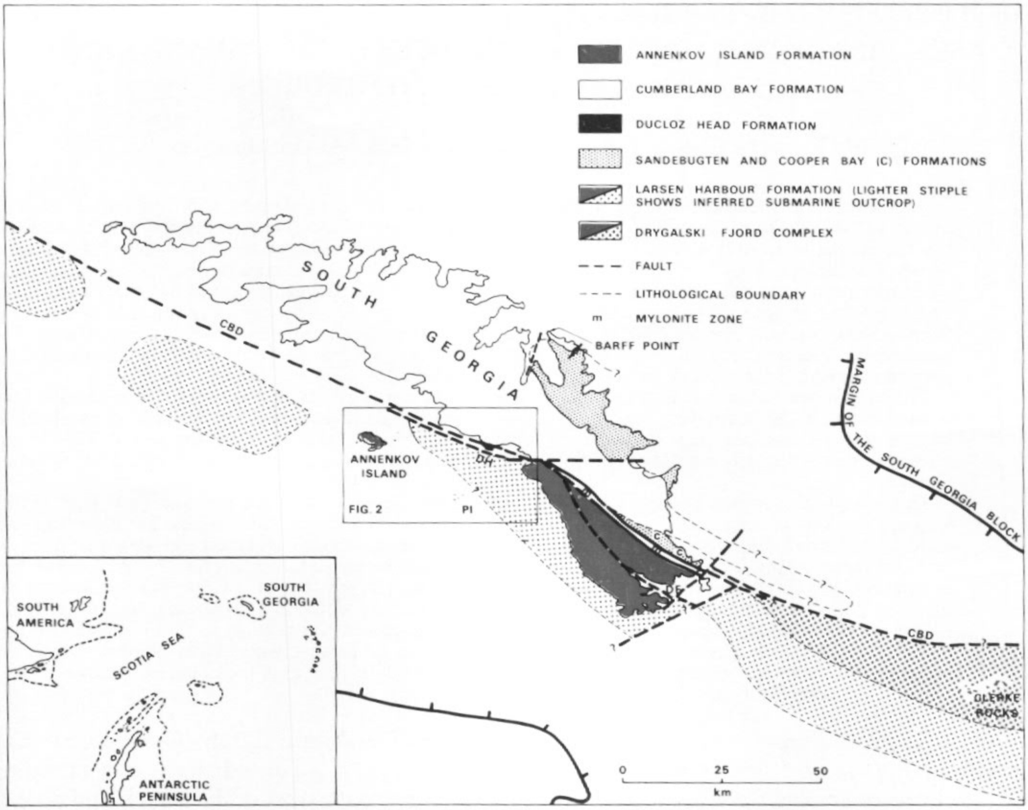


Fig. 1. Geological map of South Georgia. The submarine extensions of the outcrops of the Larsen Habour Formation and Drygalski Fjord Complex are modified from Simpson and Griffiths (in press). CBD, Cooper Bay dislocation; DF, Drygalski Fjord; DH, Ducloz Head; PI, Pickersgill Islands.

geological relationships in these areas have had to be described by reference only to sketch location maps and sections (Figs 2 and 3).

Field Relationships and Petrography

Low Reef

Low Reef is an east-north-east-trending line of low wave-washed islets and rocks which extend from the south-east end of Annenkov Island (Figs 2 and 4). All of the larger islands and rocks were visited.

Thick-bedded or non-stratified conglomerates and breccias (Fig. 5) crop out on all of the islets; graded bedding is uncommon (Fig. 6). These rocks are composed almost entirely of matrix-supported pebbles and cobbles (up to 1.2 m across) of grey andesite of differing texture; tuff fragments are rare. Sandstone beds, some showing graded bedding, locally define the stratification and a few bedding planes can be traced for up to 10 m. The beds dip consistently at 10–15° to the west. Channelling was seen at the base of a +20 m thick breccia unit but neither cross stratification nor imbrication was noted in any of the beds. A major fault trending east–west passes through the groups of small islands closest to Annenkov Island; it has a steep (*c.* 80°) dip to the north and is marked by a 7 m wide zone of crushed rocks. This fault is parallel to the high-angle reverse fault farther north (Pettigrew, 1981) (Fig. 2).

In thin section, the andesite clasts in the breccia consist of euhedral to sub-rounded hornblende, augite and plagioclase phenocrysts (all 1–2 cm across) set in a fine-grained matrix.

GEOLOGY OF AN UPPER JURASSIC–LOWER CRETACEOUS ISLAND-ARC ASSEMBLAGE IN HAUGE REEF, THE PICKERSGILL ISLANDS AND ADJOINING AREAS OF SOUTH GEORGIA

By P. W. G. TANNER, B. C. STOREY *and* D. I. M. MACDONALD

ABSTRACT. Field relations and petrography of a sequence of gently dipping sediments cut by igneous intrusions are described from Hauge Reef and the Pickersgill Islands. The sediments, which are finely banded crystal-lithic tuffs and mudstones, are part of the ~3 km thick Lower Tuff Member (Annenkov Island Formation). They rest directly on pillowed and massive lavas (oceanic crust; Larsen Harbour Formation) exposed on the easternmost island of Hauge Reef. The sediments contain basic sills and are cut and hornfelsed by igneous stocks and plutons; modal analyses show that the latter range in composition from gabbro to diorite and andesite. Biotite, garnet and (?) cordierite are developed in the hornfelses. The sequence is undeformed and gently tilted (<30°), and overlain by the Upper Breccia Member of the Annenkov Island Formation, described here from Low Reef off Annenkov Island.

Turbidite-facies rocks of the Cumberland Bay Formation were studied between Cape Darnley and Austin Head, on the south-west coast of South Georgia. The rocks are folded by a single major syncline, have a poorly developed slaty cleavage and commonly contain prehnite with some pumpellyite. Modal analyses compare closely with those of the Cumberland Bay Formation on the north-east coast of South Georgia.

Stratigraphical correlations with other units on South Georgia are discussed and two main strato-tectonic divisions are recognized: a mudstone–tuff (? shelf) facies and a turbidite facies. The mudstone–tuff facies (Annenkov Island Formation) is underlain by the Larsen Harbour Formation and separated from the turbidite facies (Cumberland Bay and Sandebugten Formations, and equivalent units) by the Cooper Bay dislocation, and in part by a sliver of older continental crust (Drygalski Fjord Complex). No floor to the turbidite facies is seen and it has developed under an entirely different sedimentary regime from the mudstone–tuff facies. Comparison with the geology of the southern Andes suggests that a similar two-fold division of the Lower Cretaceous marginal basin may also be present there. Plate-tectonic models are presented for the main sedimentary and tectonic phases in the development of the island arc–marginal basin segment on South Georgia.

MUCH of South Georgia consists of a thick sequence of andesitic flysch (Cumberland Bay Formation; Fig. 1) of Lower Cretaceous age. Trendall (1959) suggested that these turbidite-facies rocks were derived from a volcanic archipelago to the south-west of the island, and Suárez and Pettigrew (1976) have recently interpreted the tuffs and volcanic breccias in this area (Annenkov Island; Fig. 1) as material deposited on the flank of an active Lower Cretaceous island arc. Pettigrew (1981) has divided the sequence on Annenkov Island into two parts, a Lower Tuff Member and an Upper Breccia Member, with a minimum total thickness of about 1.86 km. Recent palaeontological work (Thomson and others, in press) suggests that the time range represented by these two members is from (?) Neocomian to Aptian–Albian and radiometric dating has confirmed that the lower part of the Upper Breccia Member and its contemporaneous andesite sills and intrusions are of Upper Aptian (100–103 Ma) age (Tanner and Rex, 1979).

The small islands of Hauge Reef and the Pickersgill Islands (Fig. 2) provide the only rock exposures linking the island-arc assemblage of Annenkov Island and the turbidite-facies rocks of South Georgia. In this paper we present the first complete geological description of these two areas, and of the adjacent coastline of South Georgia. This work is based on field work carried out in two brief intensive periods in 1975–76 and 1976–77 using inflatable Gemini craft operating from RRS *John Biscoe*. Ha and HB Islands in Hauge Reef were previously visited by Pettigrew (1981), who gave a description of some of the rock types present. Trendall (1959) recorded a few observations from the adjacent coastline of South Georgia. During the present work, Low Reef was visited for the first time by geologists to complete the mapping of Annenkov Island, and a landing on Mislaid Rock to the west of the island (Fig. 2) confirmed that it consists of rocks belonging to the Upper Breccia Member.

The most detailed topographic map which has been published of Hauge Reef and the Pickersgill Island is at 1 : 100 000 and there are no air photographs of either area. As the short time available for ship-supported field mapping did not enable us to make large-scale maps,

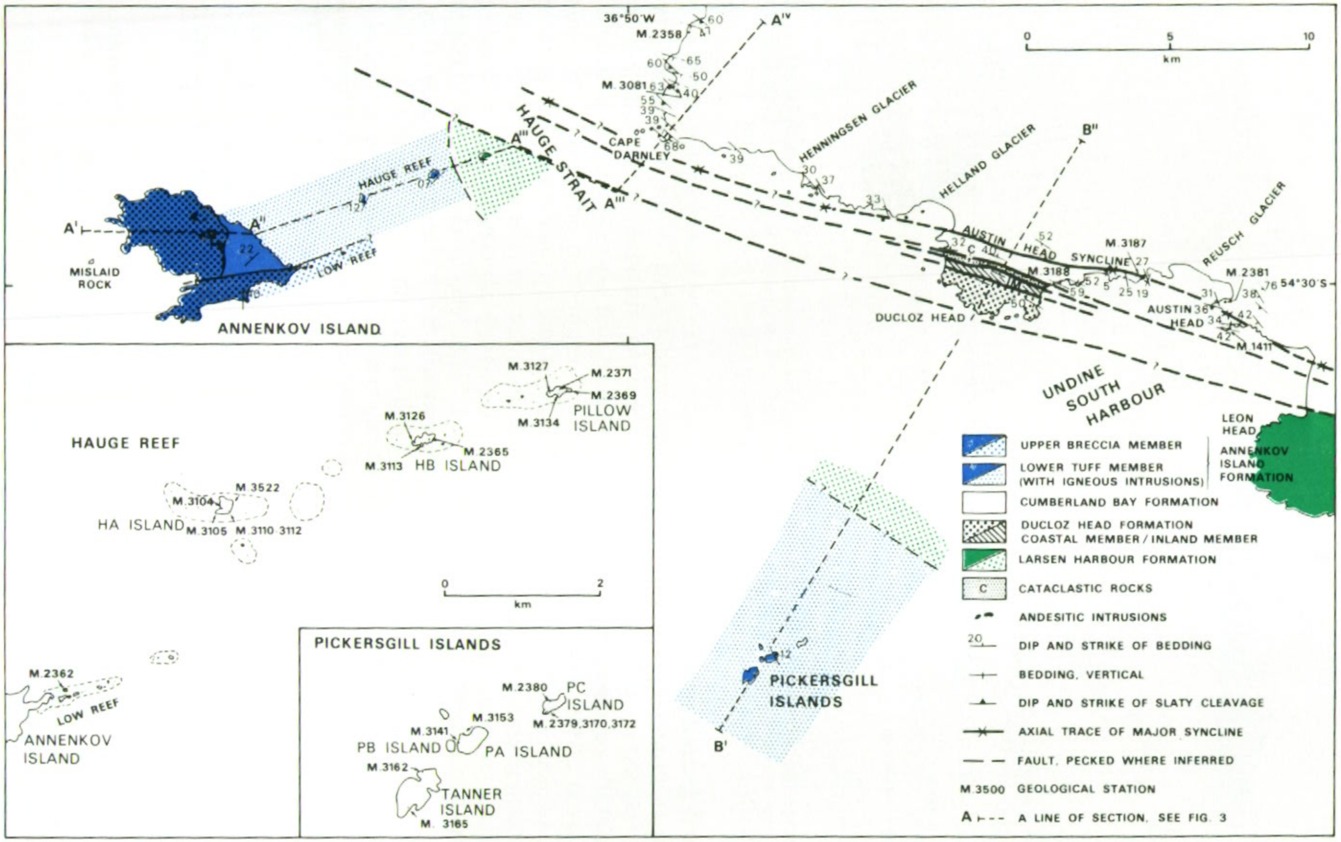


Fig. 2. Outline geology of Hauge Reef, the Pickersgill Islands and adjoining areas. The inset shows the location of geological stations, main islands, rocks and areas of broken water (pecked line) in Hauge Reef and the Pickersgill Islands. The maps are only approximate and are based on the 1 : 200 000 map of South Georgia. IM, Inland Member of the Ducloz Head Formation.

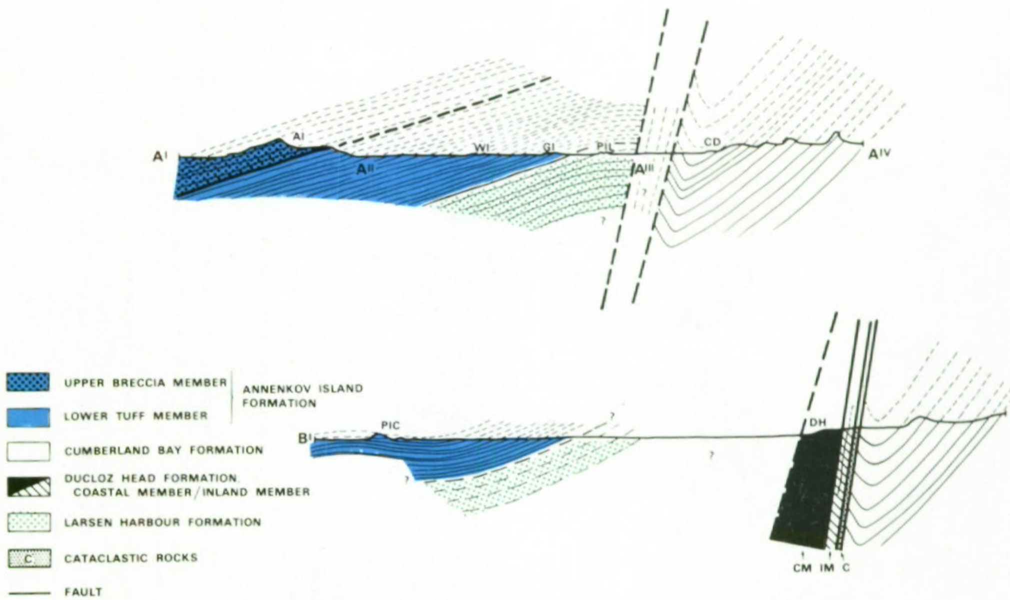


Fig. 3. True-scale cross-sections A^{I-IV} (Annenkov Island to Cape Darnley) and B^{I-II} (Pickersgill Islands to Ducloz Head). Igneous intrusions are omitted. For location see Fig. 2. AI, Annenkov Island; CD, Cape Darnley; DH, Ducloz Head; HA, HA Island; HB, HB Island; PIC, Pickersgill Islands; PIL, Pillow Island.

The hornblende is green-brown and is often rimmed with small opaque granules or has a narrow dark rim; areas of orange-brown lamprobolite occur within some of the hornblende crystals. Augite is colourless to very pale green. The andesine phenocrysts often have anorthite-rich cores and show oscillatory zoning. They are slightly sericitized and altered to carbonate, and have sodic rims. In some of the clasts the matrix cannot be resolved; in others it is microlitic and consists of minute plagioclase laths, granular (?) K-feldspar and opaque grains with some apatite needles. Large opaque crystals and patches of calcite are common. The sandstone beds and the matrix of the breccia units are very similar; they consist mainly of andesite clasts with subsidiary plagioclase crystal fragments and rare tuffaceous and felsitic clasts. The andesite clasts have a variable texture but are similar in mineralogy to the clasts in the thicker breccia beds. They have either a microcrystalline, pilotaxitic or felted matrix and clasts with a chloritic, once vitric, matrix are rare. The felsite clasts (to 2 mm) consist of an equigranular fine-grained mosaic of anhedral plagioclase and lower-relief (?) quartz or K-feldspar. The tuff fragments are dark brown and fine-grained with ragged outlines; they contain occasional andesitic clasts and small, broken sub-angular plagioclase crystals.

In one rock (M.2362.4), the interstices between some of the large angular clasts are filled with tabular intergrowths of zeolite crystals, probably heulandite. The mineral is biaxial positive, has moderate relief and low birefringence, and an optic axial plane which is at right-angles to the prominent cleavage.

Correlation and discussion. The breccias of Low Reef correspond in field appearance and petrography to the Upper Breccia Member of Annenkov Island as described by Pettigrew (1981). Confirmation that similar breccias crop out on Mislaid Rock west of Annenkov Island increases the probable minimum total thickness of the Upper Breccia Member (assuming a low average dip of 20°) to 1.2 km.

Pettigrew (1981) proposed large-scale slumping or submarine gravitational sliding as a mechanism for emplacement of the Annenkov Island breccias, whereas Winn and Dott (1978)

Fig. 4. Panorama of Hauge Reef from the easternmost island in Low Reef. The foreground shows *in-situ* cobbles and the unstratified nature of the Upper Breccia Member. Scale is given by the figure in the centre of the photograph.

