1) deformation episode and have been re-folde by the main structures.

All of the F1 (Rookery Bay) folds observed were tight or isoclinal with hinge surfaces parallel to th general attitude of the local bedding. Thus, poles to bedding plotted on a stereogram (Fig. 19) lie on an approximate great circle, which indicates that the axis of the F2 folding probably plunges 15° towards 280°. The minor F1 folds also have hinges which plunge a few degrees to the west-north-west (Fig. 19) which may be a primary orientation or may be in part due to some re-orientation during the F2 fold episode. The hinge surfaces of the F2 folds, defined by the S2 crenulation cleavage, dip at about 45° to the south-south-west (Fig. 19).

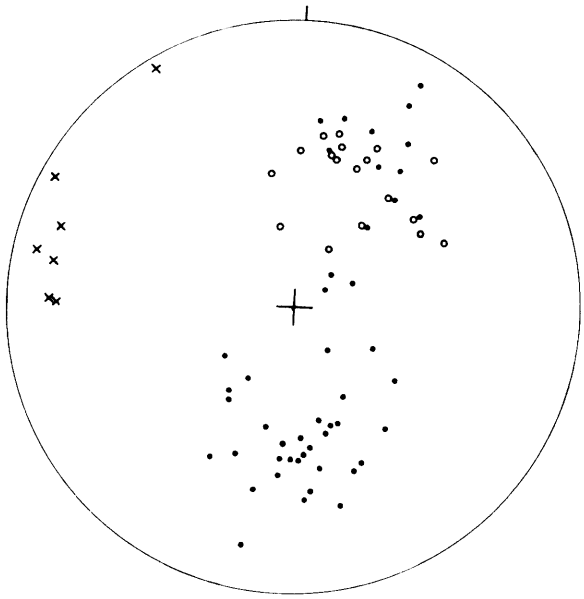

FIGURE 19

Stereogram illustrating structural data for the Barff Point Member. ● 47 poles to bedding; ○ 18 poles to the S2 crenulation cleavage; × seven minor fold hinges.

Immediately above the tectonic contact with the underlying Sandebugten Formation a mylonitic fabric has developed parallel to the thrust plane. Locally, this is concordant with the bedding and early cleavage, but elsewhere a mylonitic fabric has formed parallel to the S2 cleavage, which may have been formed by local thrusting parallel to the hinge surfaces of the F2 folds during the later stages of deformation.

2. *The area between Royal Bay and Iris Bay*

To the south of Royal Bay, the main phase (F2; Weddell Glacier) folds are large asymmetric structures with hinge surfaces moderately inclined towards the west-south-west and axial-plane separation ($\lambda/2$) of up to 1,000 m. The long normal fold limbs dip at an angle of 25–30° towards the west-south-west, whereas the short limbs are vertical or slightly overturned and have a similar strike. The hinge zones are generally concentric and the scale and style of the F2 (Weddell Glacier) phase folding is illustrated in the cross-section through the Cape Charlotte promontory (Fig. 13d) and in Plate IVb. Minor folding is fairly widespread, especially inland from Will Point, where the folds are typically tight and similar with an amplitude and axial-plane separation ($\lambda/2$) usually less than 10 m. and commonly less than 3 m. Some of these minor folds are congruous to the much larger F2 (Weddell Glacier) structures but the majority have a hinge surface steeply inclined towards the north-east and are therefore incongruous with the F2 folds and are thought to be earlier in age. They are grouped with the minor folds observed between Royal Bay and Iris Bay, which are all virtually isoclinal with axial-plane separations ($\lambda/2$) only ranging up to 10 cm., as Iris Bay phase (F1) structures which have been re-folded during the Weddell Glacier phase (F2) deformation.

A stereographic plot of poles to bedding in the Will Point and Cape Charlotte areas (Fig. 20a) defines an approximate great circle whose pole probably corresponds to the F2 (Weddell Glacier) fold axis, which is therefore sub-horizontal with a north-north-westerly trend. In the Iris Bay area, field work in December 1973 showed that a slaty cleavage sub-parallel to the bedding is cut by a crenulation cleavage which is moderately inclined to the south-west (Fig. 20b) and inferred to be parallel to the axial surface of the main Weddell Glacier phase folds (F2). The lineations produced by the intersection of the two cleavages trend consistently towards the south-south-east (Fig. 20b) sub-parallel to the F2 π-axis determined from Fig. 20a. At the time when the area between Royal Bay and Gold Harbour was mapped (February and March 1972), only one cleavage was recognized and measured in the field. However, subsequent laboratory

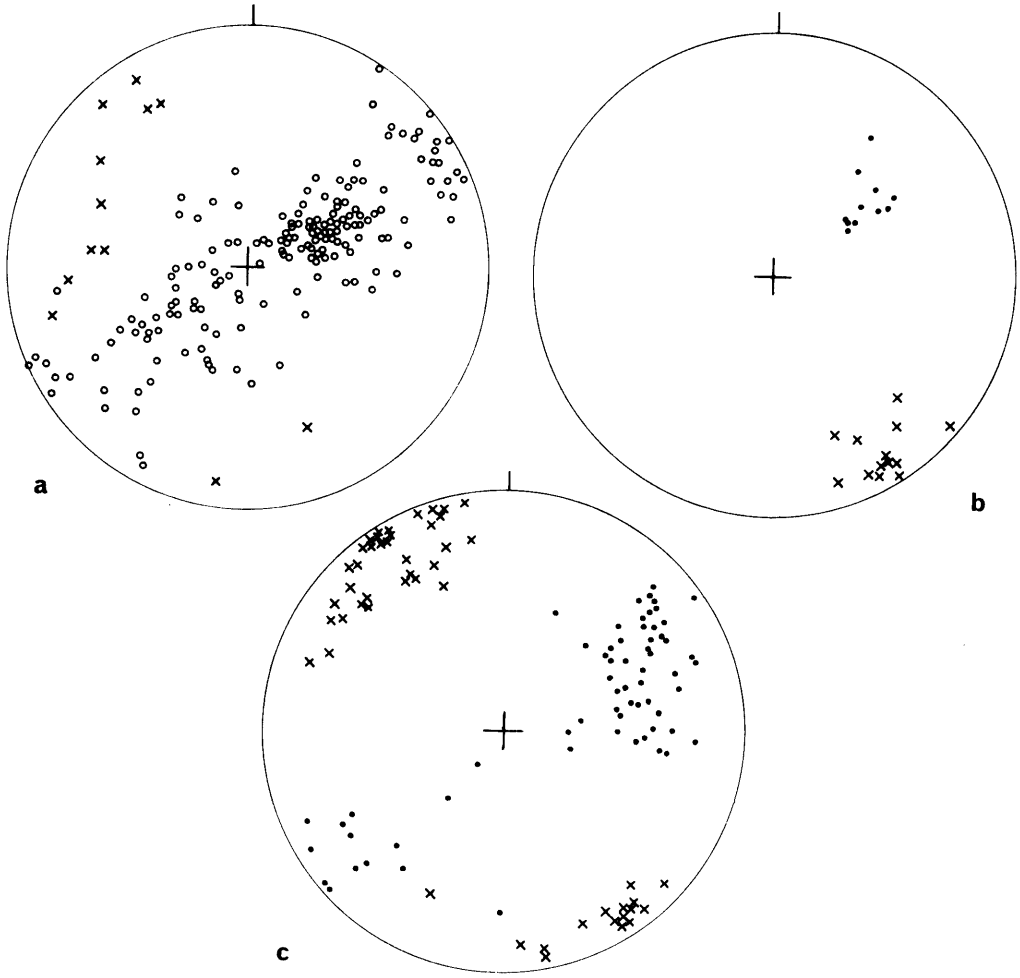

FIGURE 20

Stereograms illustrating structural data for the Cumberland Bay Formation south of Royal Bay.
a. Minor fold hinges (×) and poles to bedding (○), Will Point and Cape Charlotte.
b. L2 crenulation lineations (×) and poles to the S2 crenulation cleavage (●), Iris Bay.
c. Lineations (×) and poles to the S1 and S2 cleavage planes (●) which were not differentiated in the field, Will Point and Cape Charlotte.

