THE LARSEN HARBOUR FORMATION AND ASSOCIATED INTRUSIVE ROCKS OF SOUTHERN SOUTH GEORGIA

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ABSTRACT. The Larsen Harbour Formation is a tilted but undeformed sequence of pillow lavas, stratiform breccias, volcanogenic sediments and rhyolites; it is thought to represent a strip of Mesozoic oceanic crust formed during the development of a marginal basin within the continental margin of Gondwanaland. The formation has undergone greenschist metamorphism associated with the oceanic environment of emplacement. The spilitic affinity of these rocks is discussed but it is suggested that the lavas and associated basic rocks are better classified as metabasalts than as true spilites. A high-level "tonalite" body intrudes the lava sequence and is itself cross-cut by later swarms of basic dykes. Zones with abundant single and multiple dykes are thought to represent former spreading centres in the oceanic crust. A detailed account of the mineralogy of the lavas and intrusive rocks is given and an original map of the geology of the southern part of South Georgia is presented.

THE greater part of South Georgia (lat. 54°20′S, long. 36°40′W) consists of folded greywackes (Trendall, 1953) with an igneous complex and a sequence of basic lavas restricted to the southern part of the island (Fig. 1). Holtedahl (1929) commented on these lavas, first discovered by Heim (1912), and noted that "the geology . . . is of a complicated nature, and its elucidation requires a detailed survey. We seem to be dealing with a complex of effusive rocks and altered lavas intruded by sheets that sometimes cut the plane of bedding." This "detailed survey" was carried out during the austral summer of 1974 and 1975 by geologists of the British Antarctic Survey (Bell and others, 1977). The following account deals in greater detail with the pillow lavas and associated rocks of the southern part of South Georgia, especially their petrology and field relationships, and expands the preliminary work undertaken by Trendall (1959). The lava sequence, recently named the Larsen Harbour Formation by Bell and others (1977) comprises intrusive dyke swarms cutting units of pillow lava, interstratified breccia and volcanic sediment (Figs 2 and 3), which are structurally undeformed, dip on average to the south-west at 23° and have undergone low-grade regional metamorphism causing spilitization of certain members of the sequence.

Topographically, the southern corner of South Georgia has a deeply indented coastline, adjacent bays and fjords being separated by steep-sided ridges up to 600 m high and the inner reaches of bays usually terminating in small but active valley glaciers. An overall glacial erosion platform is evident at around 600 m, termed "Gipfelflur" by Holtedahl (1929), and this has been dissected by subsequent action of valley glaciers. Prominent peaks of about 1 200 m stand out above the dissected plateau surface. Holtedahl (1929) attributed the differing topography of this area to the igneous nature of the underlying rock, thus contrasting markedly with most other areas of South Georgia.

LARSEN HARBOUR FORMATION

The Larsen Harbour Formation is a thick sequence of basic pillow lavas, stratiform breccias, massive and amygdaloidal lavas, and subordinate acidic extrusive rocks within which the pillowed types are the most abundant. As well as the extrusive rocks, the formation includes the numerous suites of basic dykes which cross-cut the lava flows, and some of them may represent feeders to the lava sequence as it was extruded.

Pillow lava

Pillow lavas crop out along the western shores of Drygalski Fjord, Brandt Cove, Larsen Harbour, Doubtful Bay and western Smaaland Cove (Fig. 2). Their features and orientation