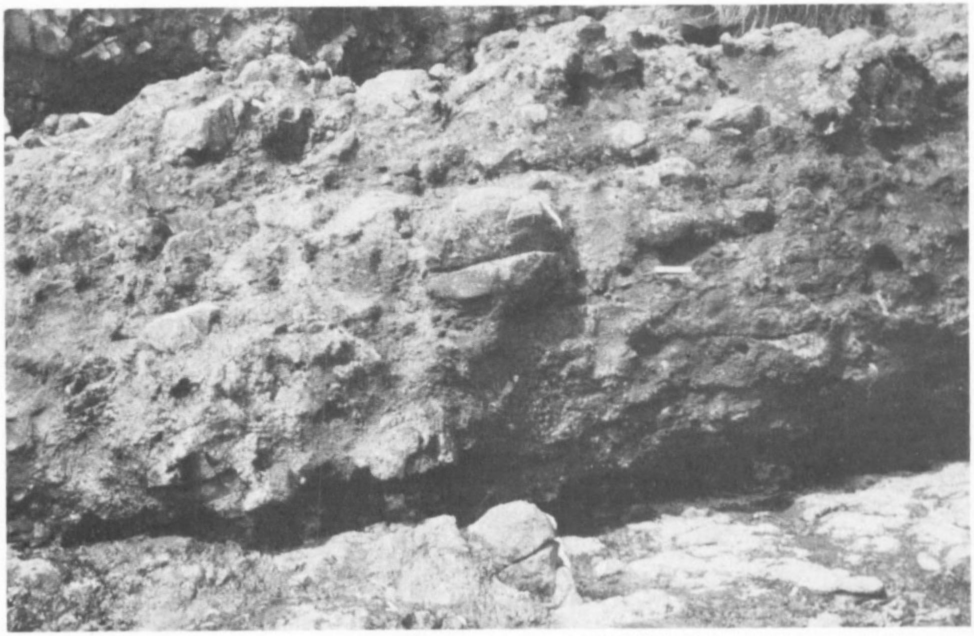


Fig. 5. Thick-bedded unsorted breccia in Low Reef near station M.2362 (Fig. 2, inset). The scale is 15 cm long.

inferred deposition from turbidity currents (possibly in inner fan channels) for closely similar beds in the upper part of the Yahgan Formation of Tierra del Fuego, Chile. From our limited observations on Low Reef, we conclude that proximal turbidite deposits and debris flow deposits (Walker, 1978, p. 943) are present.

Hauge Reef

Hauge Reef is a line of small islands and rocky shoals which trends north-north-east for 6 km between Annenkov Island and Hauge Strait (Fig. 2). All three main islands, which rise to about 30 m above sea-level, have been visited and almost all of their accessible coastlines have been mapped and sampled.

HA Island

The island consists of a gently dipping (<15°) sequence of tuffaceous sediments cut by andesite intrusions. The sediments and the basic sills which they contain are cut by a stock of hornblende-andesite and a sill-like sheet of finer-grained biotite-andesite. Enclaves of partially assimilated basic rock up to several metres across occur within the hornblende-andesite.

Sediments. Sediments are exposed on the west side of the island where they are intruded by a basic sill. On the east side of the island at station M.3110, a raft of gently dipping (8–12°) sedimentary rocks some tens of metres long and several metres thick occurs within the biotite-andesite. The raft contains a 2 m thick slightly transgressive sill which thins northward; a kink band several metres in wave-length and with a hinge plunging at 4° in a direction 351° locally folds the sediments and is the only fold seen in Hauge Reef or the Pickersgill Islands. A small outcrop of conglomerate with pebbles up to 2 cm occurs at the base of the outcrop. Part of a small heteromorph ammonite of Lower Cretaceous age collected from the tuffaceous rocks at this locality has been described by Thomson and others (in press; locality I).

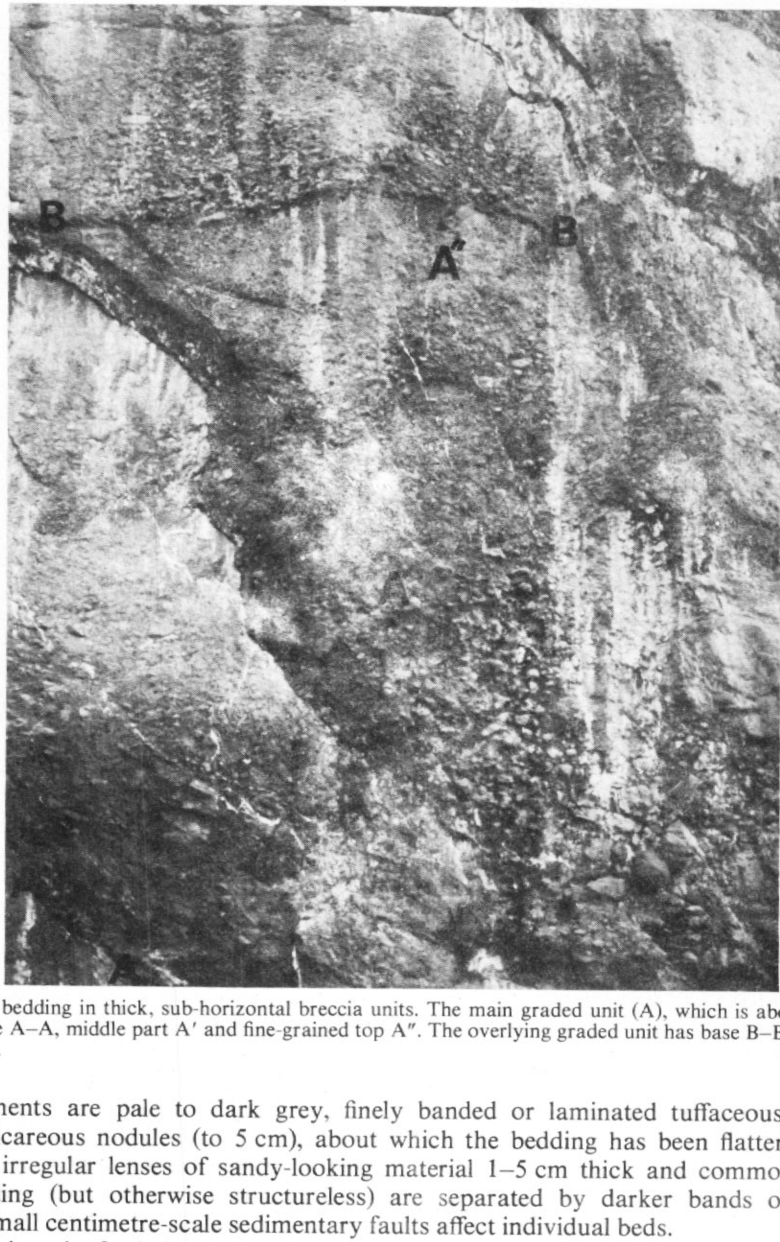


Fig. 6. Graded bedding in thick, sub-horizontal breccia units. The main graded unit (A), which is about 10 m thick, has base A–A, middle part A′ and fine-grained top A″. The overlying graded unit has base B–B (M.2362; Fig. 2, inset).

The sediments are pale to dark grey, finely banded or laminated tuffaceous rocks with scattered calcareous nodules (to 5 cm), about which the bedding has been flattened (Fig. 7). Streaks and irregular lenses of sandy-looking material 1–5 cm thick and commonly showing graded bedding (but otherwise structureless) are separated by darker bands of tuffaceous mudstone. Small centimetre-scale sedimentary faults affect individual beds.

In thin section, the finely banded rocks are seen to consist of layers of crystal-tuff with graded bedding, separated by dark mudstone or by layers of fine-grained material with disturbed banding. The tuffs contain crystal fragments, altered andesitic glass and silicic volcanic fragments. Fragments and wisps of dark tuff, or of tuff of different composition to the host, are found in all of these units. The crystal fragments are mainly plagioclase grains (An_{38-53}) (to 0.6 mm), most of which are broken or worn (angular to sub-rounded). Plagioclase is brown or grey and turbid in thin section with some development of sericitic flakes, and oscillatory zoning is preserved in a few crystals. Some quartz grains have retained original planar crystal faces. Rare,

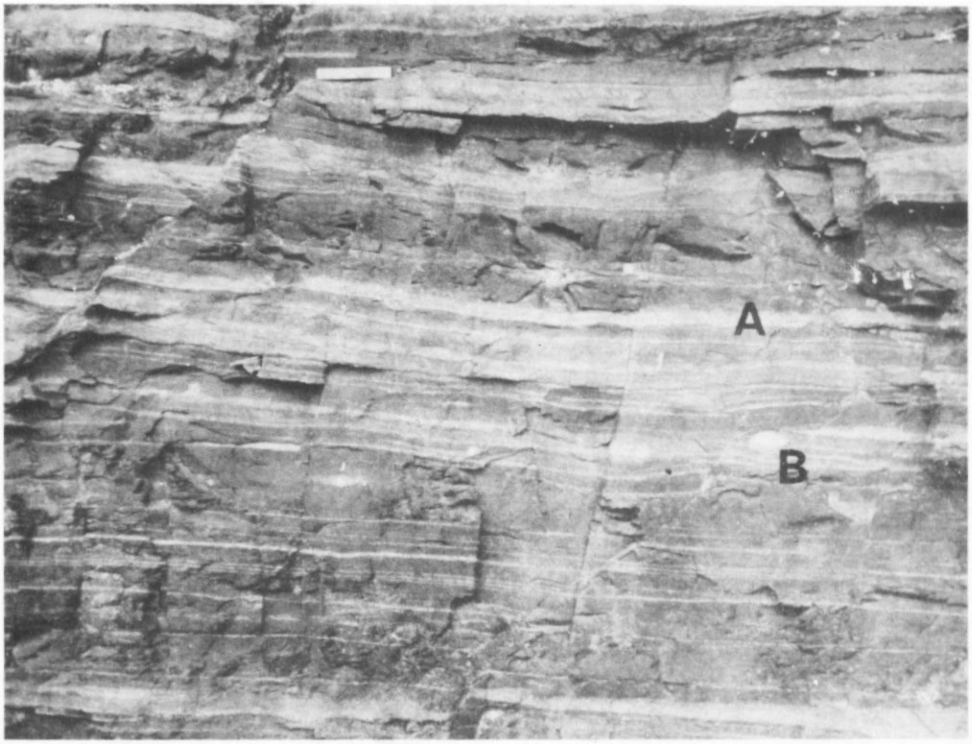


Fig. 7. Thin-bedded tuffaceous rocks on HA Island (M.3104; Fig. 2, inset). A, graded crystal-tuff showing penecontemporaneous faulting; B, calcareous concretion. The scale is 15 cm long.

perfectly rounded quartz grains have some matrix adhering to them, indicating that they are of igneous origin and were derived from partially resorbed phenocrysts. Rock fragments are common in some bands and include numerous clasts now consisting of chlorite (altered glass) with plagioclase microlites, occasional large plagioclase phenocrysts or relict sericite-filled amygdales. It is difficult to distinguish between the chlorite-rich clasts and matrix chlorite. Also present are clasts of interlocking plagioclase laths with a conspicuous dusting of opaque material and sericite–chlorite patches and amygdalar opaque-rich chlorite intergrowths. Rare dacitic clasts consist of (?) graphic quartz–plagioclase intergrowths, or plagioclase laths in a quartz matrix.

Pellet-like bodies are found in the finer-grained tuffs; they appear darker than the enclosing matrix under crossed nicols due to their higher chlorite content, although in texture and mineralogy they are otherwise identical to it. The pellets occur as large elliptical bodies (1.5 mm by 0.5 mm) or as groups of smaller, more rounded individuals (0.5 mm by 0.3 mm) (Fig. 8a). The smaller pellets are also preserved in the calcareous lenses.

Biotite is an important constituent of some of the bands and it occurs as thin plates up to 0.25 mm long. Fine sericite laths (<0.01 mm) are found in the groundmass in one specimen. Ilmenite–sphene clumps are arranged around the crystal and rock fragments, and chlorite and apatite are common in the matrix. In one specimen (M.3112.C), cuspate contorted wisps of chlorite found between clasts in the upper part of a graded crystal-tuff are probably altered glass shards.

The sandy-weathering bands and lenses consist of a granular aggregate of rock fragments (to 0.7 mm) and scattered plagioclase crystals of about the same size. The fragments are of

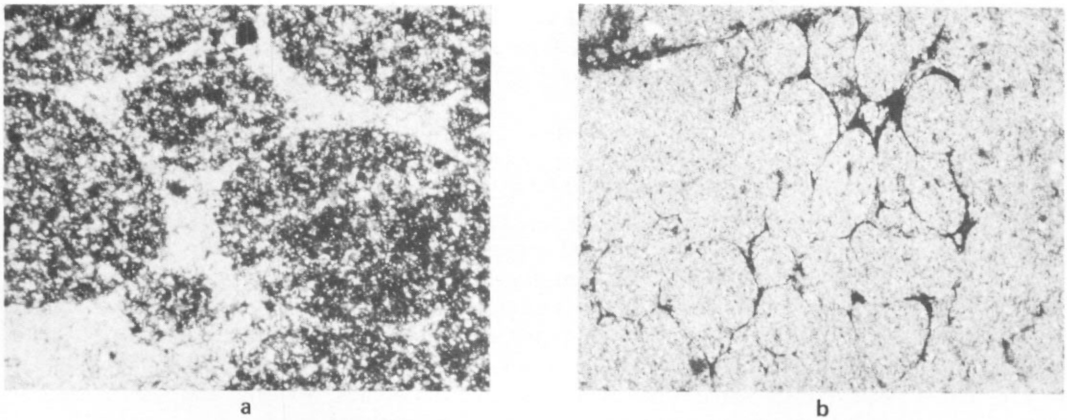


Fig. 8. a. Pellet-like bodies in fine-grained tuff from HA Island. The dark mineral is chlorite (M.3101; Fig. 2, inset) (X-nicols, ×106).

b. Pellet structure in fine-grained tuff outlined by opaque material in the interstices between the pellets; Pillow Island (M.2369.4A; Fig. 2, inset) (plane polarized light, ×28).

sericitized felsite (laths up to 0.3 mm) and andesite clasts with aligned microlitic (pilotaxitic) or non-orientated (felty) texture and interstitial chlorite (? altered glass). One band contains ragged fragments of sericite-rich material enclosing sericite–chlorite-filled (?) amygdales; they appear to have been derived from the alteration of vesicular acid glass.

Mudstone bands have a brown cloudy matrix which cannot be resolved under high power and does not show growth of sericite. They contain small pellets of pale to dark brown tuff (to 0.5 mm) and occasional fragments of dark brown turbid material (? altered glass). Euhedral, possibly authigenic, pyrite crystals are common. The calcareous lenses are largely of a carbonate mosaic with some crystal fragments and opaque granules. Radiolaria in the mudstone bands are replaced by a granular quartz–plagioclase mosaic with undulatory extinction of the minute grains (0.005 mm). In the calcareous lenses, Radiolaria are completely replaced and filled by calcite. Sphene occurs as small clusters of brownish granules scattered throughout all rock types; it appears to have developed from ilmenite granules and laths. Opaque grains are likewise common and calcite occurs as discrete grains, both as irregular patches which have locally replaced both clastic grains and matrix, and in veinlets.

The sedimentary rocks in the main outcrop are entirely undeformed and no pressure solution between grains is visible at ×600. In the "raft", however, the mudstone bands show two schistose fabrics at 90°. They are defined by sericite flakes (0.05–0.1 mm) intergrown with chlorite. Opaque granules and tuff fragments are preserved within the recrystallized matrix and pressure-solution effects are seen around these clastic grains. The crystal-tuffs contain quartz clasts which have been fractured and bent *after* the bed was deposited and are now filled with chlorite, and pressure-solution effects are seen in the matrix. It is inferred that penetrative deformation of the tuff–mudstone sequence, alteration of the plagioclase, metamorphism and possibly the formation of the two schistosities in the mudstone took place as a result of emplacement of the biotite-andesite intrusion and are contact effects. In lithology and petrography these sediments are closely similar to the unaltered and undeformed sediments found on the east side of the island.

The "conglomerate" band at the base of the rafted sequence consists of a variety of igneous and intraformational clasts. The igneous clasts are of biotite-andesite; the sedimentary clasts are of crystal-tuff and mudstone, some of which have a schistose sericite-rich matrix. These rock types can be matched with those of the adjacent andesite intrusion and its sedimentary xenolith. However, the fabrics in the sericite-rich clasts are not arranged parallel to one another and the rock cannot have formed by metamorphism of a pre-existing conglomerate. In the absence of field data relating this rock to other members of the sedimentary xenolith, it is concluded that it is a fault breccia and is not part of the sedimentary sequence.

Metabasic sills. Slightly discordant basic sheets, up to 5 m thick, occur within the tuffaceous rocks. They transgress the bedding at an angle of 10–20° and a thick basic sheet exposed on the promontory to the west side of the island (M.3105) has a markedly pillowed base. Sediments occurring beneath the sheet have been locally injected into the basic rock, especially between the lobes on the base, and have a cherty indurated appearance.

The metabasic sills are coarse-grained and consist of ophitic augite crystals (to 3 mm) in a matrix of albite laths (to 0.7 mm) with patches of chlorite and calcite. Sphene is common. Augite is pale brown in thin section; it is fresh in one specimen but completely altered to brownish green chlorite in another. Chlorite shows radial fibrous or spherulitic forms (? after olivine) and occurs in irregular masses and as narrow bands around calcite patches. Some of the matrix chlorite probably formed by alteration of pyroxene granules or intersertal glass.

Large blocks of basic rock occur as xenoliths within the hornblende-andesite. They are similar in thin section to that forming the sills described above and contain augite (to 5 mm) in ophitic intergrowth with subhedral albite crystals. However, the plagioclase is clouded and sericitized (as in the contact-metamorphosed crystal-tuffs) and two generations of chlorite are seen: bluish green chlorite (grey-blue polarization colour) occurring as radial growths replacing dull green chlorite which appears dark under crossed nicols. Skeletal ilmenite, accessory apatite and small patches of radiating prehnite crystals are also present. Small laths of pale straw to brown biotite occur within the chlorite.