study of specimens and thin sections has shown that both an S1 slaty cleavage and a very fine S2 micro-crenulation cleavage are present. Thus, the distribution on a stereogram of poles to cleavage for the Will Point and Cape Charlotte areas (Fig. 20c) can be interpreted as a point maximum, which represents the attitude of the axial surface of the F2 (Weddell Glacier) folds, superimposed on a vague girdle. The point maximum will be formed by poles to the S2 micro-crenulation cleavage (compare with poles to S2 in Fig. 20b) and the girdle by the poles to the S1 slaty cleavage, folded about the F2 axis. Similarly, lineations mapped in the field as belonging to one set are distributed (Fig. 20c) so that a point maximum coincides with the F2 π-axis, whilst the rather diffuse girdle represents the orientation of the minor, mainly F1, fold hinges (Fig. 20a).

In an area approximately 1·5–2·5 km. south and south-west of Will Point, and again immediately north-west of Gold Harbour, the S1/S2 cleavage mapped as a single structure is cut by a crenulation cleavage dipping at about 20° to 300°. This crenulation cleavage is parallel to the hinge surfaces of small (λ <50 cm.) overturned folds, the hinges of which plunge about 20° to the north-west (i.e. down dip on the crenulation planes). The attitude of this cleavage is markedly different from that of all other planes observed and it may represent a post-F2 structure.

D. Structural Correlations

The F1 fold structures in both the Sandebugten and Cumberland Bay Formations (Reindeer Valley, Rookery Bay and Iris Bay phases) are tight to isoclinal, similar or sometimes chevron in style. A considerable variation in magnitude and attitude was observed but hinges generally trend towards the north-west quadrant.

All of the F1 structures have been re-folded by major overturned folds but, whereas the hinge surfaces of the large F2 antiforms in the Cumberland Bay Formation (Weddell Glacier phase) are moderately inclined towards the south-west, the hinge surfaces of the major F2 folds in the Sandebugten Formation (Whale Valley phase) are gently inclined to the north or north-east. This opposition in the direction of overturning was first commented on by Trendall (1953, 1959) but he examined only the western side of Barff Peninsula with the result that the local attitude of F1 folds in the Sandebugten Formation (Reindeer Valley phase) was contrasted with the attitude of the major probably F2 folds in the Cumberland Bay Formation elsewhere on the island. More recently, Dalziel and others (1975) have described the Dartmouth Point area in some detail. They figured F1 folds with an axial-planar slaty cleavage overturned towards the north-east immediately above the thrust plane which truncates the S1 fabric in the Sandebugten Formation. They considered that the Sandebugten and Cumberland Bay Formations were deformed at the same time, being overfolded in opposite directions, and described a later crenulation cleavage as "anastomosing and commonly conjugate". This is probably the same as the late conjugate kink bands referred to here, and it is interesting to note that these have the same attitude above and below the thrust plane on Dartmouth Point.

The significant field observations relating to the temporal relationship of the thrusting to the fold episodes may be summarized as follows:

i. The S1 fabric in the Sandebugten Formation is sharply truncated by the thrust plane.

ii. The S2 fabric in the Sandebugten Formation south of Royal Bay does not cross the thrust plane but changes attitude to become parallel to it.

iii. The S1 slaty cleavage merges with a parallel mylonitic fabric immediately above the thrust but in the Barff Point area a mylonitic fabric has also developed parallel to S2 in the Cumberland Bay Formation.

iv. The F2 fold phase in both rock types is characterized by large-scale overturned folds.

v. The variation in attitude of the thrust plane between Barff Point, Dartmouth Point and Royal Bay is probably too great to be primary and the thrust contact itself may have been folded.

vi. The late conjugate kink bands have the same attitude on both sides of the thrust plane.

It seems most likely that the main thrust movement was a late F2 effect associated with the Weddell Glacier–O'Connor Peak fold phase. The possible folding of the thrust plane may then have occurred during the F3 (Cape Charlotte phase) large-scale open folding of the Sandebugten Formation. Kink-band formation was the latest structural event involving folding and this was followed by joint development as orogenic pressure finally relaxed. The joint planes have no strongly preferred orientation in the Sandebugten Formation but in the Cumberland Bay Formation a dominant north-east to south-west trend was observed.

A complicating factor, which must be considered when attempting to correlate the fold episodes, is the means by which the depositional basin (Fig. 21a) closed. Dalziel and others (1974) ruled out the possibility of obduction since the rocks of the basin floor appear to be entirely autochthonous, and favoured internal deformation of the basin floor or subduction, possibly towards the Pacific Ocean. This latter suggestion is compatible with their general observation from Tierra del Fuego that "Everywhere the intensity of deformation dies away rapidly towards the Atlantic". However, in South Georgia the opposite is true with the degree of deformation lessening towards the Pacific Ocean, so that even within the Cumberland Bay Formation the folding on the north-east coast of the island is much more intense than in, for example, Annenkov Island to the south-west (Trendall, 1959; Pettigrew, in press). Thus, the evidence from South Georgia suggests that if subduction was involved it was probably Atlantic-ward beneath the South American plate (Fig. 21b). In this process the sedimentary cover of the oceanic crust forming the floor of the basin (the Sandebugten and Cumberland Bay Formations) would have been scraped off, deformed and accrued by the margins of the South American plate. This would have occurred progressively so that the Sandebugten Formation may well have been intensely deformed whilst the youngest beds of the Cumberland Bay

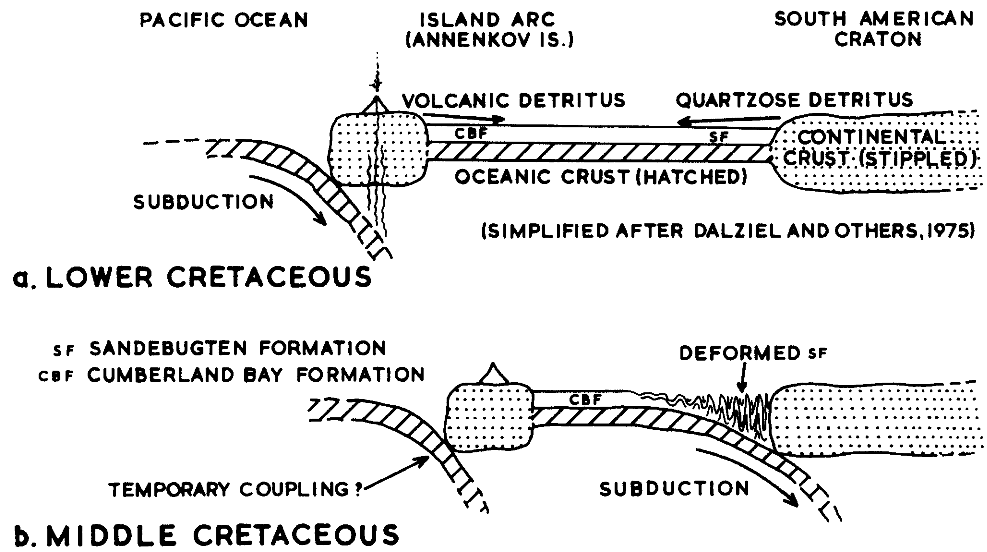

FIGURE 21

Plate-tectonic model for the closing of the depositional basin and the progressive deformation of the Cumberland Bay and Sandebugten Formations. (In part after Dalziel and others (1975).)