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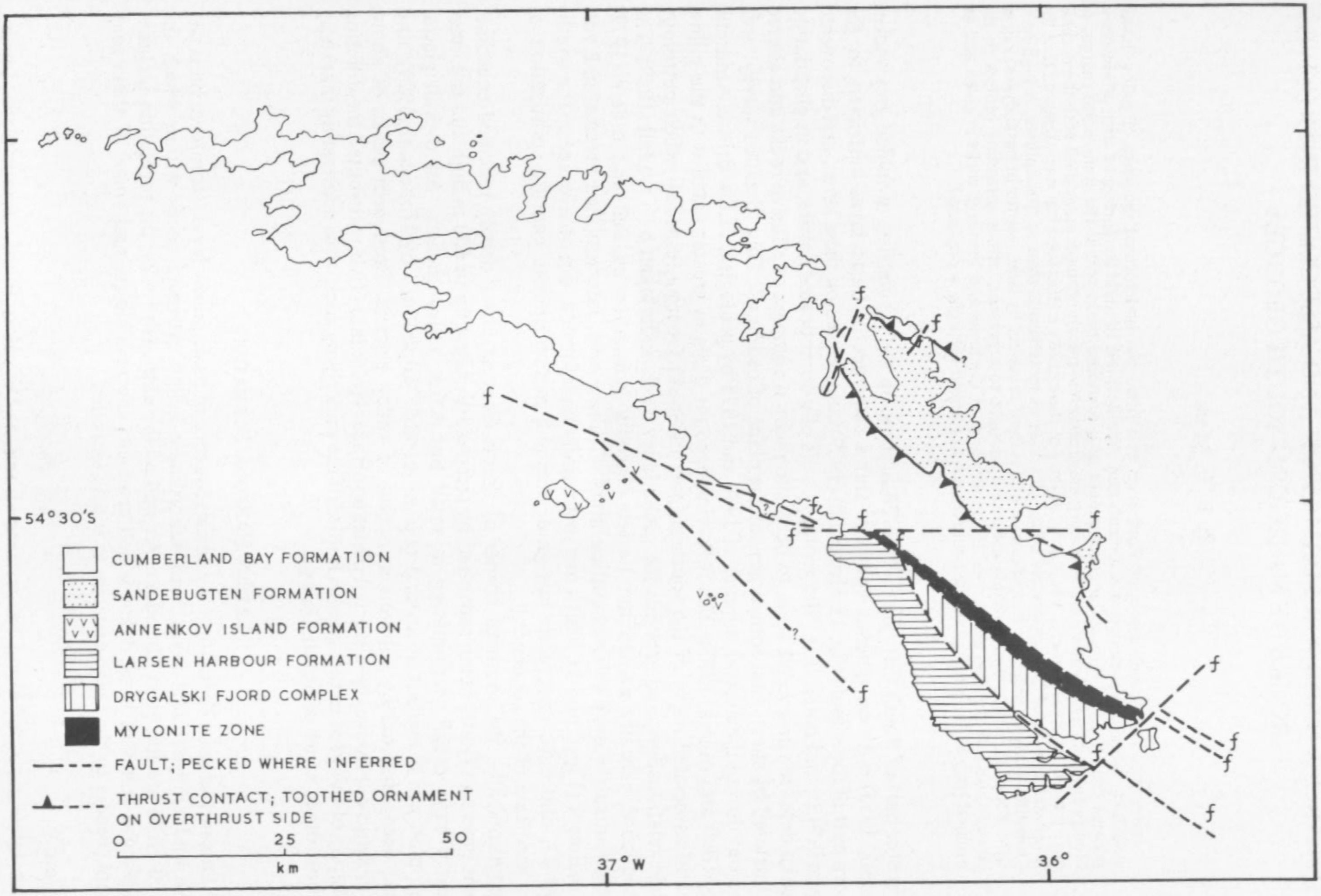

Fig. 1. Simplified geological sketch map of South Georgia showing the area of detailed study.