Biotite-andesite. A large area of this rock type (the quartz-microdiorite of Pettigrew (1981) is found on the south and south-west side of the island. Contacts with other rock types are poorly exposed but the intrusion appears to have a tabular shape. It encloses the large raft of finely banded sediments described above and the andesite cuts across the bedding where it is exposed along the upper margin of the xenolith. A faint banding within the base of the intrusion is due to a local concentration of ferromagnesian crystals (M.3522.1C). The age relationship between this andesite and the hornblende-andesite described below is not known with certainty. They are in steep faulted contact on the wave-cut platform on the east side of the island, but in a small erosional window to the south of this point the base of the biotite-andesite is seen to cut at about 10° across the bedding in sedimentary rocks which lie with apparent conformity above a rock identical to the hornblende-andesite. The base of the biotite-andesite also cuts across the contact between the other two rock types, suggesting that it was intruded as a sill after emplacement of the hornblende-andesite.

The biotite-andesite has a uniform petrography across the whole outcrop with scattered plagioclase and biotite phenocrysts set in a fine-grained matrix. The subhedral andesine (An_{34}) phenocrysts (to 1.2 mm) are cloudy and slightly sericitized. Biotite occurs as very thin pseudohexagonal plates (*c.* 0.04 mm), which are often buckled and partly or entirely altered to chlorite, (?) epidote and sphene. Hornblende is also possibly present but it has been completely altered to chlorite with opaque grains.

The intergranular groundmass is shown by staining to consist of minute dusty plagioclase crystals (<0.1 mm) and K-feldspar with chlorite, sericite, altered biotite, < 5% quartz, sphene, euhedral apatite and irregular opaque granules up to 3 mm.

Hornblende-andesite. The intrusion has a steeply dipping chilled contact against the sedimentary rocks in the west of the island and cuts the bedding at a high angle. It consists of tabular, locally pink-coloured, plagioclase crystals (to 4 mm) set in a fine- to medium-grained grey groundmass. The andesite encloses rafts and large xenolithic bodies of finely banded hornfelsed sediments (with calcareous nodules) and of basic rock with tongues of injected sediment. Both types of xenolith are occasionally intruded by veinlets of pale andesite. Small sub-rounded xenoliths of basic rock are common.

In thin section the andesite consists of euhedral to subhedral andesine (An_{46}) phenocrysts together with partially altered laths of hornblende set in a fine-grained (0.1 mm) matrix shown by staining to consist of roughly equal proportions of K-feldspar and plagioclase. The phenocrysts, some of which are cracked, are generally sericitized with narrow clear (? sodic) rims but with oscillatory zoning preserved in the less altered crystals. Small patches of secondary quartz occur within the altered phenocrysts. Hornblende (α = light brown to green brown, $\beta = \gamma$ = brownish green or green) occurs as crystals up to 1 mm across and is heavily altered in most thin sections to chlorite, sericite, opaques and sphene. The groundmass is mainly sericitized plagioclase crystals (<0.1 mm) with rare quartz grains, granules of allanite–epidote, an abundant opaque mineral, apatite and some zircon; irregular patches of calcite occur throughout. In specimen M.3522.8, quartz occurs as large (0.8 mm) crystals, one of which has been partially resorbed and is perfectly rounded. Biotite, generally altered to chlorite and sericite, also occurs in this specimen as rare laths crowded with colourless to pale green lenses of pumpellyite. Clear patches of (?) zeolite (uniaxial negative) up to 0.6 mm across and rimmed with small euhedral apatite crystals are a distinctive feature of the rock.

HB Island

This island consists of volcaniclastic sediments which dip gently to the north and are cut by numerous plug-like bodies of biotite- and hornblende-andesite.

Sediments. Dark grey finely banded or laminated tuffaceous mudstones and sandstones occur as a number of isolated rafts or outcrops between plutons. They contain pale, highly irregular bands of crystal-tuff 1–5 cm thick and occasional calcareous lenses. The sedimentary rocks are tough and generally have an indurated hornfelsed appearance and a purplish brown colour due to the presence of numerous, minute, decussate biotite flakes. Their strike is somewhat variable, possibly due to the effect of the igneous intrusions, but the dip is low (<31°).

In thin section the crystal-tuff consists mainly of blocky sub-rounded crystals of labradorite (An_{54}) (to 1.5 mm), which are zoned and faintly clouded with sericite. Quartz crystals (<5%) are scattered throughout; they reach 0.8 mm across and some have preserved pyramidal faces. Rock fragments are mainly microlitic feldspar clasts (andesitic) with a few chloritic (? devitrified) clasts containing sphene and opaque minerals. Opaque minerals are locally abundant and are partly altered to sphene, and the matrix has been largely recrystallized to a mosaic of minute biotite flakes.

In thin section, the mudstone has a spotted or mottled appearance, which is usually due to small clusters of biotite flakes and groups of sphene granules (0.05 mm across) set in a matrix containing minute (?) biotite and sericite flakes, colourless chlorite and much fine dark material, probably sphene and leucoxene. In others, clear spots up to 0.1 mm across, consisting of a fine mosaic of an unidentified low-birefringent mineral, are set in an orange-brown (? biotite-rich) matrix. Minute (0.05 mm) crystals of grey-green hornblende are found in the matrix of several rocks and sometimes occur with biotite as composite grains. Some thin sections show crystals of plagioclase up to 0.2 mm scattered in the mudstone and in one 0.02 mm irregular quartz crystals are found, though quartz is generally rare.

Calcareous lenses consist of thin discontinuous bands of diopside–calcite–chlorite rock with acicular actinolite set in a largely calcite-rich matrix. The diopside, which is colourless and biaxial positive, has been largely altered to indeterminate cloudy material and is accompanied by clinozoisite.

Some of the bands have a finely laminated appearance and in thin section are seen to have a cataclastic fabric with narrow folia of chlorite, quartz and opaque material around feldspar phenocrysts.

Andesites. Intrusions of grey andesite, locally with plagioclase and/or hornblende phenocrysts, have steeply dipping, clearly defined contacts with the sediments. The smaller bodies appear almost pipe-like in cliff sections. Chilled contacts against the sediments were not noted and brecciated rock is found locally at the contact. The andesite varies from hornblende-bearing, with rare biotite, in the south-west and centre of the island to biotite-hornblende-andesite in the north. Different facies were noted within the andesite bodies, some with chilled contacts. Pyrite is common. Angular xenoliths of baked sediment, sometimes veined by andesite and at one locality showing a new growth of feldspar porphyroblasts, occur in the andesites. Sub-rounded blocks of basic rock and one 20 cm boulder of granodiorite were also noted. Only one dyke was found, a pale grey andesite trending 120°, on the eastern promontory of the island.

At station M.2365, at the north-eastern end of the island, the andesite contains plagioclase, hornblende and biotite phenocrysts set in a groundmass of interlocking plagioclase laths and rare to uncommon quartz. The plagioclase phenocrysts are either euhedral or compound crystals (to 3 mm) with oscillatory zoning: andesine cores and oligoclase/andesine rims. Electron microprobe analysis of two zoned plagioclase phenocrysts from specimen M.2365.C gave core to rim variations of An_{29-35} and An_{36-45}. The plagioclase is fresh but it is replaced locally by patches of epidote (up to 1 mm across) and is shown by staining to contain veins and patches of K-feldspar. Biotite laths, up to 1 mm and pleochroic from colourless to foxy red-brown, are slightly altered to chlorite along the cleavage. Hornblende prisms (α = pale green brown, $\beta = \gamma$ = green brown) are common in some rocks, generally partly or completely replaced by aggregates of biotite, calcite, actinolite, chlorite and sphene. Stained thin sections show that the matrix (to 0.05 mm) consists of approximately equal amounts of sericitized plagioclase and K-feldspar which form an interlocking mosaic. Quartz occurs either as rare (0.2 mm) crystals or in one specimen (M.2365.1A) in patches of mosaic up to 1.2 mm across. Accessory minerals include apatite, zircon, sphene, zoned pale brown allanite, prehnite lenses in biotite and opaques.

Farther south, around station M.3113, the intrusion is hornblende-andesite with biotite being rare or absent. Quartz is also rare or absent but other features of the petrography are identical. Some of the hornblende is partly altered to actinolite and (?) prehnite occurs in veinlets in one rock.

Xenoliths of basic rock consist largely of actinolite prisms with some biotite, plagioclase and chlorite. The enclave of granodiorite is a coarse-grained (3–6 mm) aggregate of quartz, andesine (An_{32}), microperthite and red-brown biotite with apatite and opaques. A xenolithic rock from station M.3126 is of interest in that it contains fragments of pillow lava with spherulitic plagioclase, which can be petrographically matched with the lavas of Pillow Island described below.

Pillow Island

Pillow Island consists almost entirely of gently dipping (<15°) to almost horizontal, pillowed and massive amygdaloidal or columnar-jointed basic lavas with rare thin bands of ashy sediment, usually less than 1 m thick. Gradational relationships exist between most types of basic lava.

Sediments. The sediments between the lava flows are finely banded (0.1–3.0 cm) or laminated grey-brown tuffs with occasional calc-silicate lenses. Rounded fragments and cobbles of amygdaloidal lava up to 5 cm across are found within the sediments beneath individual units of pillow lava.

The sediments are seen in thin section to be coarse tuffs and consist of closely packed, round to elliptical pellets (0.3–0.5 mm across) which occasionally show slight differences in colour and texture between adjacent grains. They are clearly displayed where the narrow interstices between the pellets have been locally filled with an opaque mineral (Fig. 8b). Sediments from different places on the island contain ash pellets of the same size and with the same close packing but the significance of the pellet structure is not understood. Also present are larger, ragged, intraformational tuff fragments, which show a distinct contrast in grain-size and colour with the matrix. The coarser rocks are gradational to mudstone and consist of scattered plagioclase phenocrysts, lithic fragments, chlorite aggregates, (?) altered Radiolaria, calcite grains and numerous spores together with minute opaque crystals and sericite flakes set in a pale brown irresolvable matrix.

The plagioclase crystals (to 0.1 mm) generally have an uneven mottled extinction and are partly altered to calcite or sericite. Quartz is rare and only identified in one specimen; a chert fragment was also noted. Lithic fragments are mainly altered vitric clasts (now chlorite) with numerous chlorite-filled amygdales (to 0.1 mm) and some plagioclase phenocrysts or microlites. These clasts have cuspate projections around the perimeter where amygdales have been broken away, and the amygdales are filled with zoned radial fibres of bluish green chlorite, the infilling usually having a central longitudinal suture. This distinctive pattern enables the amygdales to be recognized where they commonly occur as isolated chlorite spherules in the mudstone matrix, and distinguished from altered Radiolaria of about the same size. The latter are generally replaced by clusters of minute round opaque grains. Spores and fragments of cuticle are common and well preserved. Rounded ornamented bodies of pale brown cuticle up to 40–50 μm across appear to be angiosperm spores (Fig. 9); more numerous, smaller round or elliptical bodies (10–20 μm) with no recognizable pattern are probably fungal spores (personal communication from T. H. Jefferson). Glass shards with a diagnostic curved or tricuspate shape are rare and most of the devitrified glass fragments, now chlorite, are derived from the amygdaloidal vitric lava.

A few, centimetre-thick lithic tuff bands occur within the mudstone and finely laminated sediments. They are graded, with a sharply defined irregular base, and consist mainly of devitrified lava fragments containing plagioclase microlites together with plagioclase crystals (0.1–0.2 mm), rare quartz, opaque grains and much carbonate alteration.

Deformation is revealed by pressure-solution effects around grains in restricted areas in a few of the thin sections, particularly adjacent to the margins of crystal-tuff bands. Several stylolitic sutures occur in mudstone within the area of each thin section.

Lavas. Three main lava types are found: pillow lava, massive amygdaloidal lava and massive columnar-jointed, generally non-amygdalar, lava. The pillow lavas (Fig. 10) generally contain pillows 0.1–1 m across but tubiform and sac-form "pillows" are also found (Fig. 11). Some flows (possibly sills) display columnar jointing with columns over 10 m long (Fig. 12); they also pass laterally to massive amygdaloidal lava. Massive vesicular lavas occur as discrete units and have

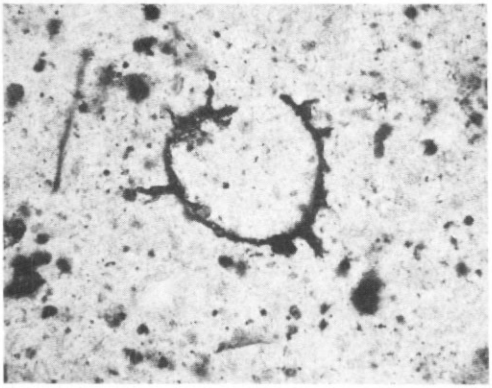


Fig. 9. Angiosperm spore in tuffaceous mudstone occurring between bedded pillow lavas on Pillow Island (M.3107; Fig. 2, inset) (plane polarized light, ×290).

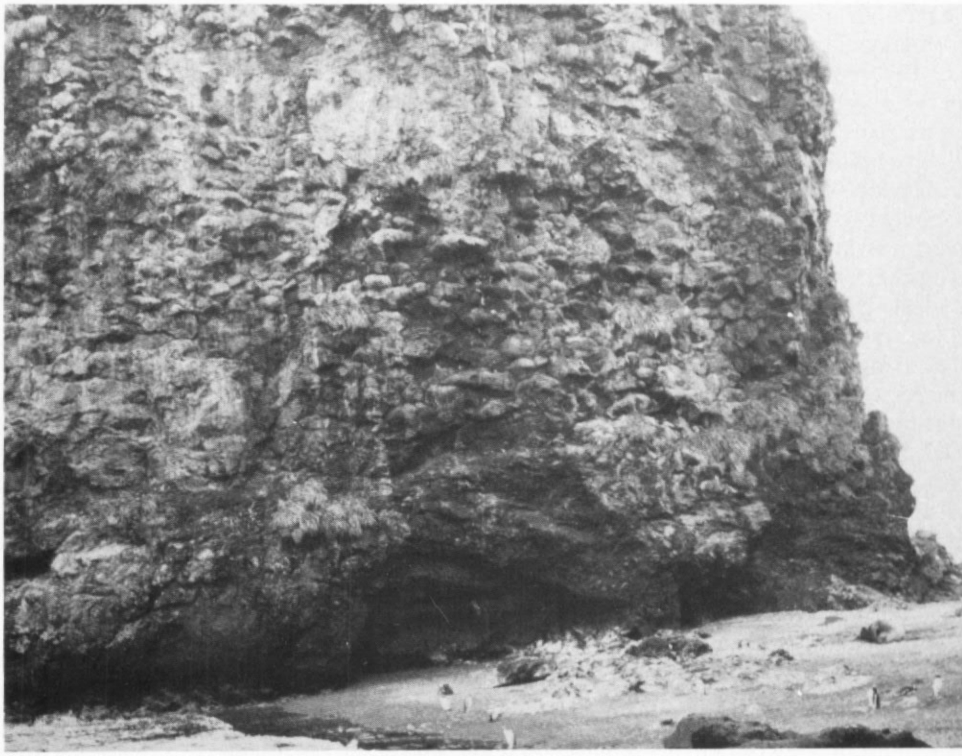


Fig. 10. Thick sequence of pillowed lava overlying and gradational into massive amygdaloidal lava; Pillow Island, looking north-east from station M.3127 (Fig. 2, inset). The gentoo penguins in the foreground are 0.75 m high.

an internal banding marked by carious weathering or by variation in the abundance of vesicles. Dykes are rare.

A detailed section was measured at station M.3134 (Fig. 2, inset). At the base of the section a 2.2 m thick amygdaloidal flow, with amygdales arranged in rows and with narrow zones of carious weathering defining the stratification, rests on sediment with contorted internal banding. The flow dies out abruptly within the sediments as it is traced southward and is overlain by <1 m of dark tuffaceous shales with isolated pillows. The section continues with 6 m of pillow lava, which passes upward without apparent break into a unit of columnar-jointed basalt over 8 m thick. The unit can be traced laterally for 70 m; within this distance, massive amygdaloidal basalt develops at the base and pillow development becomes restricted to the middle of the unit. At the north end of the section, a vertical dyke of amygdaloidal basalt merges into the base of the unit, cutting the underlying dark shales; it appears to have acted as a feeder for the pillowed and columnar unit.

At station M.2369, a 4 m thick unit of gently dipping, laminated sediments is separated from an overlying massive vesicular unit (4 m) by a zone containing cobbles of lava, disorientated rafts of sediment and rock fragments. The vesicular lava has an irregular base and passes upward into a pillowed sequence. As in the previous section, a basic dyke cuts the sedimentary unit at the base and possibly acted as a feeder for the lava flow (Fig. 13).