Formation were still being deposited (Fig. 21b). Final closing of the basin would have left the two rock types intensely deformed and sandwiched between areas of continental crust, one of which would have protected the overlying volcanic rocks, now exposed as a relatively undeformed sequence on Annenkov Island (Suárez and Pettigrew, 1976; Pettigrew, in press). Dalziel and others (1974) considered that the marginal basin closed in the Middle Cretaceous, because the youngest sediments deposited in the basin are Aptian or more probably Albian (Pettigrew and Willey, 1975) and in Tierra del Fuego the probable equivalent of the Cumberland Bay Formation (the Yahgan Formation) is cut by post-tectonic intrusions which are approximately 80 m. yr. old (Halpern and Rex, 1972). However, the youngest sediments are part of the Cumberland Bay Formation close to the island arc and these would have been the last to suffer deformation. It is therefore possible that the deformation of the Sandebugten Formation commenced earlier.

V. MINOR INTRUSIONS

IGNEOUS rocks from the north-east coast of South Georgia were first collected by whalers at Gold Harbour and these were described by Tyrrell (1916) as ophitic dolerite partially altered to epidiorite. This outcrop was later visited by Trendall, who confirmed Tyrrell's description and referred to the intrusion as a pre-tectonic sill (Trendall, 1959, p. 40). The Combined Services Expedition, 1964–65, recorded igneous rocks at the head of Lönnberg Valley (Burley, 1966) but no petrographic detail was given.

1. *Location and size*

Four very small igneous sheets, all less than 50 cm. thick, were recorded at the head of Lönnberg Valley, and a single sheet of a similar size was observed at Will Point. Much larger masses of igneous rock crop out between Gold Harbour and Björnstadt Bay and at Iris Bay; at these localities the coarse unsheared rock has a pale green gabbroic appearance.

From the north-east corner of Gold Harbour, exposures of igneous rock occur for about 2 km. along a line trending north-north-west. In all of the outcrops examined the igneous rock was intruded into slates and metagreywackes of the Sandebugten Formation, generally in conformable contact with the locally dominant planar fabric. However, there is considerable discrepancy between the local and regional fabric attitudes, which, together with the obvious variation in width of the intrusion, suggests that a boudinaged sheet or sill is involved. The thickest section of this sheet is exposed at the north-east corner of Gold Harbour, where the lower contact with the metasediments is clearly visible. A gap in the exposure conceals the upper contact but an overall thickness of at least 10 m. is indicated. In the thinner sections of sill, strong shearing accompanied by extensive recrystallization is penetrative throughout the intrusion, but the greater thickness of the intrusion at Gold Harbour has intensely sheared margins with a relatively undeformed central part. The outcrops between Gold Harbour and Björnstadt Bay are almost certainly part of the same intrusive sheet, although in one outcrop three intrusive sills are separated by thin horizons of metasediment.

Inland from Iris Bay up to three boudinaged gabbroic sheets, ranging in thickness from 10 cm. to 10 m., are continuously exposed for at least 3 km. along a line trending north-west at the margin of Herz Glacier. The igneous rock is intruded into Cumberland Bay Formation shales and greywackes, and it appears to be at least partly conformable with the original bedding. The field appearance of the rock is very similar to that of the Gold Harbour igneous intrusions but there is much less shearing at the boudin margins in Iris Bay, and an increased induration of the Cumberland Bay Formation sediments at the margins of the intrusion suggests thermal metamorphic effects.

The intrusions at Will Point and Lönnberg Valley are very much smaller and have suffered a far greater degree of shearing than the examples farther south. A penetrative fabric, parallel to the dominant local cleavage, affects the igneous rock and the intrusive bodies are exposed as lenses between 5 and 50 cm. thick and up to 4 m. long. Only one such lens was observed at Will Point but four lenses, separated by thin horizons of slate, are exposed in Lönnberg Valley. The field appearance of all of these small intrusions is identical to the sheared margins of the Gold Harbour boudins.

The moraines associated with Nordenskjöld, Cook and Heaney Glaciers contain many cobbles and boulders of igneous rock very similar to that observed *in situ*. It therefore seems likely that more sheet intrusions crop out farther inland or beneath the glaciers.

2. *Petrology*

In thin section all of the igneous material is very similar. The centres of the larger boudins preserve a coarse-grained ophitic texture, but the boudin margins and the thinner sheets are usually highly sheared and thoroughly schistose.

Despite the high degree of alteration, all of the coarse-grained sections have the characteristics of an oversaturated dolerite. Essentially plagioclase, ranging in composition from labradorite to albite, is in an ophitic relationship with two pyroxenes, dominantly augite with an accessory orthopyroxene, possibly enstatite. The presence of small quantities of primary interstitial quartz shows that the rock was originally oversaturated. The quartz usually forms small euhedral crystal aggregates but occasionally it occurs as myrmekitic intergrowths with plagioclase, and in one case it is intergrown in a graphic relationship with rare accessory alkali-feldspar. The most important primary accessory mineral is sphene but, instead of the normal wedge-shaped crystal form, it is moulded around plagioclase laths, is bounded by their plane faces and is clearly of a late phase or possibly deuteric origin. This primary sphene grades into sphene which is clearly secondary and associated with penninitic chlorite. Primary ore minerals have altered almost completely to leucoxene but the characteristic skeletal form of ilmenite is retained.

Thus the original rock type consisted essentially of plagioclase and two pyroxenes with accessory sphene, quartz, orthoclase and ilmenite. From this assemblage, dynamothermal metamorphism has produced considerable alteration effects, varying in intensity with the degree of shearing the rock has undergone. The plagioclase has been more or less completely saussuritized to form sericite, clinozoisite and a little calcite embedded in a groundmass of secondary albite. Hornblende, pleochroic from very pale yellow to pale brown, has widely replaced the clinopyroxene, sometimes forming a spectacular fringe of acicular actinolite crystals which cut cleanly across the pyroxenes and feldspars of the original fabric. The orthopyroxene is uralitized and in some cases appears to be extensively altered to fibrous bastite, which may also be a rare alteration product of the clinopyroxene. Where the alteration of the pyroxenes is almost complete, pseudomorphs of bastite or uralite occur as fibro-lamellar aggregates.

A medium or rarely coarse-grained rock, consisting essentially of plagioclase in the labradorite range in an ophitic relationship with two pyroxenes, of which the clinopyroxene is dominant, may be termed a dolerite, or microgabbro to emphasize the pyroxene proportions. As a result of dynamothermal metamorphism, however, the labradorite–pyroxene composition now tends towards albite–hornblende and the rock is thus in a broad sense dioritic. Epidiorite may therefore be a more justifiable name for these minor intrusions.

3. *Time of intrusion*

The close petrographic similarity between all of the sheet intrusions of the north-east coast of South Georgia suggests that they represent a single phase of intrusion. Trendall (1959, p. 40) considered that the Gold Harbour sheet was pre-tectonic and certainly all of the intrusions into the Sandebugten Formation are affected by the F2 fabrics. At Iris Bay, the igneous sheets are partially conformable with the bedding and are affected by the fabrics associated with the F2 folding of the Cumberland Bay Formation. A pre-F2 phase of dolerite intrusion therefore seems to be very likely but the relationship of intrusion to the F1 fold episode is not certain.

VI. SUMMARY OF THE GEOLOGICAL HISTORY OF SOUTH GEORGIA

THE Cumberland Bay Formation of South Georgia has yielded a sparse Mesozoic fauna but so far only fragmentary plant remains, trace fossils and Radiolaria, none of which have proved stratigraphically useful, have been recovered from the Sandebugten Formation. Nevertheless, the results of recent field work (Dalziel and others, 1975; this report, p. 6) indicate that the two formations are facies variants of the same age which were deposited contemporaneously by turbidity currents during the Upper Jurassic and Lower Cretaceous. The Cumberland Bay Formation was derived from an active volcanic island-arc source of andesites and trachytes situated, in terms of the present-day geography, to the south-west of South Georgia (Trendall, 1959; Suárez and Pettigrew, 1976), although turbidity current flow was predominantly longitudinal towards the north-west. In similar terms, the Sandebugten Formation was derived from a continental area probably to the north (Dalziel and others, 1975) composed of quartzites, silicic volcanic rocks, granite, schists and gneiss (p. 18). In some parts of the basin, turbidity flows from each of the source areas apparently combined to deposit a mixed lithology. In pre-drift reconstructions of the Scotia arc (e.g. Dalziel and Elliot, 1971), South Georgia has been placed very much closer to the South American craton, from which the Sandebugten Formation was probably derived. The abundant quartzite grains may have originated from the late Palaeozoic metasediments which now form part of the South American basement, and acid volcanic debris could have been associated with the extensive Middle–late Jurassic silicic volcanic rocks which overlie much of the basement (Dalziel and others, 1975). These acid volcanic rocks are variously known as the Porphirica Formation, the Tobifera Formation or the Quemado Formation.

Burial metamorphism of the South Georgia greywacke sequence in an area with a geothermal gradient in excess of 40° C/km. (Skidmore, 1972) resulted in the extensive prehnitization of much of the Cumberland Bay Formation. Over the greater part of the island, subsequent polyphase deformation involving up to four fold episodes (Clayton, in press; Stone, this report, p. 36–40) was accompanied by metamorphism ranging up to the greenschist facies. The metamorphic peak in the Sandebugten Formation was, however, post-F2 and produced small rosettes of acicular biotite (p. 27). At an early stage in the structural history of this area, dolerite sheets were intruded which have subsequently been transformed into epidiorite (Tyrrell, 1916; Trendall, 1959; this report, p. 40–42).

The time of folding of the South Georgia greywackes can only be deduced from indirect evidence. The youngest of the sediments in the depositional basin envisaged by Dalziel and others (1974, 1975) are probably the Albian deposits of Annenkov Island (Pettigrew and Willey, 1975) and these must pre-date the onset of folding at that locality. In Tierra del Fuego, the probable equivalent of the Cumberland Bay Formation is the Yahgan Formation (Katz and Watters, 1966), which has also been regarded as part of the sedimentary fill of the Upper Jurassic–Lower Cretaceous marginal basin envisaged by Dalziel and others (1974, 1975). The Yahgan Formation is cut by post-tectonic intrusions which have been dated at 80 m. yr. (Halpern and Rex, 1972). This, together with the fossil evidence from Annenkov Island, suggests that the folding of the Yahgan, Cumberland Bay and Sandebugten Formations probably occurred during the mid-part of the Cretaceous. However, if the depositional (marginal) basin closed as a result of subduction, the deformation is likely to have been progressive such that (as in Fig. 21) the earliest deformation of the Sandebugten Formation may have preceded that of the Cumberland Bay Formation. If this were the case, the fold episodes recognized in the Sandebugten and Cumberland Bay Formations need not necessarily be coeval.

The final break-up of the continental isthmus joining South America and the Antarctic Peninsula, and the main phase of eastward drift of the fragments (one of which now forms the South Georgia continental block), is believed to have occurred in the early Cenozoic (Dalziel and Elliot, 1971).

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PLATE I

a. Part of the Allardyce Range viewed from the east across the heavily crevassed Cook Glacier. The three main peaks are Mount Kling (left; 1,845 m.), Nordenskjöld Peak (centre; 2,353 m.) and Mount Roots (right; 2,158 m.).

b. Steep screes developed beneath cliffs of tightly folded Sandebugten Formation shales and greywackes in the centre of Barff Peninsula.

c. Looking west along the southern shore of Royal Bay. The succession of small coves and rocky headlands is typical of the more exposed parts of the north-east coast of South Georgia.

a

b

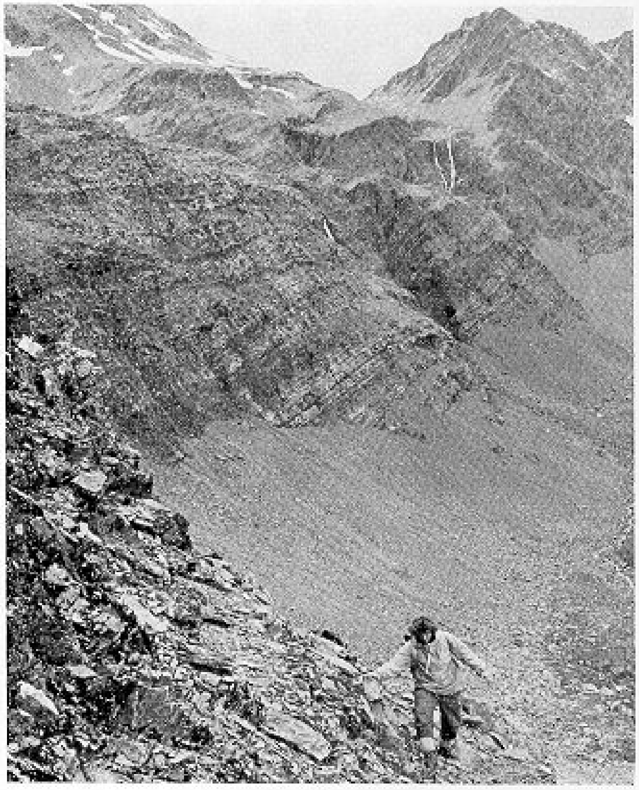
PLATE II

PLATE II

a. The tectonic contact between the Cumberland Bay Formation (above) and the Sandebugten Formation on the south side of Royal Bay 0·5 km. east of Weddell Glacier (M.617). The hammer shaft is 35 cm. long.

b. Tight, steeply inclined chevron folds; looking south-east towards Black Peak. The main cliff is approximately 150 m. high (M.364).