All of these lava types are petrographically similar and have a doleritic texture. They consist of interlocking plagioclase laths (to 1 mm), chlorite, calcite, abundant opaque material and sphene–leucoxene aggregates with relict pyroxene and rare quartz in some rocks. Amygdales

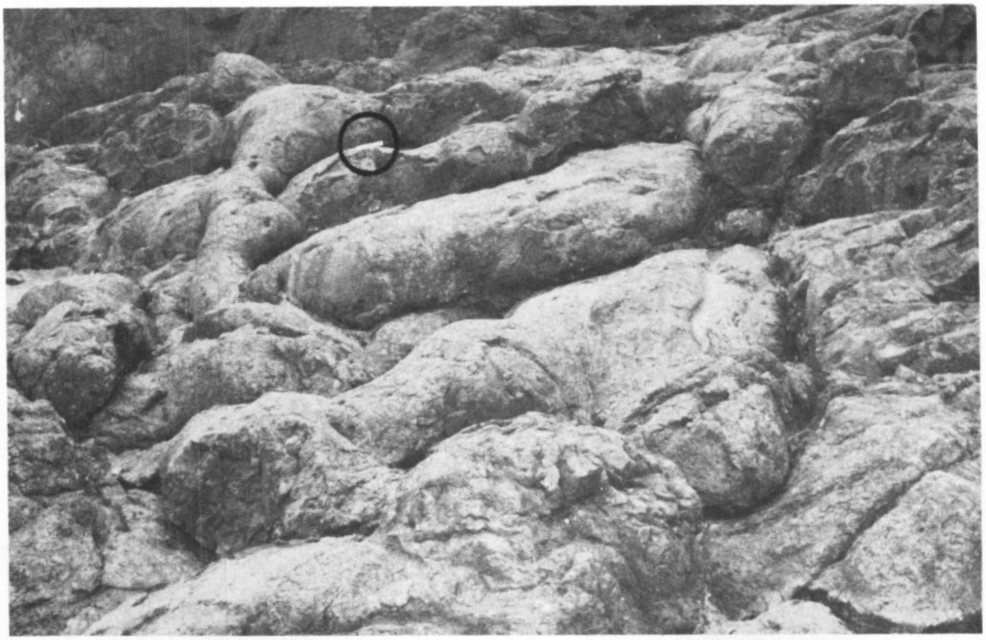


Fig. 11. Sac-form pillowed lava; Pillow Island, a few hundred metres west of station M.3134 (Fig. 2, inset). The scale (ringed) is 15 cm long.

Fig. 12. Columnar-jointed basalt several tens of metres thick overlying pillowed lava; Pillow Island (M.3134; Fig. 2, inset).

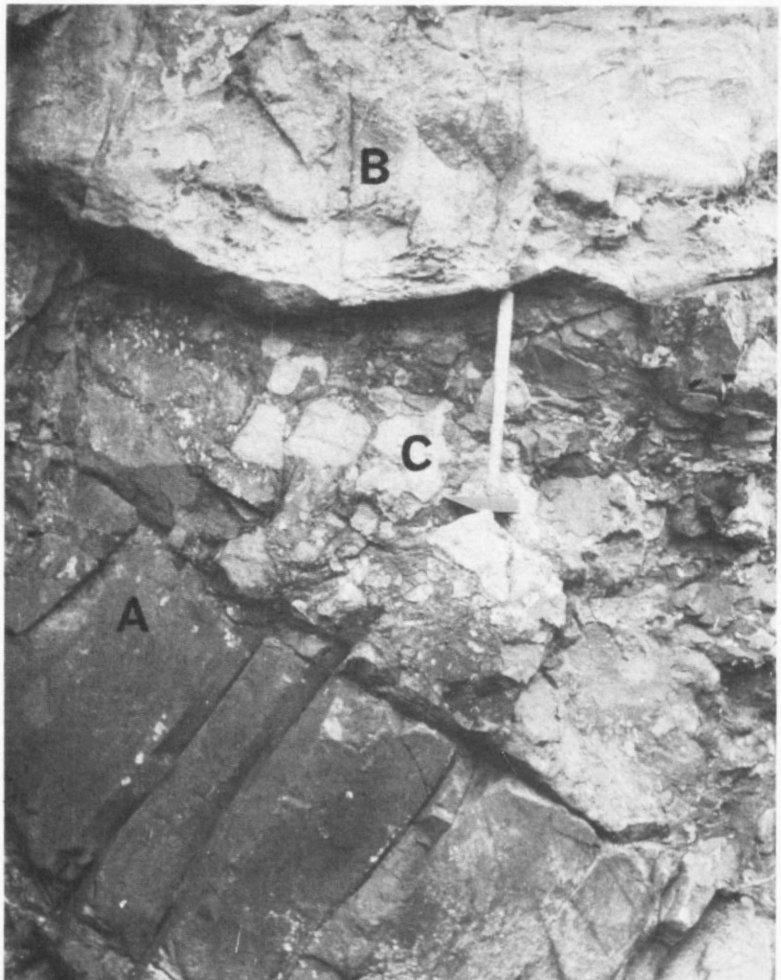


Fig. 13. Feeder dyke (A) to amygdaloidal lava flow (B) cutting pillow breccia (C); Pillow Island (M.2369; Fig. 2, inset). The hammer shaft if 65 cm long.

have dark rims; in the massive lavas they are filled with carbonate, chlorite or quartz–plagioclase, whereas those in the pillowed lavas are chlorite-filled.

Plagioclase is faintly sericitized and occurs both as uncommon phenocrysts 1–2.5 mm across and as a main constituent of the matrix (0.8–1.0 mm). It is secondary albite–oligoclase with uneven extinction and with albite rims. Augite (to 0.5 mm) is least altered in the columnar-jointed lavas, uncommon in the other massive lavas and completely replaced by chlorite and calcite in the pillowed lavas. Chlorite is common and forms patches or interstitial areas with a mosaic or spherulitic texture; two generations of chlorite are seen. In the non-pillowed lavas, many of the chlorite patches contain either minute feldspar blebs or larger (0.1 mm) rounded patches of plagioclase (biaxial negative) with uneven extinction. Quartz is only found in one specimen of the non-pillowed lavas (M.2371.2B), where it encloses minute clusters of (?) pumpellyite. It is rare in the pillowed lavas, where it occurs as small grains in the matrix or as small crystals or crystal groups (0.4 mm) with an embayed margin enclosed in sericitized plagioclase. Calcite is common in all of the basic lavas and is regularly distributed in patches up to 0.5 mm across. Opaque minerals occur either as small fern-like or feathery growths, most common in the pillow lavas, or as larger equidimensional crystals scattered throughout the rock. The degree of alteration of ilmenite to leucoxene and sphene varies from one rock to another.

Amygdales in all rocks have a characteristic dark fine-grained rim but this feature is best developed in the pillow lavas. Amygdales up to 4 mm across contain pale to yellowish green chlorite in rosette form (0.2–0.3 mm), which in some cases is accompanied by and intergrown with a colourless magnesian chlorite (uniaxial positive) with low birefringence and a lower refractive index than the green chlorite. Rims to these amygdales consist of fern-like growths of an opaque mineral (to 0.1 mm) (Fig. 14a), albite spherulites clouded with opaque dust, and patches of chlorite, calcite and sphene–leucoxene granules. An unusual feature of these rims is that they include "hollow" chlorite-filled prisms of plagioclase (Fig. 14b). The prisms have a square or rectangular cross-section with a narrow outer skin of plagioclase enclosing a chlorite-filled interior. In longitudinal section they are either fang-shaped at either end with a solid central part or are seen as prisms with a central zone of chlorite throughout. At the outer margin of the dark rim around the amygdales there is an abrupt increase in grain-size and some of the large plagioclase crystals in this zone are also "hollow-ended".

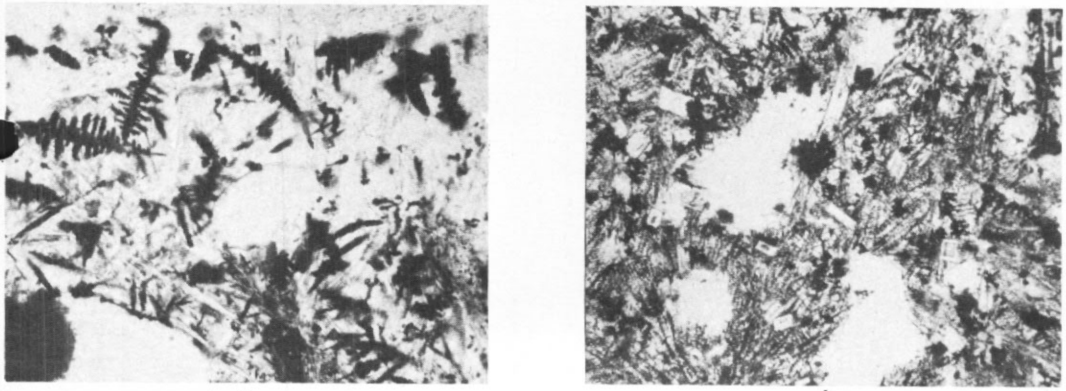
Hollow, acicular plagioclase microlites have been described previously from submarine pillow basalts. They have been interpreted as quench structures (Bryan, 1972) resulting from rapid growth combined with a low rate of diffusion in the supercooled, highly viscous margins of the pillows. The fern-like morphology of the opaque grains is also probably due to rapid growth from a supercooled magma.

Amygdales in the massive lavas vary from calcite-filled in one specimen to chlorite- and calcite-filled in others. In specimen M.3127 some of the amygdales are filled with a mosaic of quartz crystals with the grains arranged radially around the periphery and enclosed by an outer rim of cloudy acicular albite and an outer skin of chlorite–calcite.

The dyke rock (M.2369.2) is similar in petrography to that of the basic lavas and contains plagioclase phenocrysts up to 1 mm across and interstitial quartz crystals. It also contains small laths (0.05 mm) of a pale brown to colourless phyllosilicate, possibly biotite.

Correlation and discussion

Hauge Reef consists of a unit of pillowed and massive lavas in the east (Pillow Island), succeeded to the west by a thick sequence of gently dipping tuffaceous sediments with metabasic



a b

Fig. 14. a. Fern-like growths of opaque mineral and albite microlites from the rim of an amygdale in pillowed lava. The clear areas are chlorite (M.2372.2; Fig. 2, inset) (plane polarized light, ×333).

b. "Hollow-ended" albite prisms showing rectangular cross-sections, accompanied by feathery growths of opaque mineral. The clear areas are chlorite (M.2372.2; Fig. 2, inset) (plane polarized light, ×110).

sills (HB and HA Islands). The sediments are cut by numerous biotite- and hornblende-andesite plutons and are affected by contact metamorphism, giving rise to a biotite-hornfels. The metabasic sills on HA Island are earlier than the hornblende-andesite and occur as xenoliths in the latter.

As the finely banded sediments of Hauge Reef are identical in lithology with the Lower Tuff Member described by Pettigrew (1981) from Annenkov Island, we re-define the Lower Tuff Member to include the sediments of Hauge Reef (Fig. 3). On Annenkov Island, the total exposed thickness of the Lower Tuff Member is 860 m (Pettigrew, 1981). Extension of the outcrop of this member to HB Island increases the total possible thickness, excluding faults, but including igneous intrusions, to about 3 km (Fig. 3).

Petrographic features in common between the tuffs on Annenkov Island and those on Hauge Reef include the abundance of vitric clasts and spores, the presence of Radiolaria, plagioclase-crystal-tuffs and fragmental tuffs, and the uncommon occurrence throughout of acid and lithic clasts. Some consistent differences are however noted: quartz grains are more plentiful in the sediments on Hauge Reef (2.5–4.8%; Table I) than on Annenkov Island (0–1.7%; Pettigrew,

TABLE I. MODAL ANALYSES OF CRYSTAL-LITHIC TUFFS FROM HAUGE REEF, THE PICKERSGILL ISLANDS AND ANNENKOV ISLAND

	PA Island	*HA Island*			*Annenkov Island*
	M.3153	M.3112.C	M.3111	M.3522.3A	M.1196.7
1 Andesite	1.0	—	—	—	0.2
2 Altered feldspathic glass	—	—	10.0	—	—
3 Altered glass	0.3	7.8	20.0	6.2	4.9
4 Dacite	2.0	—	7.5	—	—
5 Felsite	—	4.5	—	0.5	—
6 Plagioclase	46.3	41.7	21.0	50.0	44.5
7 Pyroxene	—	—	—	—	0.2
8 Quartz	14.7	2.5	3.0	4.8	—
9 Polycrystalline quartz	7.3	—	—	—	—
10 Matrix	26.7	43.5	38.5	38.5	47.5
11 Other	1.7	—	—	—	2.7
12 Andesitic fragments	1.9	13.7	48.8	10.2	10.2
13 Silicic fragments	2.8	8.0	12.2	0.8	0.0
14 Feldspar	64.6	73.9	34.1	81.3	89.4
15 Ferromagnesian minerals	—	—	—	—	0.4
16 Quartz	30.7	4.4	4.9	7.7	0.0
Number points counted	300	400	200	400	?

All figures in rows 1–11 are percentages.

Rows 12–16 are the totals of the various classes, made into percentages without rows 10 and 11 in the total. They are made up thus: 1 + 2 + 3 = 12; 4 + 5 = 13; 8 + 9 = 16.

Analysis M.1196.7 is from Pettigrew (in press, table 3, No. 7).

1981, table III; hornblende and pyroxene crystal fragments are absent from the Hauge Reef tuffs but are present (up to 2.1%) in most thin sections of rocks from Annenkov Island (Pettigrew, in press); and glass shards which are common on Annenkov Island have only been positively identified in one specimen from Hauge Reef.

Differences due to increased grade of metamorphism in Hauge Reef are also noted. The tuffs on Annenkov Island have a carbonate cement; glass is altered to a green/brown amorphous material, analcime or an unidentified colourless mineral; zeolites (analcime and laumontite) are common; and there is no evidence of penetrative deformation or pressure-solution effects between grains. In similar rocks in Hauge Reef, the matrix or cement is chloritic; glass is altered to aggregates of chlorite crystals; zeolites have not been noted; and local effects of pressure solution are seen. These effects are partly due to increased depth of burial and partly to an increase in thermal gradient adjacent to the andesite plutons, which locally results in the formation of a biotite-hornfels. A single andesitic pluton is present within the Lower Tuff Member on Annenkov Island and hornfelses have not been reported. Spilitic sills of irregular shape and with tongues of sediment protruding into the igneous rock (cf. HA Island) have been reported from the Lower Tuff Member on Annenkov Island by Pettigrew (1981), who suggested that they were intruded into unconsolidated sediments.

The lavas of Pillow Island are correlated with the uppermost part of the Larsen Harbour Formation described by Storey and others (1977), and Mair (in press). The thin interbedded sediments are of particular interest as they contain abundant algal and angiosperm spores derived from a nearby land area. These sediments also resemble in field appearance and petrology the sediments found within the Larsen Harbour Formation on Leon Head (personal communication from B. F. Mair). Basic dykes, which are common in the lower part of the sequence on South Georgia, are rare on Pillow Island; stratiform breccia is absent and the lavas contain thick rapidly chilled units of columnar basalt similar to the Larsen Harbour Formation at Leon Head. The lavas of Pillow Island, like those of the Larsen Harbour Formation, have been metamorphosed to a low metamorphic grade probably by hydrothermal alteration and circulation of sea-water during their emplacement. A major fault is inferred between Pillow Island and the main outcrop of the Cumberland Bay Formation on South Georgia (Fig. 2).

The contact between the lavas on Pillow Island and the Lower Tuff Member on HB Island is not exposed but thin layers of sediment found between the lavas include crystal-tuffs identical to those occurring within the Lower Tuff Member. This suggests that the Lower Tuff Member is in continuity with, and underlain by, the lavas on Pillow Island. This inference is supported by (a) the regional dip of the sediments (Fig. 2), and (b) the presence of xenoliths, which can be matched with the Pillow Island lavas, within a biotite-andesite pluton that cuts the Lower Tuff Member on HB Island. It follows from this conclusion that the spilitic sills on Annenkov Island and Hauge Reef may be derived from the same source as the lava sequence.

Pickersgill Islands

The Pickersgill Islands are a group of five islands arranged in a tight cluster 22 km south-south-east of Hauge Reef and 13 km from the South Georgia mainland (Fig. 1). They are generally inaccessible and difficult to land on from a boat even in settled weather and minimum swell. The three larger islands were mapped, a brief visit was made to PB Island and only the small island north-west of PA Island was not visited (Fig. 2, inset).

PA Island

The island consists of gently dipping ($<30°$) tuffaceous sediments (Fig. 15) intruded by thick concordant hornblende-(quartz)-andesite sills, and a large andesite pluton on the south-east side. The andesite sills and pluton have been affected by (?) contact metamorphism and the sediments

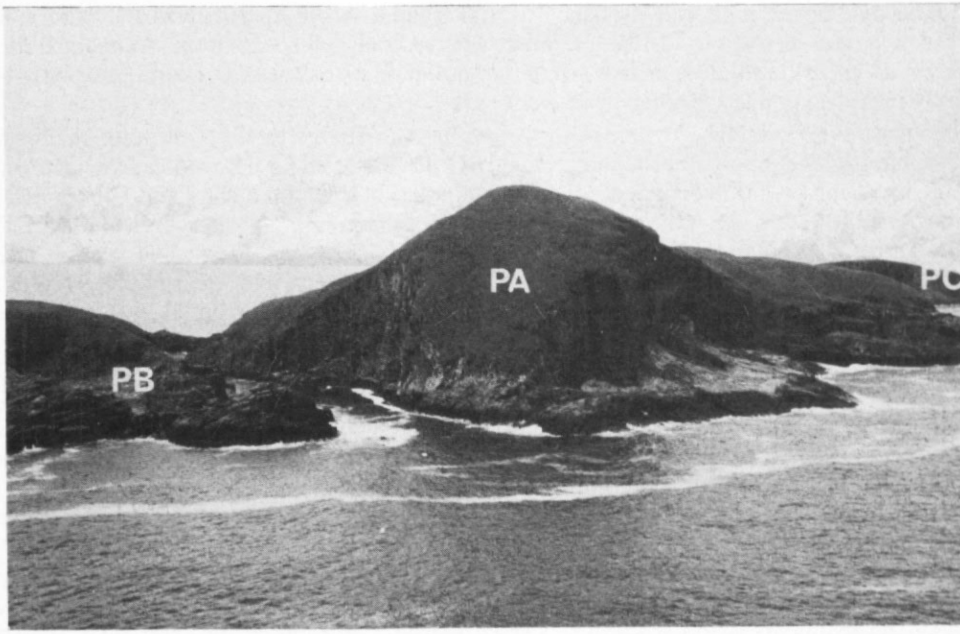


Fig. 15. PB Island (PB), PA Island (PA) and PC Island (PC) in the Pickersgill Islands viewed from Tanner Island. South Georgia forms the backdrop.

altered to a biotite-hornfels. Both groups of rocks are cut by a few thin, steeply dipping basic dykes.

Sediments. The rocks are planar bedded, grey to dark brown and weather to a cream or pale brown colour. They contain indistinct bands generally 1–4 cm thick but occasionally reaching 8 cm (Fig. 16), each with internal parallel laminations and sometimes an indistinct (?) cross lamination. They include thin graded beds, indurated mudstones and greenish grey calcareous lenses (up to 5 cm long and 2 cm thick). Strike direction is variable but the dip is generally east-north-easterly, varying between 10° and 17°, and locally reaching 25°.

In thin section, graded crystal-tuffs several centimetres thick with sharply defined lobate bases are associated with siltstones having millimetre-banding and altered mudstones. Opaque granules and feldspar replacing (?) Radiolaria are still recognizable in the altered mudstones. Crystals andesine (An_{36}) and quartz (up to *c.* 30%) crystals occur in the crystal-tuffs together with some lithic fragments, mainly felsite and andesite. Modal analysis of one specimen showed an unusually high percentage of quartz fragments (Table I). Some of the crystal fragments have been bent or broken after sedimentation with the matrix having crystallized between the separated parts.

The matrix in all rock types has been recrystallized to a biotite fabric; it is coarse-grained between fragments in the crystal-tuffs and fine-grained (<0.02 mm) in the mudstones, and associated with abundant opaque material. Garnet euhedra (to 0.4 mm) are especially common in the biotite-rich tops to graded units and garnet crystals are found in most thin sections. Pale grey-green actinolite laths and sheaf-like aggregates (0.2 mm) have grown across the bedding and appear to be replacing biotite in one thin section. Clear patches (to 0.1 mm) of granular low-refractive index (?) cordierite occur in several rocks. Quartz crystals have locally recrystallized either as strain-free mosaic patches or have formed a number of separate domains with minute

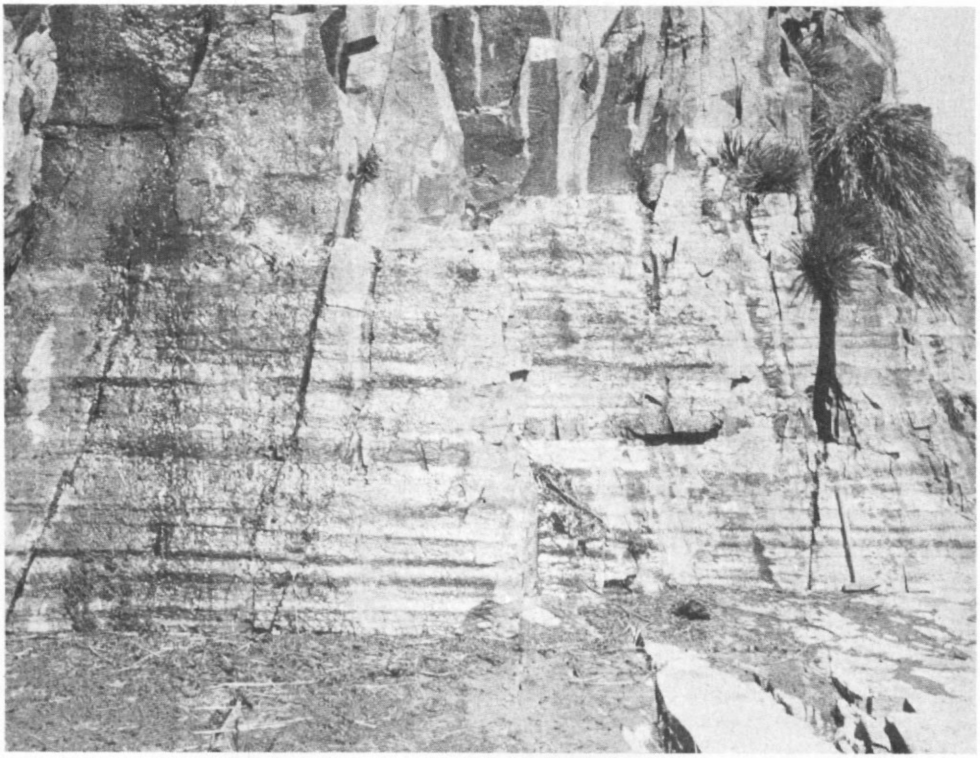


Fig. 16. Andesite sill in transgressive contact with gently dipping tuffaceous sediments; PA Island (M.3153; Fig. 2, inset). The hammer shaft is 58 cm long.

quartz grains crystallized along the boundaries. The calc-silicate lenses are largely composed of granular diopside and calcite with some feldspar and quartz. Parageneses are as follows:

biotite$\pm$actinolite
garnet$\pm$actinolite–biotite
cordierite$\pm$garnet–actinolite–biotite
diopside–calcite

All assemblages contain plagioclase, quartz and opaque minerals. Small veinlets are reasonably common in those rocks and contain biotite–plagioclase–quartz, muscovite–plagioclase–quartz, diopside, and actinolite associated with the different parageneses.

Andesite sills and pluton. The andesite intrusions are of greenish brown altered hornblende-(quartz)-andesite with phenocrysts of hornblende up to 1 cm long which can be seen in the hand specimen to be partly altered to an aggregate of biotite flakes.

Two main sills, 1.5 and 8 m thick, occur on the north side of the island and appear concordant to the sediments. However, at one locality the sediments beneath the thicker body are contorted and a slight angular discordance is seen between its base and the bedding in the sediments (Fig. 16). A small plug, about 10 m in diameter, which occurs in this area is petrographically identical to the main sill. On the south side of the island a large irregularly shaped andesite pluton is well exposed along the coast section. Sill-like apophyses extend from the intrusion parallel to the bedding in the enclosing tuffs. The pluton contains angular to sub-rounded basic xenoliths and a single gabbroic xenolith was noted.

In thin section, the andesites consist of bluish green or green-brown hornblende and labradorite (An_{58}) (to 3.5 mm) phenocrysts set in a finer-grained matrix (0.03–0.1 mm) of andesine (An_{42}), K-feldspar, biotite and hornblende crystals with some interstitial quartz. The labradorite phenocrysts are cut by albitic veinlets and contain small patches of K-feldspar. Quartz forms patches up to 1.3 mm across in some thin sections and in one case it reaches 10–15% (quartz-andesite). The hornblende phenocrysts contain many small (? secondary) biotite laths, sometimes with actinolite, or are completely pseudomorphed by biotite; in several cases they retain partially replaced cores of augite. Aggregates of biotite flakes are found in the matrix and are associated with groups of distinctive grey apatite crystals, which are zoned and clouded with minute opaque inclusions. Plagioclase phenocrysts in the thick dyke and the plutonic rocks have calcic (labradorite, An_{62}) cores and sodic margins, and show oscillatory zoning; those in the thin 1.5 m sill only show simple twinning and non-oscillatory zoning, and do not show such marked differences in composition between core and rim. A second difference between the two groups is that only the thin sill shows a flow texture in the matrix. Large opaque granules are common in all of the andesites, sphene is commonly found in the biotite aggregates and can be seen rimming ilmenite in one instance, and allanite occurs as an accessory mineral.

The gabbroic xenolith in the main pluton contains the assemblage green-brown hornblende–labradorite with a small amount of biotite.

Dykes. Several sets of steeply dipping dykes are found on PA Island. They are uncommon but may be divided into those of altered andesite, apparently related to the andesite intrusions, and others which are less altered and of andesitic or basaltic composition.

At station M.3141 a dyke appears to connect with and feed the 8 m sill. This dyke and others which cut the andesite pluton in the south of the island are of hornblende-andesite and are identical in appearance and mineralogy to other members of the andesite suite.

Grey-green porphyritic dykes, which are near-vertical and cut the andesite sills and intrusions, are 0.3–1.0 m thick and have trends of 073°, 085°, 087°, 120° and 125°. In thin section, these dykes contain green hornblende (to 3 mm) and labradorite phenocrysts with narrow zoned sodic rims in a fine matrix of albite laths (<0.1 mm). Quartz occurs in the matrix associated with chlorite (? amygdales). The secondary alteration of minerals is different from that seen in the andesites and the dykes are characterized by yellowish green epidote-rich spots. Hornblende is altered to chlorite and calcite, and patches of calcite (to 2 mm) and chlorite are commonly found in the matrix as well as areas of epidote mosaic (to 0.8 mm). Sphene granules are common.

Basaltic dykes consist of ragged hornblende laths, crystals of biotite and pyroxene, and zoned labradorite (An_{61}; 0.2 mm) crystals with sodic rims set in a matrix of albite grains. Hornblende contains inclusions of plagioclase, biotite and pyroxene. In addition, a few microgranite veins cut the andesite intrusions in the southern part of the island. They consist of hornblende and zoned andesine phenocrysts in a groundmass of sodic plagioclase, biotite, K-feldspar, perthite and quartz.

PB Island

The island is separated by a narrow channel from PA Island (Fig. 15). A microdiorite intrusion cut by microgranite dykes forms the eastern part of the island; sediments similar to those on the adjacent island and including coarse tuff bands with intraformational clasts up to 1.5 cm long are found to the west. The intrusive body, whose form is not known, consists of ragged poikilitic hornblende crystals with plagioclase in a matrix of andesine (An_{46}) crystals, some interstitial quartz and accessory apatite. Hornblende appears fresh in the hand specimen but it shows alteration to small flakes of biotite in thin section; it encloses plagioclase crystals and sometimes contains (?) relict cores of augite. Labradorite (An_{46}) has sodic rims and shows oscillatory zoning.

The intrusion is cut by microgranite dykes which range in thickness from 0.1 to 0.65 m and trend at 064° and 067°. The microgranite dykes consist of andesine (to 1 mm), biotite and rare green-brown hornblende set in a granoblastic plagioclase–perthite–(?) K-feldspar matrix. Quartz crystals have embayed lobate margins and there is slight alteration of other minerals to sericite, chlorite and epidote. Graphic intergrowths between quartz and K-feldspar are common. Apatite is an accessory mineral in both types of dyke and prehnite lenses occur in biotite.

Tanner Island

Much of the island was examined and it was found to consist of a composite, mainly micro-quartz-monzodiorite, intrusion cut by a few basic and aplitic dykes. The margin of the intrusion is not exposed.

Quartz-monzodiorite. The pluton varies slightly in composition, texture and grain-size from place to place and there is local field evidence that an earlier basic phase was followed by a paler, more acid, phase. The monzodiorite contains small basic xenoliths, which are generally uncommon, as well as rare mafic-rich inclusions.

In mineralogy, the intrusion is variable and the specimens examined include granite, quartz-monzodiorite and quartz-monzonite (Table II). It consists of hornblende, biotite and plagioclase phenocrysts set in a matrix of andesine to sodic plagioclase with K-feldspar, myrmekite and interstitial quartz. The poikilitic green hornblende (to 4 mm) is sometimes moulded around relict cores of colourless spongy augite or intergrown with the pyroxene, and in a few cases it has retained the twinning shown by the augite. The hornblende is generally fresh but in places it contains small laths of secondary biotite and is occasionally altered to a mosaic of pale blue-green amphibole in the centres of large crystals. Biotite occurs as poikiloblastic plates up to 2 mm across. The plagioclase phenocrysts have highly calcic cores and sodic rims, and show oscillatory zoning; laths in the matrix are of (?) andesine. Microprobe analysis of two zoned phenocrysts in specimen M.3165.B gave a core to rim variation of An_{47-80} and An_{35-95}. Epidote (to 0.2 mm) and chlorite are uncommon but they occur as alteration products. Accessory minerals include apatite, sphene, zircon and opaque minerals. Pumpellyite and prehnite occur as lenses in biotite.

A basic xenolith, which was sectioned, is of fine-grained monzodiorite and consists of

TABLE II. MODAL ANALYSES OF PLUTONIC ROCKS FROM TANNER ISLAND

	M.3165.E	M.3165.H	M.3165.B	M.3165.A
Plagioclase	32.5	48.9	54.1	50.2
Quartz	31.5	6.6	8.4	18.6
K-feldspar	29.0	7.7	6.5	17.6
Biotite	6.0	6.7	6.0	10.0
Hornblende	—	24.7	21.5	1.2
Chlorite	0.4	—	—	0.4
Apatite	—	1.2	0.6	0.6
Opaques	0.6	4.2	2.9	1.4
*Name**	Granite	Quartz-monzodiorite	Quartz-monzodiorite	Leucocratic quartz-monzodiorite

* Nomenclature after Streckeisen (1973). 1 000 points counted per specimen.

hornblende, augite, biotite, andesine, K-feldspar and quartz. Some of the plagioclase has been altered to (?) albite and clinozoisite. A more ultramafic xenolith consists mainly of clinopyroxene (to 0.7 mm) enclosed in poikilitic green hornblende with interstitial calcic plagioclase and large opaque grains. Some of the hornblende is altered to biotite.

Dykes. There appear to be two sets of andesitic dykes, both of which dip steeply to the south: (a) fine-grained basaltic dykes 2–3 m thick which trend 092° and 112°, and contain rounded basic xenoliths up to 25 cm across, and (b) a set of andesitic dykes up to 1 m thick which trend 147–152° and have chilled margins against the country rock. The two sets differ in grain-size and texture.

Type (a) dykes contain hornblende and andesine (An_{47}) phenocrysts in a microcrystalline matrix. The andesine crystals have calcic cores and the albite rims show some sericitization.

Type (b) dykes consist of hornblende (to 0.5 cm) and plagioclase laths (1.5 mm) in a dark grey, fine-grained pilotaxitic matrix. The plagioclase is mainly andesine with labradorite cores and albitic rims; the crystals show oscillatory zoning. Rare small patches of interstitial quartz and K-feldspar occur between the andesine laths of the matrix.

Aplite and microgranite dykes cut and displace pegmatitic bands in the microtonalite and also cut the 092–112° set of basic dykes at the southern end of the island. In thin section, the aplite consists of a granular intergrowth (<0.4 mm) of quartz, slightly sericitized sodic plagioclase, K-feldspar and perthite. The assemblage contains thin plates of biotite largely altered to chlorite and opaques, and small muscovite flakes. Graphic intergrowths are common. The microgranite contains zoned sodic plagioclase with calcic cores, quartz, K-feldspar, some hornblende, and biotite which has been almost completely altered to chlorite.

PC Island

Although access was difficult, over half of the coastal exposure on PC Island was examined. A large intrusive body, which contains a dioritic and a gabbroic assemblage, crops out on the western side of the island. On the eastern side, andesitic sills similar to those of PA Island intrude hornfelsed sediments. The relationship between the andesitic sills and the dioritic assemblage of the intrusive body is uncertain; the contact is poorly exposed and was not examined in detail. Andesitic dykes cut the intrusive body, sediments and andesitic sills.

Intrusive body. The intrusion exhibits marked local variation in grain-size, texture and composition: pyroxene-hornblende- and hornblende-pyroxene-gabbros, leuco- and meladiorites, and quartz-diorites were all recorded (Table III). Coarse-grained and porphyritic meladiorites and gabbros, which mainly crop out on the south-west corner of the island, locally show 2–4 cm banding and cross-lamination (Fig. 17) defined mainly by variation in hornblende content. The leucodiorites and quartz-diorites form the margins of the body. Minor shear zones and fracture zones, in which pyrite, quartz veining and chlorite are developed, cut the pluton; it is also altered to chloritic material in areas up to 2 m across.

In thin section, variable proportions of pyroxene (to 0.8 cm) and hornblende (to 1.5 cm) phenocrysts together with some biotite are present in a matrix of andesine–labradorite laths with some interstitial quartz and K-feldspar. Accessory minerals are sphene, opaques and apatite. Alteration and secondary minerals include biotite, chlorite, prehnite, tremolite–actinolite and serpentine.

Orthopyroxene (faint pink to pale green pleochroism), often enclosed in hornblende, is present in some rocks (M.2379.1 and 2). It is partially or completely altered to a pale green and a yellow-brown serpentine (bastite) with some biotite, opaque minerals and small laths of (?) pumpellyite. Augite varies from large rectangular crystals (to 0.8 cm) with complex zoning, twinning and schiller structure to remnant inclusions within poikilitic hornblende. Inclusions of feldspar are common in the margins of large ragged hornblende and pyroxene prisms. Inclusions and rims of

TABLE III. MODAL ANALYSES OF PLUTONIC ROCKS FROM PC ISLAND

	M.2379.1	M.3170	M.2379.9	M.3172	M.2379.9	M.2379.2	M.3528.3
Hornblende	38.0	17.8	74.1	62.4	48.25	13.6	15.5
Plagioclase	29.4	36.6	10.6	33.4	45.0	65.0	69.25
Augite	20.2	42.4	2.9	—	—	3.2	—
Hypersthene	1.4	—	—	—	—	—	—
K-feldspar	1.6	—	—	0.7	0.75	2.1	5.25
Quartz	0.8	—	—	0.2	—	3.0	6.0
Chlorite	0.8	1.2	2.3	1.4	—	—	—
Biotite	3.2	0.2	4.5	1.3	2.25	8.0	2.0
Opaques	2.0	1.8	4.5	0.4	3.5	5.0	2.0
Sphene	—	—	—	0.2	—	—	—
Apatite	2.6	—	1.1	—	0.25	0.1	—
*Name**	Pyroxene-hornblende-gabbro	Hornblende-pyroxene-gabbro	Meladiorite	Meladiorite	Diorite	Leucodiorite	Quartz-leucodiorite

* Nomenclature after Streckeisen (1973). 500 points counted per specimen.

optically continuous hornblende are found within and around the pyroxene (Fig. 18a and b). Hornblende, which is the main ferromagnesian mineral in the dioritic assemblage, forms large prisms and shows some alteration to actinolitic hornblende and disorientated flakes and aggregates of reddish brown biotite. Complete pseudomorphs of disorientated pale green and colourless actinolite laths, dusty opaques and chlorite are common within specimen M.2379.1. Occasional biotite poikiloblasts, up to 3 mm, are partially altered to epidote, chlorite and prehnite.