a



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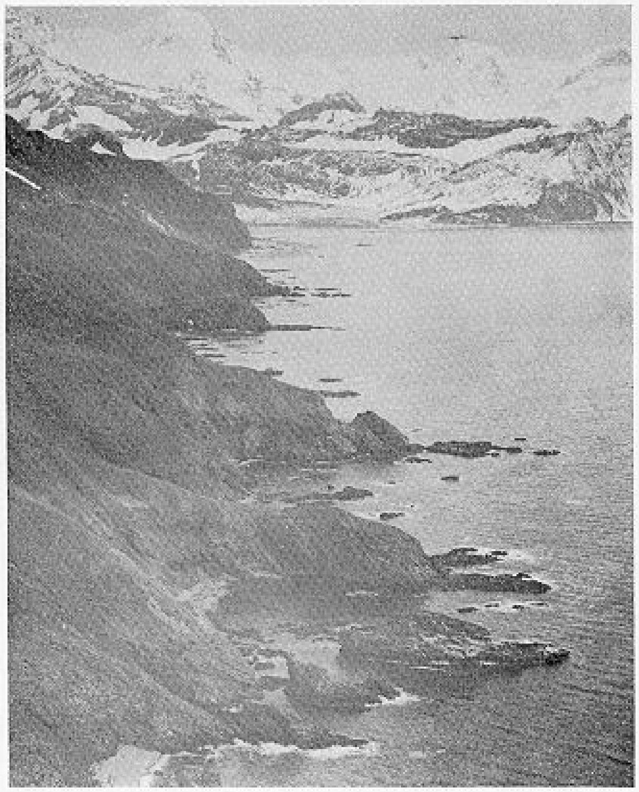


c

PLATE III

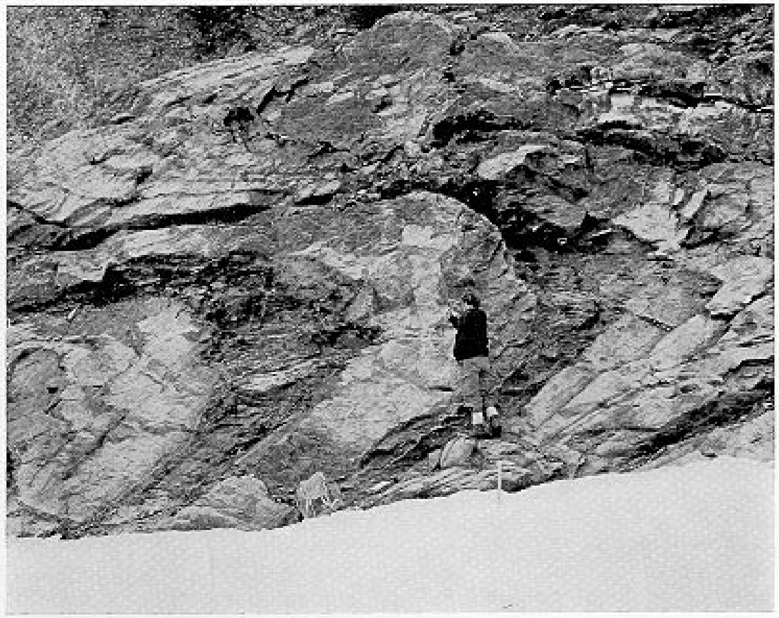
a. Tight, upright similar folds; looking north across Reindeer Valley. The right-hand side of the main cliff is approximately 75 m. high (M.309).

b. Tight recumbent chevron and similar folds with bulbous hinge structure. The photograph was taken looking east (M.329).

c. Superposition of F1 and F2 structures in the St. Andrews Bay area. Large-scale re-folding of F1 chevron folds; looking west (M.706). The approximate position of the F1 hinge trace is indicated by the pecked line.

d. Medium-scale F2 folds in Little Moltke Harbour (M.547).

a



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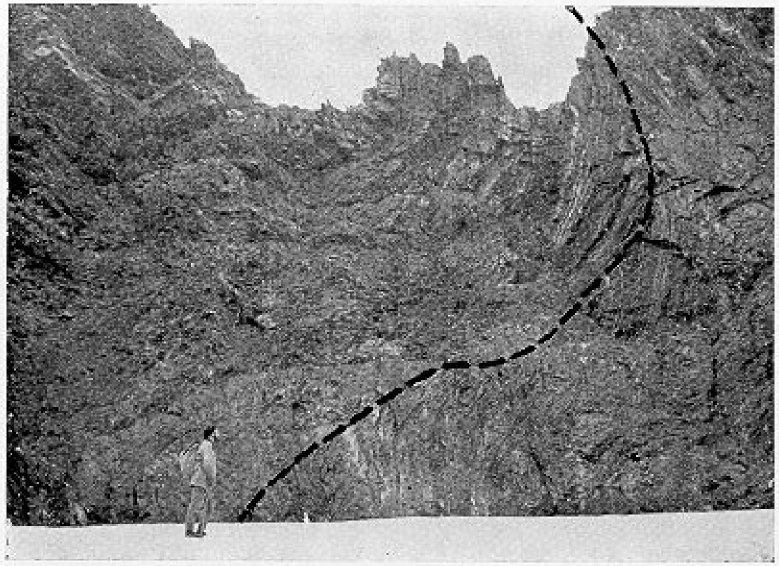


c

d

PLATE III

PLATE IV

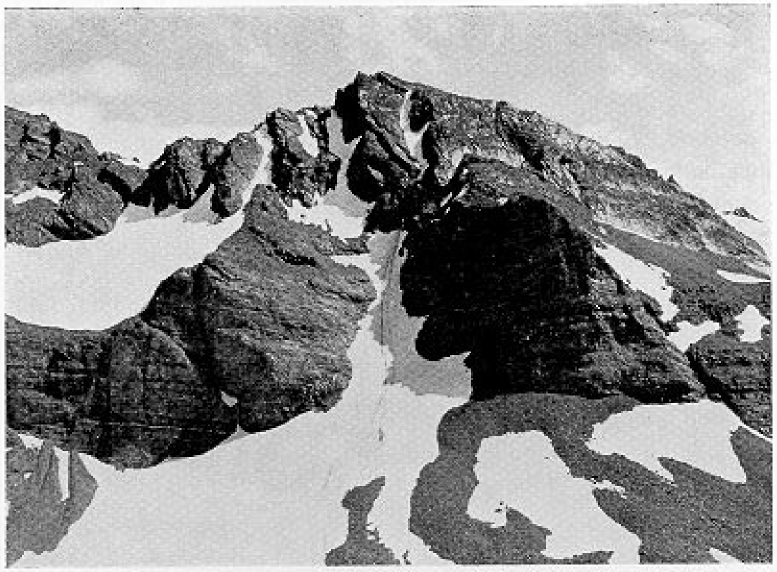
a. An S2 crenulation cleavage affecting earlier planar fabrics in St. Andrews Bay (M.703). Note that quartz veins are both earlier than S2 and developed parallel to it. The pencil is 15 cm. long.

b. Part of a Weddell Glacier phase (F2) fold hinge on the western side of the Will Point promontory (M.652). The main cliff is approximately 250 m. high and the photograph was taken looking north-west.

c. A series of concentric discs forming the nucleus of a calcareous concretion exposed near St. Andrews Bay (M.701). The pencil is 12 cm. long.

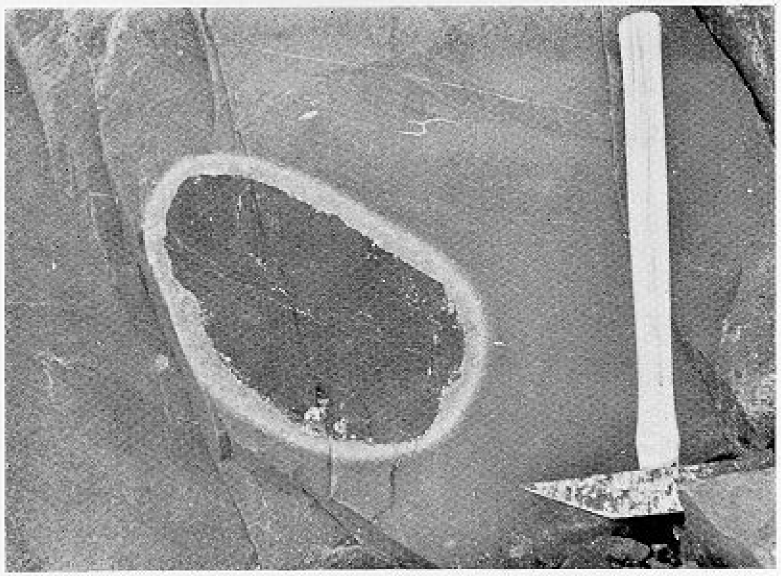
d. A large siltstone inclusion with a pale-weathering halo in an ungraded Cumberland Bay Formation sandstone (M.651). The hammer shaft is 35 cm. long.

a



b

c



d

PLATE IV

PLATE V

An ABCE Cumberland Bay Formation turbidite unit with convolute lamination-like ripples developed in the C division and merging upwards into flame structures. The vertical rule is 33 cm. long.