The feldspars are variable in composition. Within the gabbroic assemblages occasional large labradorite porphyroblasts occur together with medium-grained labradorite and andesine laths. Within the diorites, the andesine laths, which may contain cores of calcic plagioclase, are zoned and have sodic rims. K-feldspar forms interstitial patches and poikiloblastic sheets and veins within the plagioclase laths. The calcic plagioclase laths are partially altered to sericite, prehnite (M.3170) and epidote. Stumpy apatite prisms up to 1 mm are a common accessory.

Andesite sills. The andesite sills which occur within the hornfelsed sediments on the eastern side of the island are hornblende- and pyroxene-andesites. Plagioclase, hornblende and pyroxene phenocrysts (2.5 mm) are set in a matrix, often pilotaxitic, of sericite, plagioclase, pyroxene, hornblende, epidote, K-feldspar, biotite and calcite. The andesine phenocrysts show oscillatory zoning and have calcic, slightly sericitized, cores. Hornblende and pyroxene are partly altered to aggregates of epidote, calcite, chlorite and sphene. One hornblende crystal encloses a grain of pumpellyite and this mineral occurs in the matrix of specimen M.2380.3. Dusty zoned apatite crystals are common especially in the biotite aggregates. Small veins are numerous and are filled with varying combinations of pyroxene, hornblende, biotite, epidote and an opaque mineral dependent on the mineralogy of the host rock. In mineralogy, texture and presence of zoned apatite crystals, these rocks are identical to the andesite suite on PA Island.

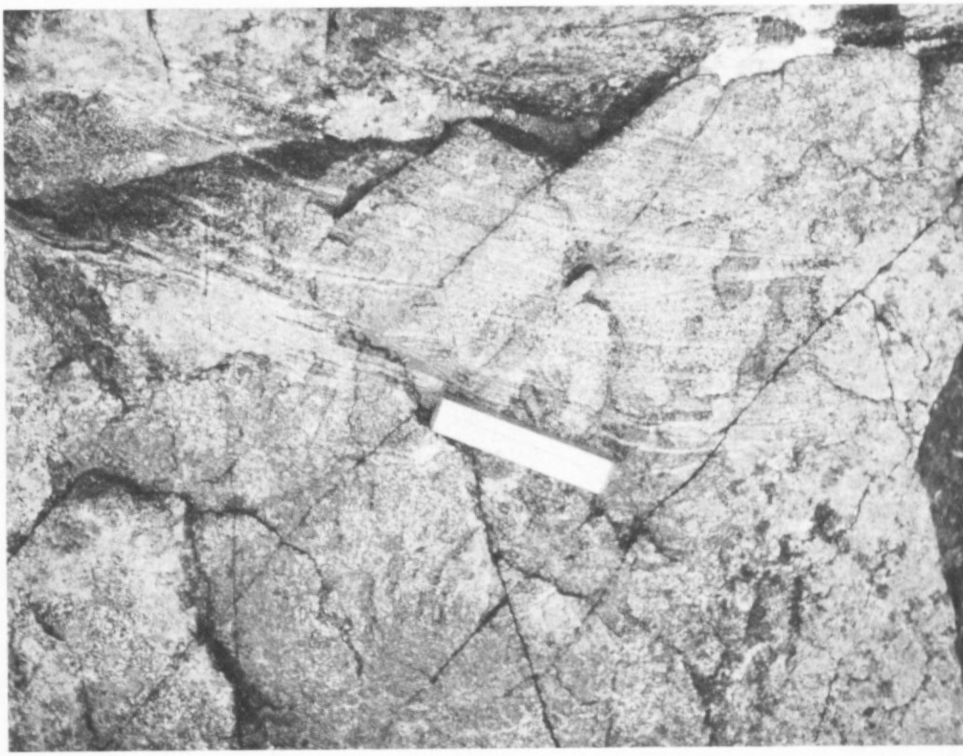


Fig. 17. Layering and cross lamination in the meladiorite on PC Island (M.2379; Fig. 2, inset). The engraved scale is 10 cm long.

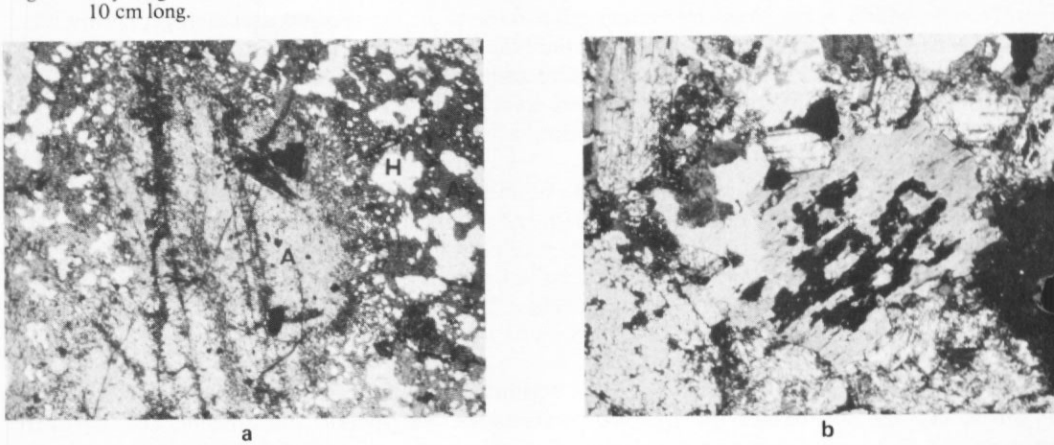


Fig. 18. a. Inclusions of optically continuous hornblende (H) within the margins of a zoned augite crystal (A) (M.2379.1; Fig. 2, inset) (X-nicols, ×17).
b. Hornblende–pyroxene intergrowth in a pyroxene-hornblende-gabbro (M.2379.1; Fig. 2, inset) (X-nicols, ×18).

Sediments. The hornfelsed sediments are dark grey to brown and contain much biotite. Aggregates of actinolite crystals up to 1 mm across occur in a matrix of actinolite laths, biotite and plagioclase crystals (0.1–0.2 mm) with a patchy development of chlorite.

Dykes. Andesite dykes are rare. One dyke, which cuts the microdiorite in the south-west corner of the island, has hornblende and augite phenocrysts in a pilotaxitic matrix. Hornblende is partly altered to pistacite, and chlorite and pumpellyite occur in the matrix. A similar dyke cuts the interbanded andesite-hornfels sequence on the other side of the island and contains ferromagnesian phenocrysts, which have been largely altered to aggregates of hornblende and biotite with remnant pyroxene.

Correlation and discussion

In the Pickersgill Islands, the finely banded sediments are included within the Lower Tuff Member. They have the same macroscopic character as the tuffs on Annenkov Island and Hauge Reef, and are intruded and hornfelsed by a wide variety of igneous intrusions. The hornfelses develop garnet and cordierite, and most of the primary features of the sediments have been destroyed. Andesite sills, petrographically similar to those in Hauge Reef occur within the sediments, and andesite dykes both feed and post-date the sills. The plutonic suite ranges from gabbro to diorite in composition; the relationship between these rocks and the porphyritic andesite sills is nowhere exposed but the strong contrast in grain-size and texture indicate that the sills are not connected to, or part of, any of the plutons. The sills were probably derived from the same parent magma as the plutons but they were intruded slightly earlier in the development of the island arc.

The complex gabbro–diorite intrusion on PC Island displays some of the features of the main diorite body on PB Island and the monzodiorite of Tanner Island; a primary gabbroic assemblage (pyroxene–labradorite) is overgrown and partially replaced by a dioritic (hornblende-andesine) assemblage. On PC Island the gabbroic assemblage is well preserved. We suggest that this variation in the assemblages is a primary feature and that the magma passed from the pyroxene crystallization field and into the hornblende field during crystallization, with late-stage development of quartz, sodic plagioclase and K-feldspar. Remnant pyroxene and labradorite cores are also found within phenocrysts in the andesite suite.

Cape Darnley to Austin Head

Within this area (Fig. 2) the rocks are mainly of turbidite facies and belong to the Cumberland Bay Formation. The geology of Ducloz Head, which lies in the centre of the coastal strip, has recently been described by one of us (Storey, in press); it consists of faulted slices of Ducloz Head Formation separated from the Cumberland Bay Formation by a major fault.

A major upright syncline follows the coastline from Cape Darnley to Austin Head and plunges gently to the west-north-west. The hinge zone is exposed in several places and most of the rocks in the area lie on the northern limb of this fold. An associated "hackly" slaty cleavage is poorly developed in the pelitic beds (Fig. 19) but absent in the coarser-grained units; there is a weak cleavage/bedding intersection lineation developed in some places. Both of these structures are difficult to detect in the field.

The rocks may be separated into alternating "proximal" and "thin-bedded" groups as defined by Walker (1978, p. 936). Over most of the area the sand-dominated "proximal" groups form the bulk of the succession (Fig. 20). Sandstone beds range in thickness up to 10 m (a channelled gritty conglomerate at Austin Head) but they are usually no more than 2–3 m thick, with an average of 0.5–1 m (Fig. 21). The thickest beds are commonly structureless or display a crude basal grading; in the thinner ones parallel lamination and cross lamination are developed. Although intraformational shale clasts are very common and there is much load casting and basal erosion, amalgamation of units seems to be rare. The thin-bedded units are of shale with subordinate thin, graded, rippled and flat-laminated fine sands and silts (Fig. 22). Convolute lamination is developed rarely in the finer units; at one locality at Cape Darnley tabular cross stratification was observed in a fine conglomerate.

A chaotic association of rafted blocks of sandstone (some with preserved sedimentary

Fig. 19. Small-scale cross lamination and hackly cleavage in part of a thin-bedded turbidite sequence (Cumberland Bay Formation) north of Cape Darnley (M.3081; Fig. 2). The scale is 5 cm long.

Fig. 20. Typical alternation of "proximal" (thick sandstone beds) and thin-bedded units of the Cumberland Bay Formation seen between Cape Darnley and station M.3081 (Fig. 2). The beds are viewed from the north-west and dip to the south-south-west.

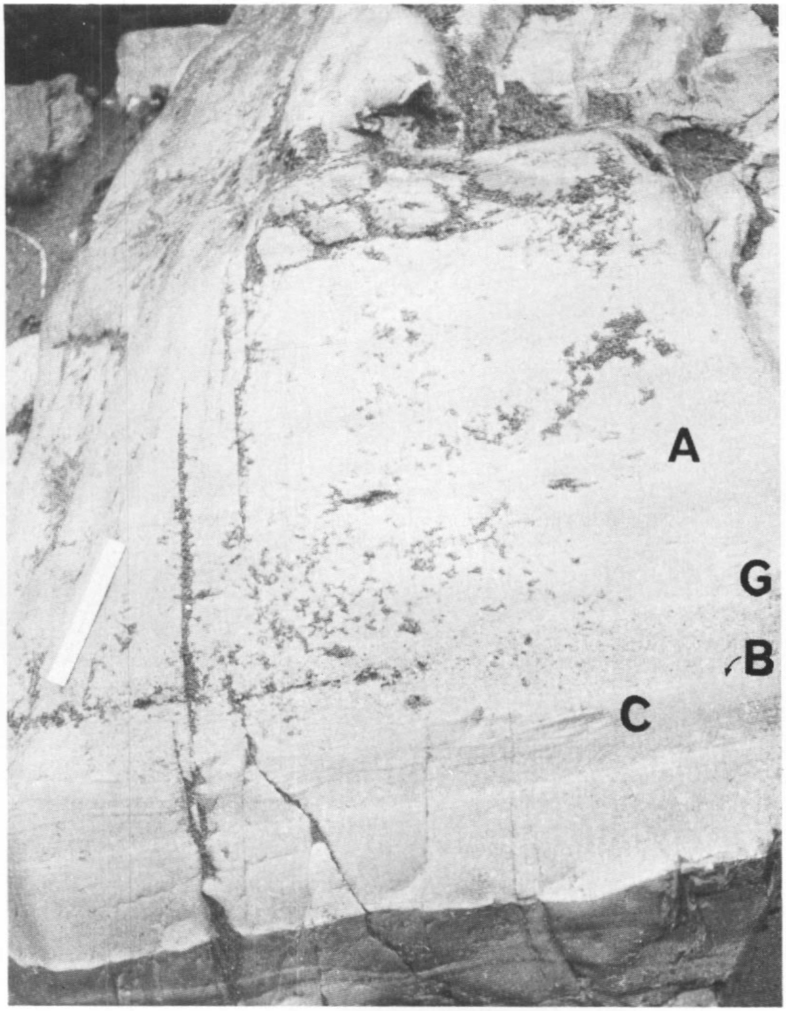


Fig. 21. Thick sandstone unit in the Cumberland Bay Formation with a sharply defined base (B), lower graded part (G) and showing possible amalgamation (A). It overlies a unit with well-developed cross lamination (C) (M.3188; Fig. 2). The engraved scale is 10 cm long.

structures) in a shale mixture seen in a poorly exposed area on the coast of Austin Head possibly represents a major slumped unit. It is overlain by a series of coarse-grained (?) channelled deposits, usually 5–10 m thick. Elsewhere in the area there are a few slump folds generally with a wave-length of 0.5–1 m.

Bottom structures were rarely seen, as the beds are right way-up and gently dipping. However, eight tool marks measured at Cape Darnley indicate an average south-east to north-west dispersal direction with associated flutes in one case giving an unambiguous north-west sense. This is in agreement with previously published results from farther to the north-east (Trendall, 1959; Dott, 1974).

Other features include calcareous nodules and prehnite haloes round intraformational shale clasts; both of these are common elsewhere in the Cumberland Bay Formation. Wood fragments are common and in one case are orientated on a bedding plane and give a direction in agreement with the tool marks. There are no hard-bodied fossils but trace fossils are found, notably

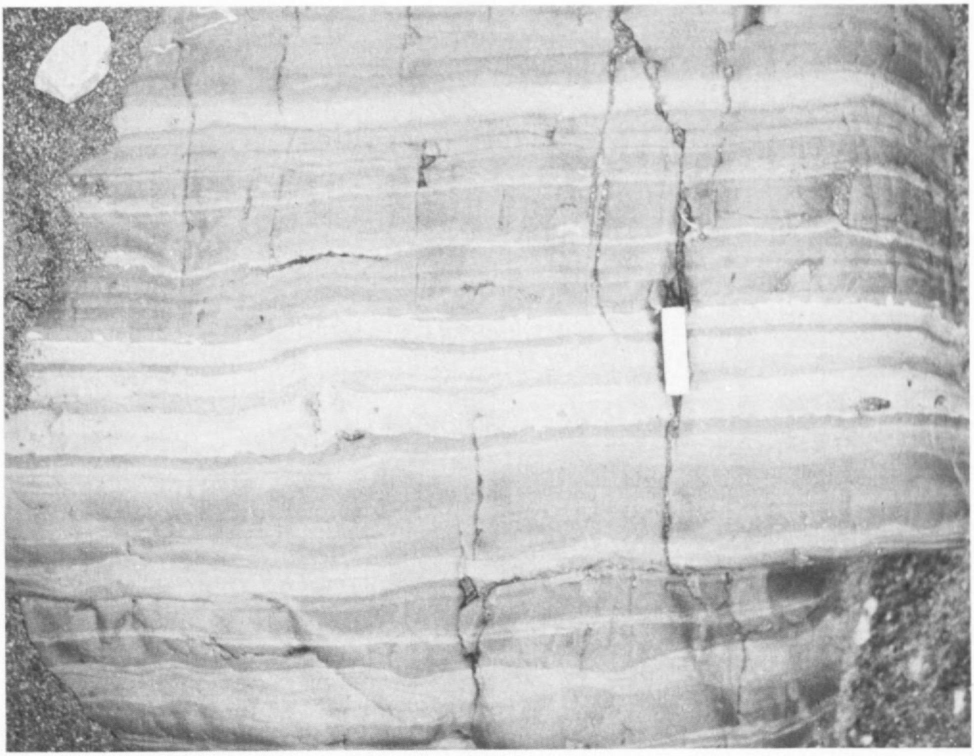


Fig. 22. Thin-bedded sequence in the Cumberland Bay Formation. The pale sandstone beds in the centre have been extensively prehnitized (M.3188; Fig. 2). The scale is 5 cm long.

Chondrites. At one locality north of Cape Darnley, *Palaeodictyon* was collected—this genus is previously unrecorded on South Georgia.

Point counting and measurement of the long axes of the 25 largest grains was performed on nine samples, six of which were stained using the method of Bailey and Stevens (1960) to indicate the presence of plagioclase and K-feldspar (Table IV). The results of this indicate a positive linear correlation between maximum and mean grain-size and a positive correlation between grain-size and percentage of rock fragments in the grades above coarse sandstone. In these grades, the rock fragments (principally andesite and andesitic glass with subsidiary amounts of silicic volcanic rock) varied from 50 to 85%. Crystal fragments, which become more important with declining rock-fragment percentage, consist mainly of plagioclase with small percentages of K-feldspar, hornblende, augite and quartz. Due to the difficulty of point counting the medium sand grades and below, it is not known for certain whether the maximum grain-size/rock-fragment per cent relationship holds good, but by inspection there seems to be a continuous spectrum with declining grain-size. There are subsidiary amounts of intraformational siltstone, tuff and shale clasts, polycrystalline quartz, (?) metamorphic quartz–plagioclase rock, and graphic granite. The percentage of matrix is generally 20–30%—the rocks are all lithic greywackes as defined by Pettijohn and others (1972); the coarser ones *may* be a rudaceous equivalent.