PLATE V

E

C

B

A

A

E

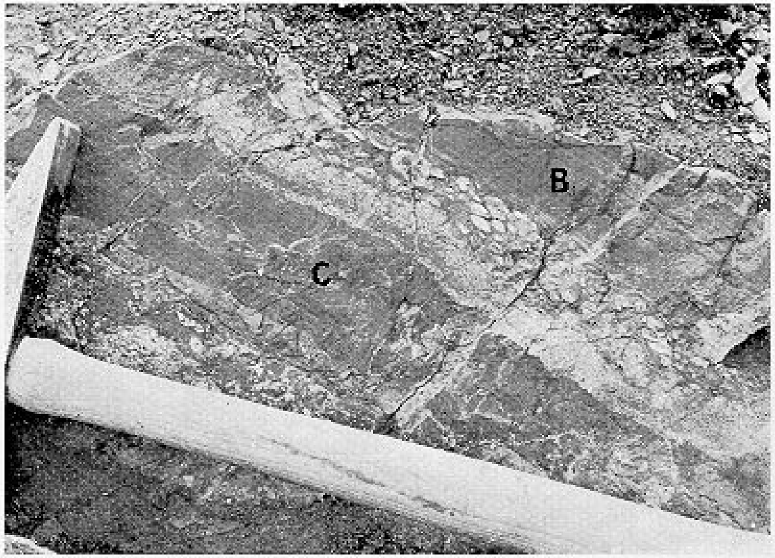
PLATE VI

a. Prehnitized pseudo-nodules associated with parallel (B) and cross laminations (C) in an inverted sequence near Barff Point (M.391). The hammer shaft is 35 cm. long.

b. A prehnitized radiolarian with a trace of radial rib ornamentation preserved. (M.632.3; X-nicols; ×445)

c. Extensive bioturbation of Cumberland Bay Formation siltstone by simple unbranched burrows. (M.412.2; ×1.35)

d. A meandering grazing trace on a Cumberland Bay Formation bedding surface (M.652.3 The coin is 2 cm. in diameter.



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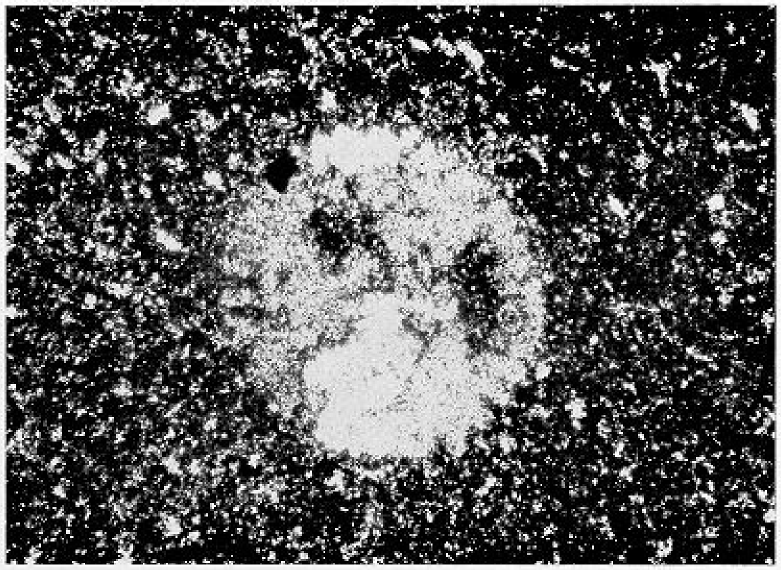

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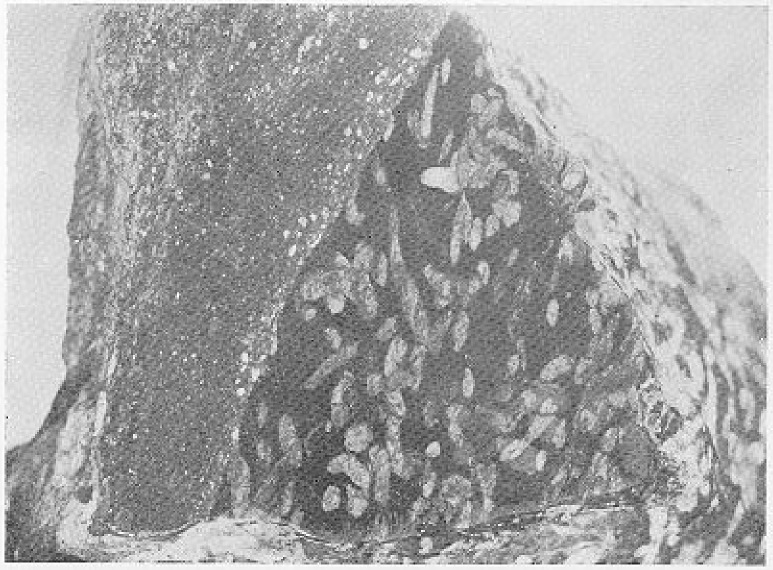

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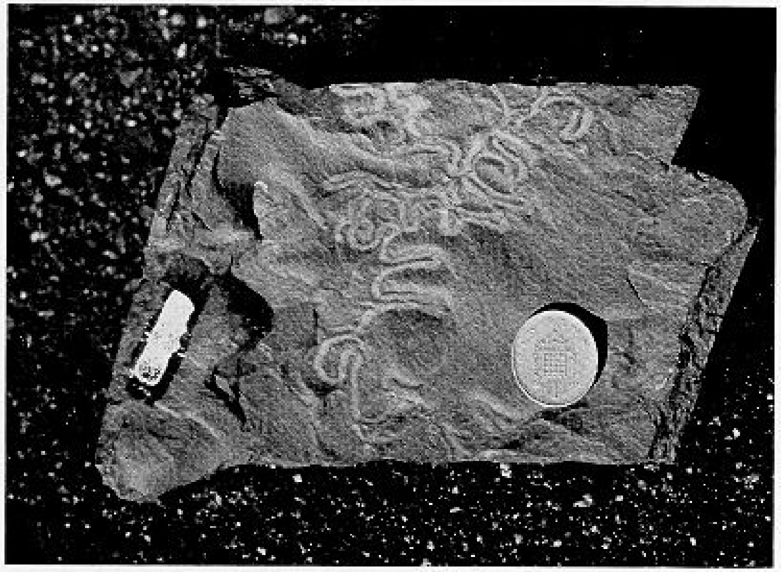


d

PLATE VI

PLATE VII

a. A detrital quartz grain recrystallizing at its margins into an incipient schistosity. Sandebugten Formation. (M.330.1; X-nicols; ×100)