The andesites exhibit a continuous variation from holocrystalline, with phenocrysts of plagioclase and ferromagnesian minerals, to totally glassy rocks now altered to chlorite. The coarsest type is medium-grained with phenocrysts (up to 4 mm) of plagioclase (An_{16-38}), augite

TABLE IV. MODAL ANALYSES OF CUMBERLAND BAY FORMATION GREYWACKES

	Undine South Harbour				*Cape Darnley*	
	1411	3188C	3187	2381.5	2358.6B	3081A
1 Andesite	53.0	30.5	28.5	35.5	30.7	23.7
2 Altered feldspathic glass	2.4	4.5	5.5	4.0	4.2	3.0
3 Altered glass	4.0	7.0	4.2	2.5	2.5	7.5
4 Amygdalar andesite	4.6	tr	1.0	1.0	6.5	4.5
5 Quartz-andesite	3.4	4.0	1.7	2.7	4.5	3.2
6 Dacite	1.2	1.5	0.8	2.5	2.2	2.5
7 Felsite	0.2	0.5	2.2	0.3	1.2	6.5
8 Rhyolite	0.2	—	0.3	0.3	—	—
9 Plagioclase	9.2	18.2	19.0	13.5	16.5	13.7
10 K-feldspar	tr	0.5	1.5	1.0	—	—
11 Amphibole	—	0.5	0.3	1.2	0.8	—
12 Pyroxene	0.4	0.3	1.7	2.2	0.8	1.3
13 Quartz	0.6	1.3	1.3	0.8	0.8	1.3
14 Polycrystalline quartz	0.2	1.0	0.8	1.0	0.8	1.8
15 Matrix	19.8	28.7	28.7	28.0	26.5	28.0
16 Sediment	tr	tr	—	—	—	—
17 Unidentifiable	0.8	0.5	2.0	3.0	2.0	2.7
18 Other	—	1.0	0.5	0.5	—	0.3
19 Andesitic fragments	84.9	66.0	59.4	66.8	67.8	61.0
20 Silicic fragments	2.0	2.9	4.8	4.4	4.9	13.0
21 Feldspar	11.6	26.9	29.8	21.2	23.1	19.9
22 Ferromagnesian minerals	0.5	1.0	2.9	5.1	2.1	1.8
23 Quartz	1.0	3.2	3.1	2.5	2.1	4.3
24 Maximum grain-size (mm)	8	5	4	4.25	3.5	3
25 Mean of 25 largest grains (mm)	4.58	3.14	2.34	1.96	2.18	1.59
26 Number of points counted	500	400	400	400	400	400

All figures in rows 1–23 are percentages.
"tr" refers to clast types present but not counted.
Rows 19–23 are the totals of the various classes, made into percentages without rows 15–18 in the total. They are made up thus: 1 + 2 + 3 + 4 + 5 = 19; 6 + 7 + 8 = 20; 9 + 10 = 21; 11 + 12 = 22; 13 + 14 = 23.

and hornblende (α = pale brown to pale green, $\beta = \gamma$ = brown to green-brown; sometimes altered to chlorite) set in a matrix of plagioclase laths, which may or may not be orientation (Fig. 23a). Anhedral potash feldspar is a common constituent of the groundmass. Plagioclase crystals, especially the phenocrysts, are frequently altered in varying degree to stubby sericite laths.

There are two types of non-porphyritic andesite—those with flow orientation (Fig. 23b) and those without. Both types bear a striking resemblance to the groundmass of the respective types of porphyritic andesite and it is possible that most of them are derived from such a rock. However, in the coarsest sample (M.1411) there are clasts greater than 5 mm across of non-porphyritic andesite with a flow fabric which suggests this is a distinct rock type. A subordinate clast type consists of an equigranular mosaic of interlocking anhedral plagioclase—in one of these clasts in specimen M.3188.C there is a "vein" of unorientated sheaves of plagioclase laths.

Some of the fragments have rounded amygdales filled with chlorite (Fig. 23c), plagioclase and occasionally epidote. Irregular patches of interstitial glass, usually altered to chlorite, are common. In one specimen, oval blebs of clear chlorite were observed orientated parallel to the flow direction. There is a spectrum of clast types with increasing percentage of glass. In many of these only a few microlites of plagioclase are present in a chloritic matrix (Fig. 23d); this suggests that the elongated areas of chlorite with jagged ends and dark rims, which are commonly found, are altered andesitic glass and represent the end member of a range of textural types.

The existence of a compositional series is suggested by the presence of clasts of quartz-andesite (Fig. 23b), in which plagioclase phenocrysts are set in a matrix of small, euhedral plagioclase crystals, anhedral potash feldspar and variable amounts of subhedral and interstitial quartz.

In all the andesitic types, sphene is a common accessory; small subhedral grains are evenly spaced throughout the rock. It has probably replaced ilmenite.

With an increasing percentage of quartz, these rocks grade into the silicic volcanic rocks, which were identified as rhyolite, dacite and felsite (where the feldspars were indeterminate). Dacitic clasts consist of a fine mosaic of quartz and plagioclase (Fig. 23e), sometimes with large subhedral or rounded quartz grains up to 2.5 mm across. Rhyolite is very rare and revealed in unstained sections by the flow banding.

Other lithic clasts are even-grained polycrystalline quartz; (?) metamorphic quartz–plagioclase rock consisting of a "felted" equigranular mass of altered plagioclase with indistinct grain boundaries and small oval "augen" of quartz; possible basaltic clasts of plagioclase laths in an intersertal texture with chlorite and sphene (? after pyroxene); graphic granite with cuneiform quartz set in large plates of alkali-feldspar; a few epidosite grains; altered skeletal ilmenite; and rare grains with spherulitic texture. Undoubted clasts of metamorphic schist have not been identified.

The crystal fragments are subsidiary in the coarse grades and form the bulk of the fine sand grade. Plagioclase is the main constituent together with a few grains of hornblende and pyroxene. Some of the plagioclase crystals show alteration to radiating aggregates of white mica; detrital white mica is uncommon. Detrital biotite flakes, often partly chloritized, also occur but no rock fragments containing biotite have been noted. In thin section, the cleavage is marked by pressure-solution effects between clastic grains and by limited growth of fine sericite crystals. Clastic mica flakes are bent and deformed around other grains and largely remain orientated parallel to bedding.

Slates and mudstones consist of fine crystal fragments, much opaque material and indeterminate matrix with detrital white mica and biotite flakes. Radiolaria replaced by either prehnite, sodic plagioclase or calcite are common. A new generation of sericite flakes defines a weak slaty cleavage parallel to that defined by pressure-solution effects between clastic grains.

Pumpellyite is found in the coarser grades as minute clusters of granules up to 0.1 mm across and as radiating sheaves growing in quartz (Fig. 23f); it has not been identified in the fine-grained rocks. Prehnite is common throughout, in quartz–prehnite veins and in irregular coarse-grained

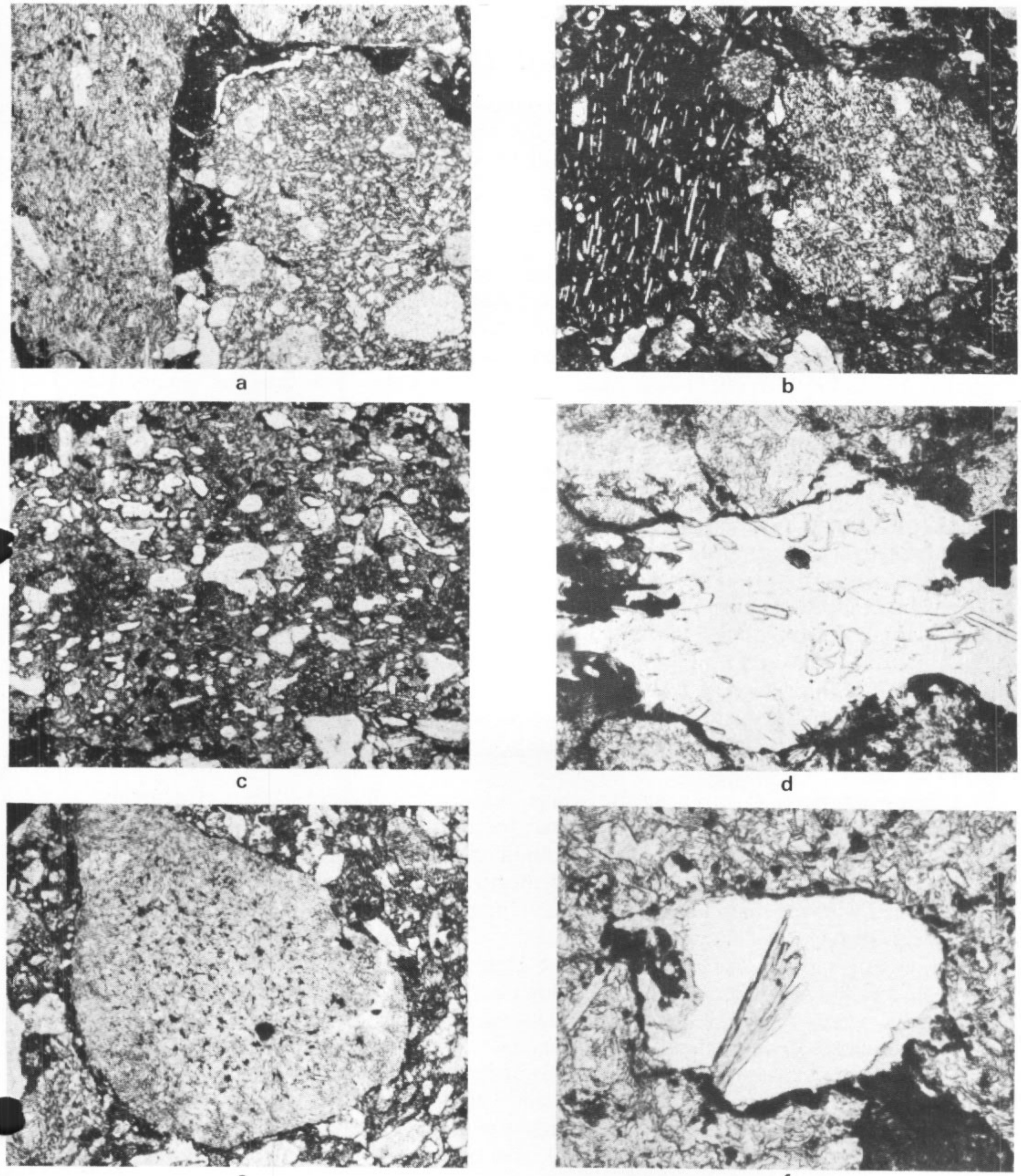


Fig. 23. a. Two clasts of porphyritic andesite, the left-hand one with flow orientation of the plagioclase laths in the groundmass. The right-hand clast is of the non-flow-orientated type (M.2358.3; Fig. 2) (plane polarized light, ×27).

b. Flow-orientated non-porphyritic andesite on the left with plagioclase laths in a groundmass of finely-disseminated opaque minerals, contrasted to a quartz-andesite clast with irregular phenocrysts of quartz in a groundmass of flow-orientated feldspar laths (M.2358.6B; Fig. 2) (plane polarized light, ×27).

c. Part of a clast of amygdalar andesite showing irregular chlorite-filled amygdales, some rimmed with opaque minerals, in a fine-grained groundmass of feldspar and disseminated sphene. The radial structure and central suture can be discerned in the large amygdale at the centre of the field (M.2381.5; Fig. 2) (plane polarized light, ×27).

d. Irregular clast of chloritized glass with plagioclase microlites, rimmed by sphene and ilmenite (M.2381.5; Fig. 2) (plane polarized light, ×100).

e. Clast of dacite showing fine-grained intergrowth of anhedral quartz and feldspar with occasional plagioclase laths and a dusting of sphene (M.3081.4; Fig. 2) (plane polarized light, ×30).

f. Sheaf of pumpellyite growing in recrystallized quartz in an andesite clast (M.2358.6B; Fig. 2) (plane polarized light, ×132).

patches which tend to mask the clastic grain boundaries. Calcite occurs as interstitial grains and small opaque granules are common.

The metamorphic paragenesis is prehnite–albite–chlorite–opaques ± epidote ± pumpellyite ± muscovite.

Discussion

The turbidite-facies rocks which crop out between Cape Darnley and Austin Head probably belong to the youngest part of the Cumberland Bay Formation (Tanner, in press; Fig. 1). We have studied the petrography of these rocks in some detail as nearly all of the previous work on this formation was on material from much lower stratigraphical levels to the north-east (Trendall, 1953, 1959; Winn, 1978; Stone, 1980). Our data show that the Cumberland Bay Formation at these two levels (possibly separated by >5 km of sediment) is remarkably similar both in the type and percentage of detrital fragments, and in general petrography. Cape Darnley–Austin Head rocks contain a higher ratio of andesitic : silicic clasts than the rocks around Cumberland Bay to the north-east. However, considering the difficulties encountered in identifying non-andesitic fragments, further modal analysis of stained thin sections is needed before any conclusions can be drawn from this observation.

A further reason for studying the Cumberland Bay Formation was to look for petrographic similarities between lithic clasts in the formation and igneous rocks in the island-arc assemblage (? source area). Igneous rocks within the Annenkov Island Formation have so far given rather young ages (81–110 Ma; Tanner and Rex, 1979) compared with the probable age range for the Cumberland Bay Formation of 100–150 Ma. However, the uniformity of lithic clasts throughout the latter suggests that igneous activity in the source area may not have changed appreciably in composition over this period and that petrographical comparisons between the two formations may be relevant.

The following comparisons can be made between lithic and crystal fragments in the Cumberland Bay Formation (CBF) and igneous rocks in Hauge Reef and the Pickersgill Islands:

i. Hornblende- and pyroxene-bearing andesite clasts, and isolated green-brown hornblende and pale green pyroxene crystals and plagioclase phenocrysts may be petrographically matched with the main andesite suite on Annenkov Island. These andesite sills and stocks were considered by Pettigrew (1981) to have been intruded contemporaneously with the development of andesitic breccia in the Upper Breccia Member. Ilmenite is common in these andesites together with some epidote; both minerals occur in the CBF.
ii. Quartz occurs as partially resorbed crystals in quartz-andesite (HB Island) and quartz-monzodiorite (Tanner Island); similar crystals occur in the CBF.
iii. K-feldspar occurs in plagioclase crystals as irregular veins and blebs, and in the matrix of both monzodiorite and andesite intrusions in the island-arc assemblage; it also occurs within plagioclase crystals and in the matrix of some andesitic clasts in the CBF.
iv. Biotite, which is rare in the CBF, could have been derived from the biotite-andesites in the island-arc assemblage.
v. Dacite, felsite and rhyolite are the only rock types not represented at the present level of erosion in the island-arc assemblage.

The original composition of clasts in the Cumberland Bay Formation can only be deduced from their relict igneous texture and from the nature of the phenocrysts, as their mineralogy (especially plagioclase composition) has been drastically altered by metamorphism. Dickinson (1970) suggested that microlitic grains are largely derived from intermediate lavas, whereas lathwork grains (plagioclase in intersertal and intergranular textures) mainly represent basaltic lavas. On this basis, a significant proportion of the andesitic fragments which comprise 59–84% of the identifiable clasts (Table V) is probably basaltic. However, as there is a complete gradation in texture between microlitic and lathwork grains, we have not attempted to subdivide these "andesites" and believe that they largely belong to the andesite clan. According to Dickinson

TABLE V. DETRITAL MODES FROM THE CUMBERLAND BAY FORMATION

	*Cumberland Bay area (intermediate volcaniclastics)**		*Cape Darnley–Austin Head†*
	Mean	*Range*	*Range*
Andesitic fragments	60	52–91	60–85
Silicic fragments	17		2–13
Plagioclase	15	4–37	11–30
K-feldspar	0.1	0–1	0–2
Quartz	2.4	0–10	1–5
Ferromagnesian minerals	0.3	0–3	1–3

* Data from Winn (1978, table 1), G.S.A. Depository # 78–3 and Table IV; 37 specimens.
† Data from Table IV.

(1970), andesitic provinces are characterized by detritus with (i) dominantly microlitic grains and subordinate lathwork and felsitic grains, (ii) a high plagioclase/total feldspar ratio, and (iii) nearly complete absence of quartz grains. This description accords precisely with the petrography of the detritus in the Cumberland Bay Formation.

DISCUSSION

It has been proposed by several workers in recent years that South Georgia lies close to the junction between a fossil Lower Cretaceous island-arc assemblage and the turbidite infill of a contemporaneous marginal basin (for summary, see Tanner (in press)). Based on details of the continental side of the same basin in the southern Andes (Bruhn and Dalziel, 1977) and our own work on South Georgia, the possible plate-tectonic configuration of this region during the Lower Cretaceous is shown in Fig. 24.

Two separate sedimentary facies are recognized in the south-western part of South Georgia: the finely banded crystal-lithic tuffs and mudstones of the *mudstone–tuff facies* (probably deposited largely by ash fall from volcanic eruptions, turbulent slurries and re-working by oceanic currents) and the volcaniclastic sandstone–shale rocks of the *turbidite facies* (Fig. 25a). The two facies are possibly equivalent in age (Upper Jurassic–Lower Cretaceous) but no transition is seen between them. They are separated by the Cooper Bay dislocation and in part also by the Drygalski Fjord Complex (Table VI).