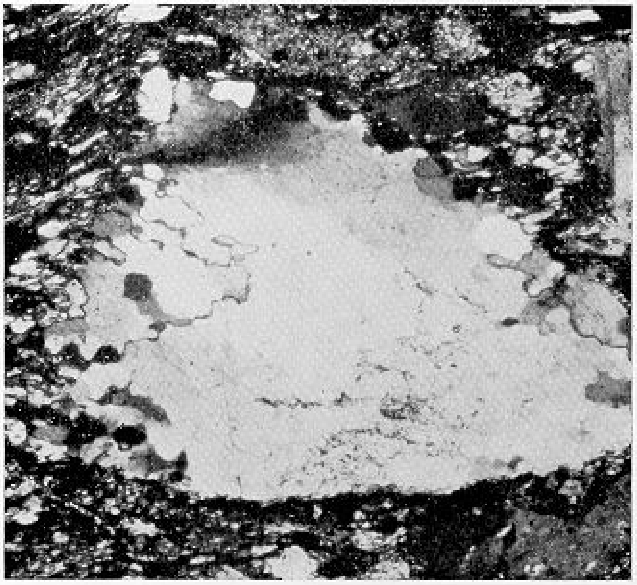
b. A late crenulation cleavage deforming earlier fabrics. Sandebugten Formation. (M.553.2; ordinary light; ×75)

c. Cataclastic shattering of plagioclase crystals. The fragments have been re-cemented by secondary quartz and chlorite. Sandebugten Formation. (M.606.3; X-nicols; ×75)

d. A chlorite-filled amygdale in unstrained, probably volcanic quartz. Sandebugten Formation. (M.529.1; X-nicols; ×100)

e. Partially developed granoblastic texture in detrital quartzite. Sandebugten Formation. (M.546.1; X-nicols; ×95)

f. Detrital grain of felsite incorporating a large plagioclase phenocryst. Sandebugten Formation. (M.313.3; X-nicols; ×87·5)



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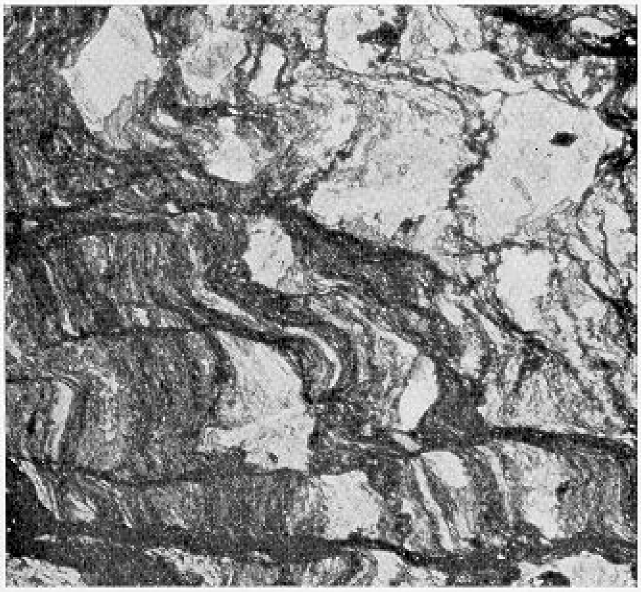

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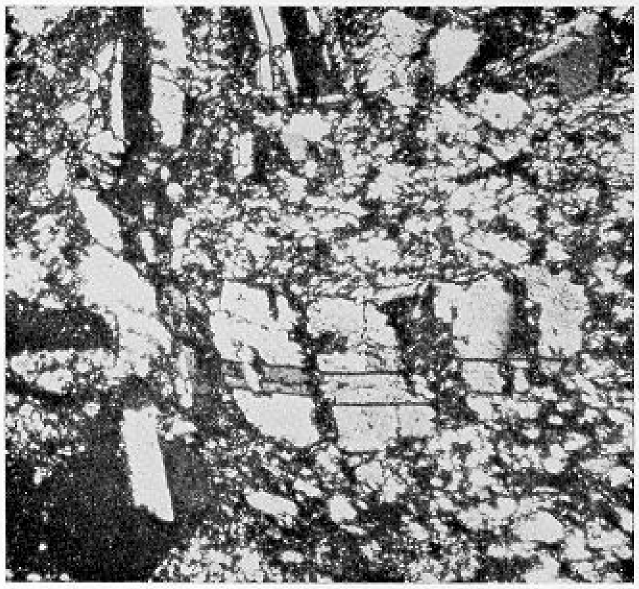

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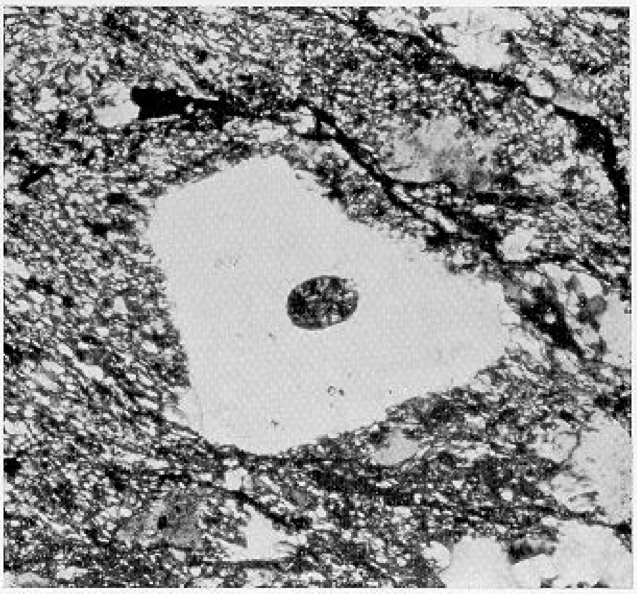

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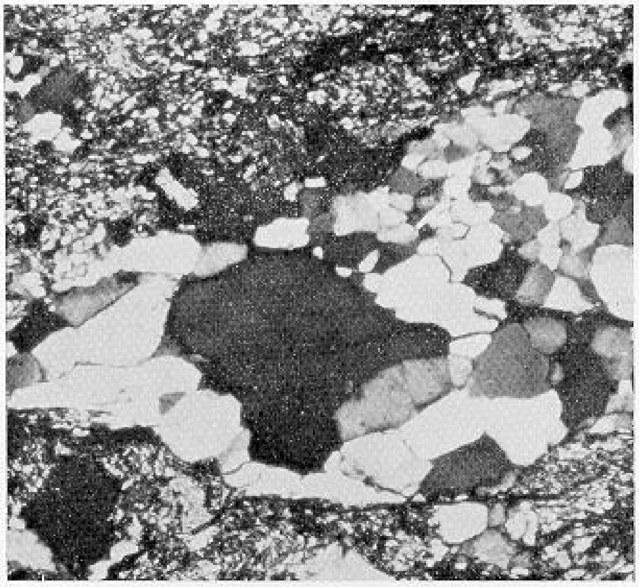

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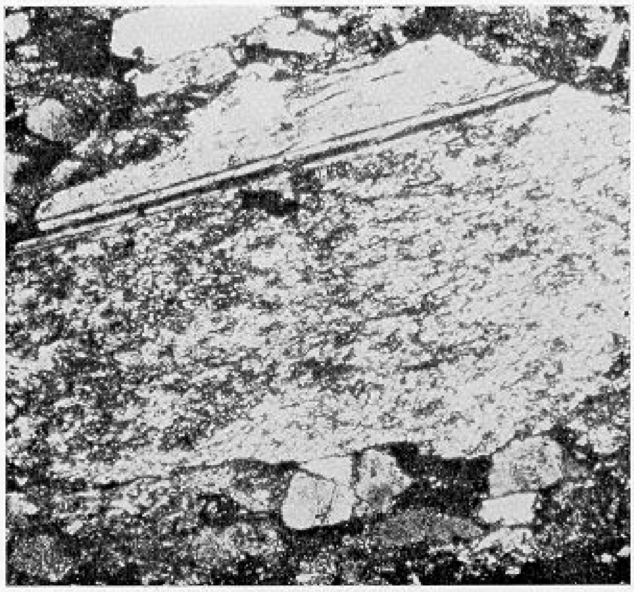


f

PLATE VIII

a. A rounded detrital grain of microcline-granite. Sandebugten Formation. (M.434.2; X-nicols; ×75)

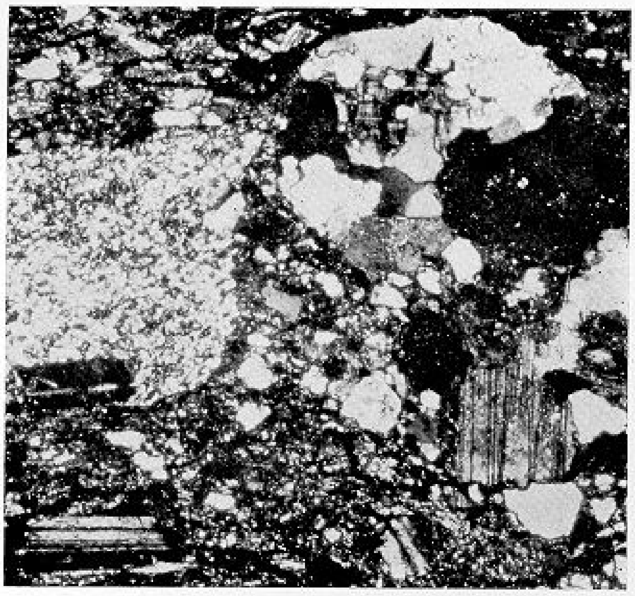
b. Rosettes of post-tectonic secondary biotite. Sandebugten Formation. (M.343.1; ordinary light; ×100)

c. Detrital felsite containing phenocrysts of quartz and feldspar. Cumberland Bay Formation. (M.659.1; X-nicols; ×65)

d. A typical grain of trachytic lava. Cumberland Bay Formation. (M.602.1; ordinary light; ×65)

e. A detrital grain of ophitic dolerite. Cumberland Bay Formation. (M.633.3; X-nicols; ×75)

f. Devitrified glass shards. Cumberland Bay Formation. (M.390.1; ordinary light; ×300)



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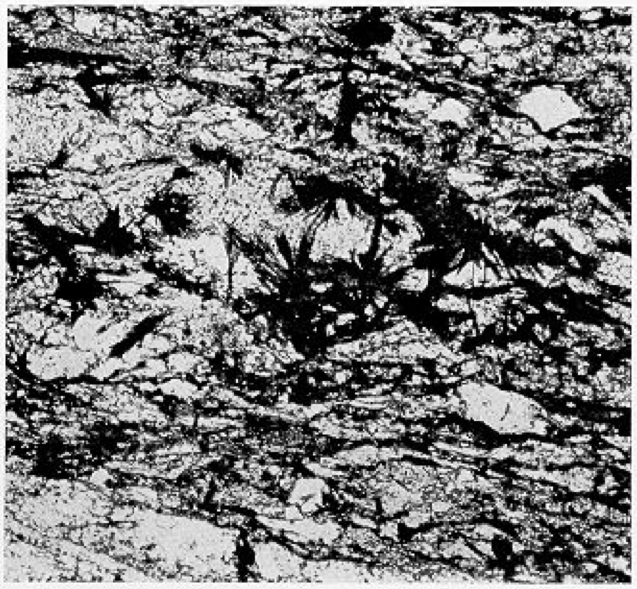

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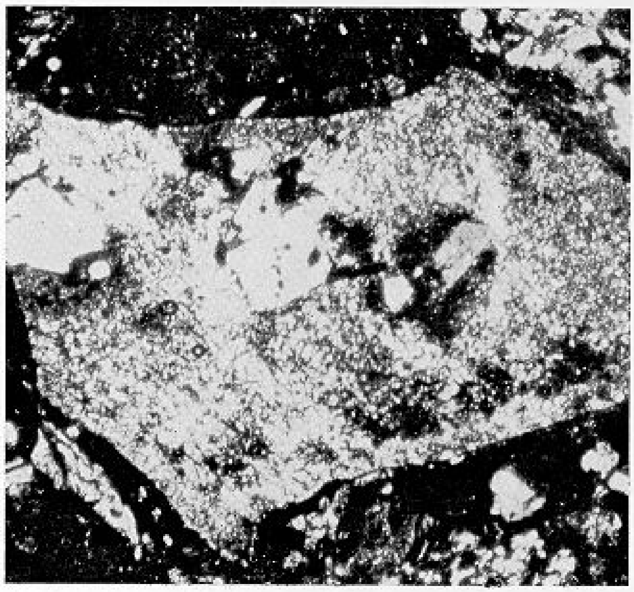

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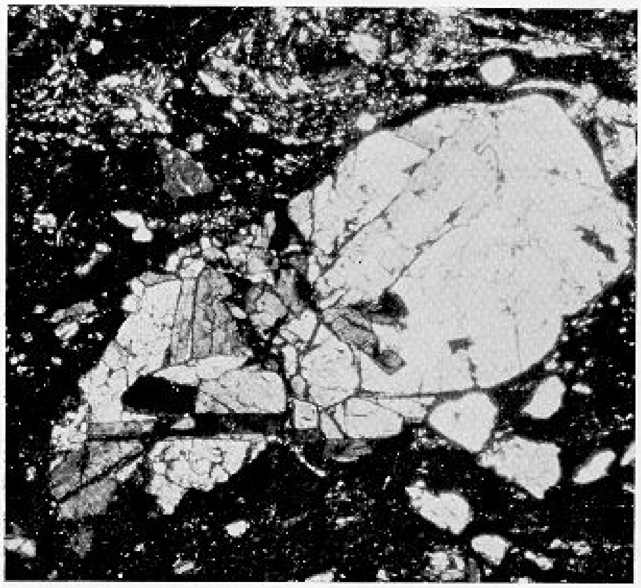

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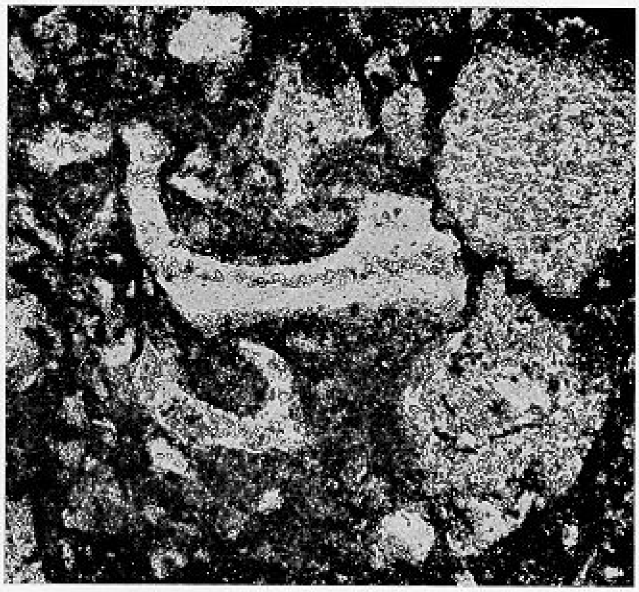

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