The data presented in this paper and independent work by Mair (in preparation) show that oceanic crust (Larsen Harbour Formation) at least in part underlies the mudstone–tuff facies (Annenkov Island Formation). Recognition of the Larsen Harbour Formation as the upper part of an ophiolite complex is based on comparison of field relations, petrology and geochemistry with known ophiolite complexes elsewhere (Mair, in preparation). The immediately overlying sediments (Lower Tuff Member) were considered by Suárez and Pettigrew (1976, p. 312) to have resulted from "undisturbed sedimentation in fairly deep water". We envisage that the mudstone–tuff assemblage formed a narrow apron or shelf along the south-western boundary of the turbidite basin. Sediment was supplied largely by ash fall, down-slope turbidity flow and slumping. This narrow "shelf" was cut by submarine canyons, which supplied detritus to the adjacent turbidite basin, and was probably covered by a depth of water almost equivalent to that in the basin.

By analogy with the southern Andes (Dalziel and others, 1974), oceanic crust was also thought to form part of the floor of the Cumberland Bay turbidite basin (Storey and others,

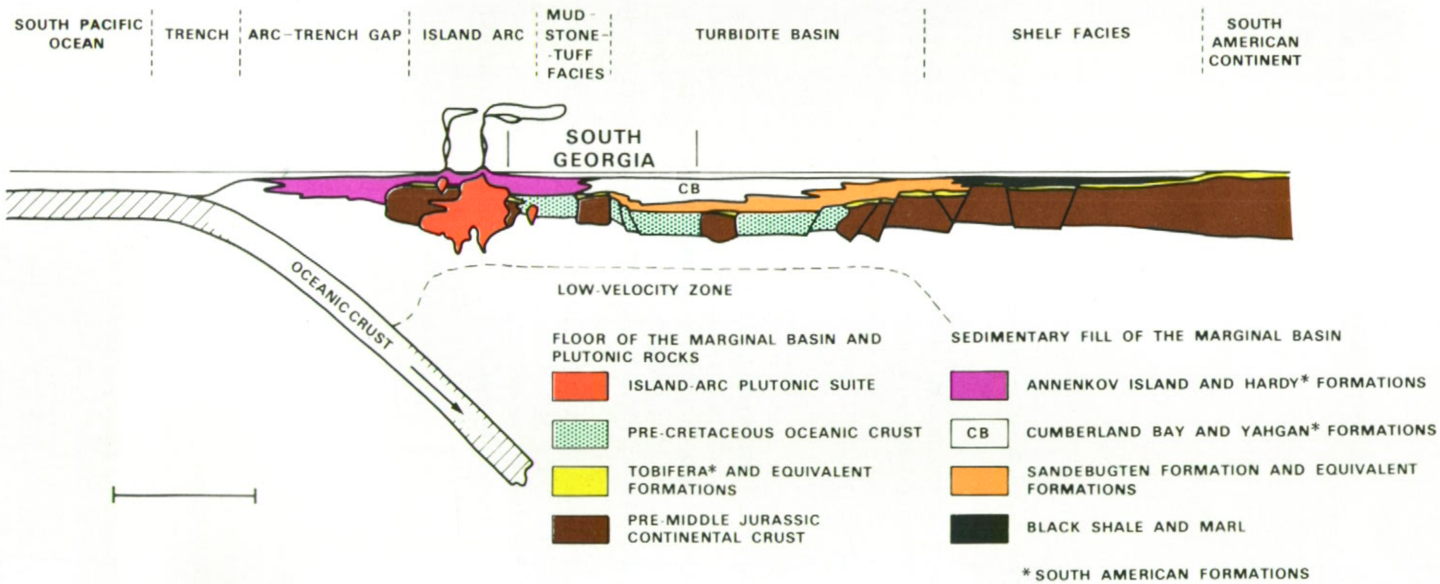


Fig. 24. Plate-tectonic cartoon of the island-arc–turbidite-basin system in the mid-Cretaceous. Details of the South American (eastern) part of the system are modified from Bruhn and Dalziel (1977). The profile is not drawn to scale but the bar represents ~50 km.

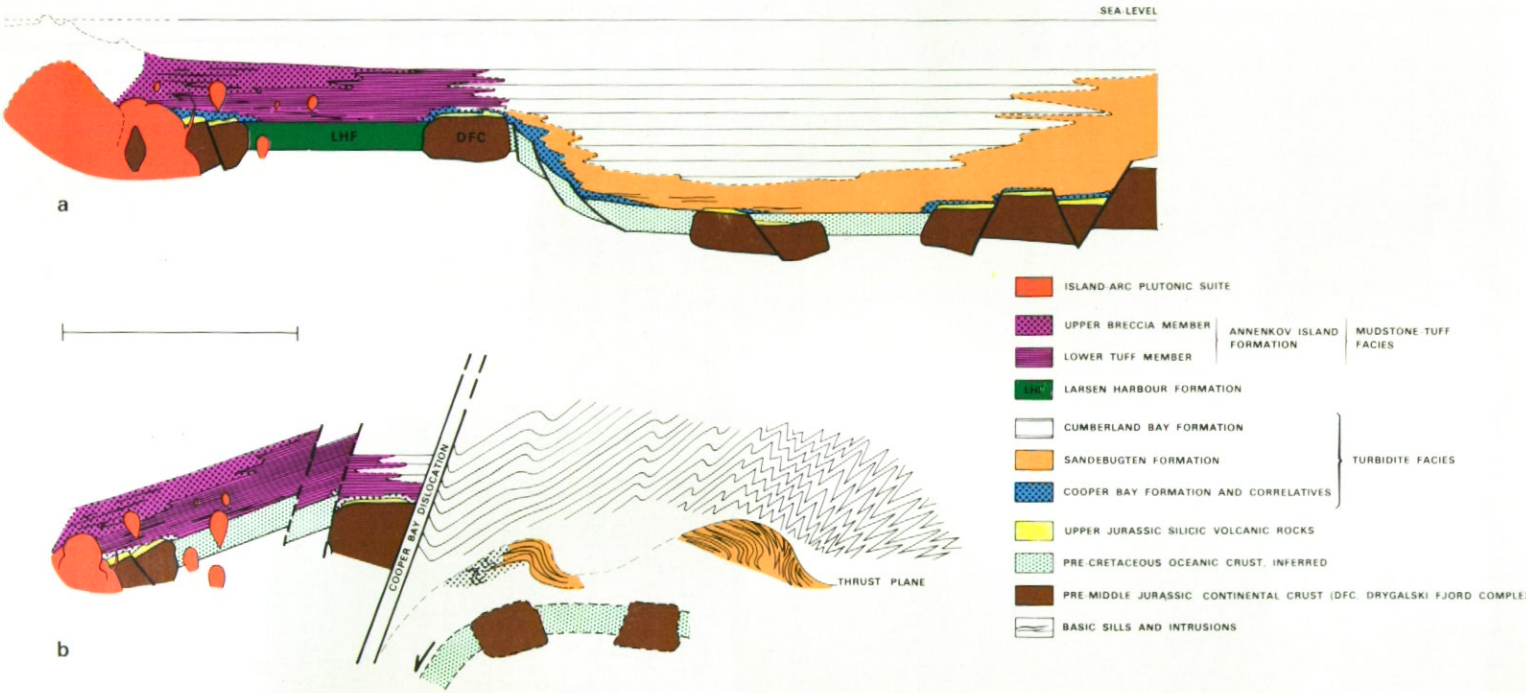


Fig. 25. Schematic reconstructions of the South Georgia area: (a) at the close of sedimentation in the mid-Cretaceous, and (b) after the Andean (lower Upper Cretaceous) deformation. Both profiles are drawn along an approximate line through Annenkov Island and Barff Point (Fig. 1); they are not to scale but the bar represents ~25 km. Lateral relationships between formations have been considerably telescoped for clarity and the island-arc plutonic suite, for example, is situated at a considerably greater distance from the Larsen Harbour Formation than is shown here.

TABLE VI. STRATIGRAPHICAL SEQUENCES ON SOUTH GEORGIA

Mudstone–tuff facies		Cooper Bay dislocation / Drygalski Fjord Complex	*Turbidite facies*	
Annenkov Island Formation ~3 km thick	*Upper Breccia Member* younger than Upper Aptian (< 110 Ma)		*Cumberland Bay Formation* (?) Upper Jurassic–Aptian/Albian; 8–10 km thick	
	—*Conformable contact*—			
	Lower Tuff Member ≡ *Inland Member*, Ducloz Head Formation (?) Upper Jurassic–Upper Aptian			
			—*Thrust contact*—	
			Sandebugten Formation, Cooper Bay Formation, Coastal Member, Ducloz Head Formation	Probably stratigraphically equivalent and of (?) Upper Jurassic to earliest Cretaceous age; thickness unknown
—*Transitional contact*—				
Floor consists of the *Larsen Harbour Formation*, the upper part of an ophiolite complex of Upper Jurassic (pre-140 Ma) age			Floor not seen	

1977). The occurrence of pillowed lava in the Coastal Member of the Ducloz Head Formation and of numerous basic sills in the Cooper Bay Formation suggests either the presence of (?) strips of oceanic crust or of concentrations of basic dykes in the floor of the basin (Fig. 24a). Submarine geophysical work (Simpson and Griffiths, in press) has, however, failed to either refute or give support to these ideas and the nature of the floor is not known. Sediment-dispersal directions in most of the turbidite basin trend west to north-west (Trendall, 1959; Dott, 1974; Winn, 1978; Tanner, in press) parallel to the (?) faulted southern margin; they indicate deposition from turbidity currents originating from a submarine canyon mouth located to the south-east of present-day South Georgia. However, recent work suggests that some of the sediment on the South Georgia mainland north from Cape Darnley was derived from the south-west. There is no strict control on the age of the turbidite basin; the floor is not seen and the oldest fossils are of "Upper Jurassic–lowest Cretaceous" age (Stone and Willey, 1973). Deposition may have begun earlier than in the area of mudstone–tuff deposition and at a time when volcanism was still taking place over the present site of the Drygalski Fjord Complex. The latter could then have been split off from the main volcanic arc during the emplacement of oceanic crust to the south-west.

Both palaeontology (Pettigrew and Willey, 1975) and radiometric dating (Tanner and Rex, 1979) agree on an age of 100–110 Ma (Aptian–Albian) for the lower part of the Upper Breccia Member on Annenkov Island. The underlying Lower Tuff Member is in the order of 3 km thick and appears to rest directly on oceanic crust (Larsen Harbour Formation). As radiometric dating suggests a minimum age of 140 Ma for emplacement of this segment of oceanic crust (Tanner and Rex, 1979), upwards of 40 Ma were available for the deposition of the tuffaceous rocks. In contrast, the Cumberland Bay Formation, which was deposited during approximately the same time span, is at least 8–9 km thick (Tanner, in press). It is everywhere separated from the Annenkov Island Formation by a major fault zone, the Cooper Bay dislocation (Fig. 1). The main dislocation zone is marked by a unit of mylonitized rocks up to 1 km thick along the north-east margin of the Drygalski Fjord Complex (Fig. 1) but fault-bounded, steeply dipping blocks of the Ducloz Head Formation farther north are also probably located within the same general zone.

The Sandebugten and Cooper Bay Formations occur east of the dislocation zone (Fig. 1); they have many petrographic features in common (Stone, in press), in particular high detrital quartz content. They contain basic sills and lenses, have been affected by polyphase deformation and have been metamorphosed to the greenschist facies with the development of stilpnomelane. The Coastal Member of the Ducloz Head Formation (Table VI) has also been compared with the other two units by Storey (in press); it is petrographically similar, also contains basic lenses and has been affected by complex deformation. The Coastal Member contains detrital garnet and biotite, which are rare or absent from the other two formations, and it is of prehnite–pumpellyite facies. Storey has suggested that it was deposited during the development of the probable rift-zone precursor (Suárez and Pettigrew, 1976; Bruhn and others, 1978) to the marginal basin and was derived from erosion of continental crust and overlying acid volcanic rocks (? Tobifera Formation) on the island-arc (Pacific) side of the basin.

Although there is no palaeontological or radiometric evidence for the age of the Sandebugten Formation (Thomson and others, in press), Cooper Bay Formation or Coastal Member, we infer that deposition of these units began before that of the Cumberland Bay Formation (Table VI; Fig. 24a); they are now separated from it by major tectonic breaks (Fig. 24b). The Sandebugten Formation was previously considered to have been derived from Jurassic silicic volcanic rocks (Tobifera Formation) and sediments on the northern (continental) side of the marginal or back-arc basin (Dalziel and others, 1974; Winn, 1978) (Table VII). However, a significant part of the formation may have been derived from the same island-arc side of the marginal basin (? Drygalski Fjord Complex) as the Coastal Member of the Ducloz Head Formation (Storey, in press), and published palaeocurrent data from the Sandebugten Formation (Dott, 1974; Winn, 1978) do not exclude this possibility.

On South Georgia the main "Andean" orogenic event took place in the mid-Cretaceous around 80–90 Ma (Thomson and others, in press). During this event the Larsen Harbour Formation and its overlying thin cover of volcaniclastic tuffs and breccias (Annenkov Island Formation) was gently tilted to the west and fractured but remained undeformed internally (Fig. 25). A major fault movement developed along the pre-existing (? fault-controlled) junction between the two facies and elements of both the mudstone–tuff (Inland Member, Ducloz Head Formation) and turbidite (Coastal Member) facies are preserved within the fault zone. The presence of finely banded tuffaceous rocks equivalent to the Lower Tuff Member *east* of the rocks equated with the Sandebugten and Cooper Bay Formations suggests that the Lower Tuff Member may have been continuous (at a high structural level) across the junction of the two facies and overlain, or interdigitated with, the Cumberland Bay Formation. Lateral movement may have accentuated the contrast in sedimentary facies now seen across this zone.

Deformation within the Cumberland Bay Formation increases progressively north-eastward

TABLE VII. COMPARISON OF STRATIGRAPHICAL SEQUENCES ON SOUTH GEORGIA AND IN THE SOUTHERN ANDES

South Georgia	*Southern Andes*	
Annenkov Island Formation	Hardy Formation	Upper Jurassic or earliest Cretaceous to Aptian/Albian sediments
Cumberland Bay Formation, Sandebugten Formation and correlatives	Yahgan Formation	
Larsen Habour Formation	Tortuga Complex	Ophiolite complex
?	Tobifera Formation	Middle to Upper Jurassic silicic volcanic suite

away from the Cooper Bay dislocation; upright folds associated with poorly developed cleavage pass to folds with inclined axial planes and pronounced slaty cleavage (Tanner, in press). Parallelism between the axial trace (and probably the axial surface) of the Austin Head syncline and the Cooper Bay dislocation (Fig. 2) suggests a common causal relationship. The geometry of the folds within the formation suggest that deformation of the turbidite sequence has been achieved by subduction of part of the floor of the turbidite basin beneath the island arc and adjoining shelf (Fig. 21b), a suggestion first made for the southern Andes by Dalziel and others (1974) but later refuted (Bruhn and Dalziel, 1977) on the premise that the mafic floor had remained autochthonous. The underlying Sandebugten Formation has been affected by more intense polyphase deformation (Stone, 1980) and is everywhere separated from the Cumberland Bay Formation by a major thrust plane (Dalziel and others, 1974; Stone, 1980; Tanner, in press).

Correlation with the Southern Andes

The relationships described above from South Georgia may be an important feature of the marginal basin in the southern Andes. An extensive belt of pillow lava occurs between the Patagonian batholith and the outcrop of the Yahgan Formation in the area south of Tierra del Fuego (Suárez and Pettigrew, 1976) and is overlain by, or associated with, undeformed or weakly deformed members of the Hardy Formation. The Hardy Formation was equated with the Annenkov Island Formation by Suárez and Pettigrew; it includes acid volcaniclastic rocks and rhyolites not seen in the equivalent sequence on South Georgia. The unit of pillow lava and finely banded volcaniclastic rocks occupies a position along the south-western (Pacific) side of the marginal basin analogous to that of the Larsen Harbour and Annenkov Island Formations on South Georgia. There is an abrupt change northward from rocks of the Hardy Formation to folded turbidite-facies rocks (Yahgan Formation) which are identical in most respects to the Cumberland Bay Formation.

The nature of the boundary between the Hardy and Yahgan Formations has not been described and basement rocks (cf. Drygalski Fjord Complex) appear to be absent except for the pre-Jurassic granitic gneisses reported by Suárez and Pettigrew (1976, p. 311). We suggest that two separate depositional zones may be recognized in the southernmost part of the southern Andes: (i) a western zone of relatively undeformed volcaniclastic and volcanic rocks <1.3 km thick (Suárez and Pettigrew, 1976) overlying oceanic crust, and (ii) an eastern zone consisting of a thick (7–8 km; Winn and Dott, 1978) sequence of turbidite-facies rocks which has been strongly folded. The Tortuga Complex is part of an ophiolite sequence which is generally considered to underlie the Yahgan Formation (De Wit and Stern, 1978); however, the entire Yahgan Formation exposed to the north of it dips southward (Katz and Watters, 1966) with the uppermost stratigraphical levels in south-western Isla Navarino (Winn, 1978) occurring due north of the complex. The contact between Yahgan Formation sediments and rocks of the Tortuga Complex is not exposed and is probably fault-controlled (Suárez and Pettigrew, 1976). Thus, from available published field data it is equally likely that the Tortuga Complex is part of unit (i) and that the true floor of the marginal basin beneath the Yahgan Formation is nowhere seen in the southern Andes.

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