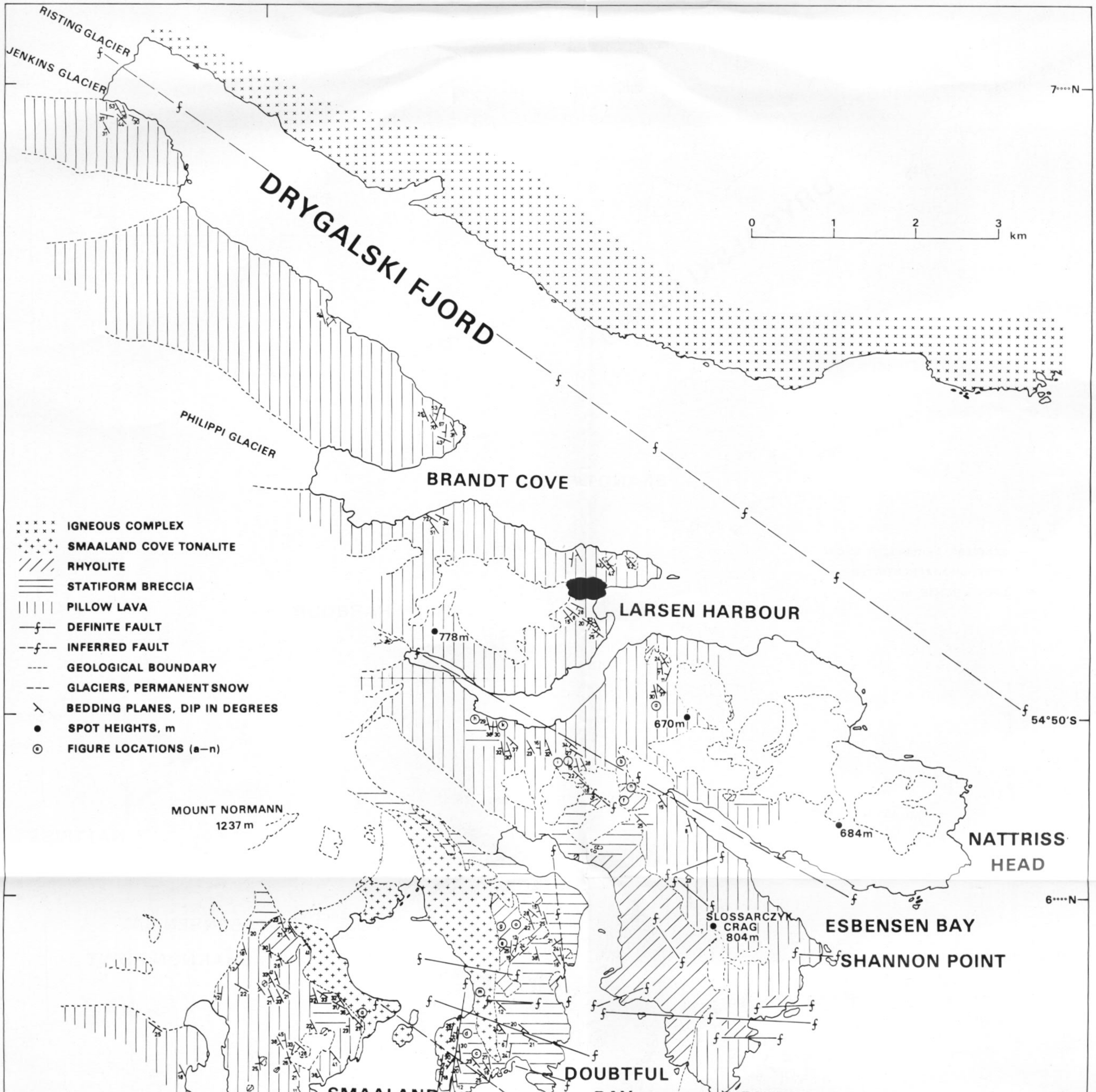

Fig. 2. Detailed geology of the area south-west of Drygalski Fjord, southern South Georgia.

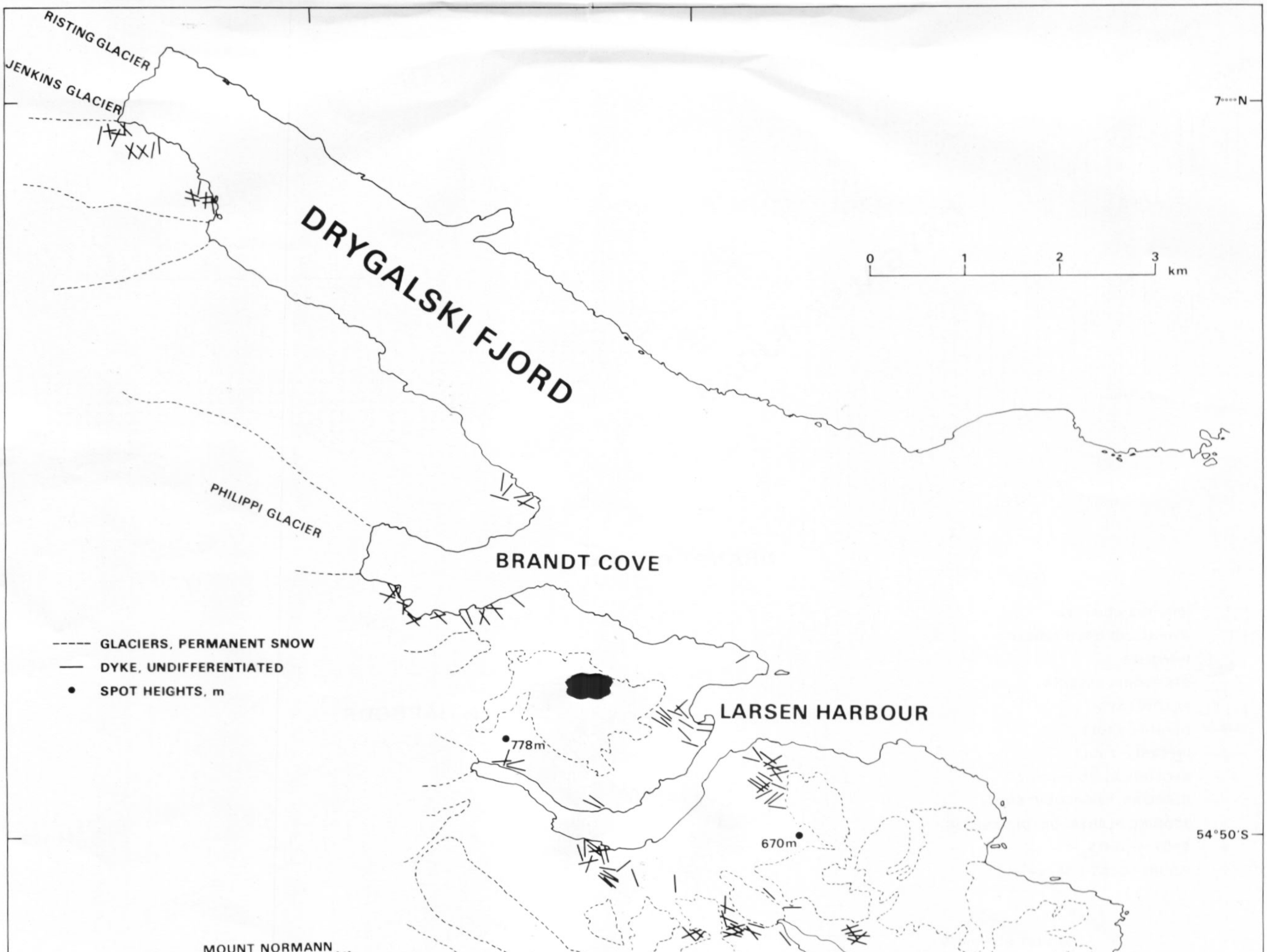

Fig. 3. Dyke orientations within the Larsen Harbour Formation.

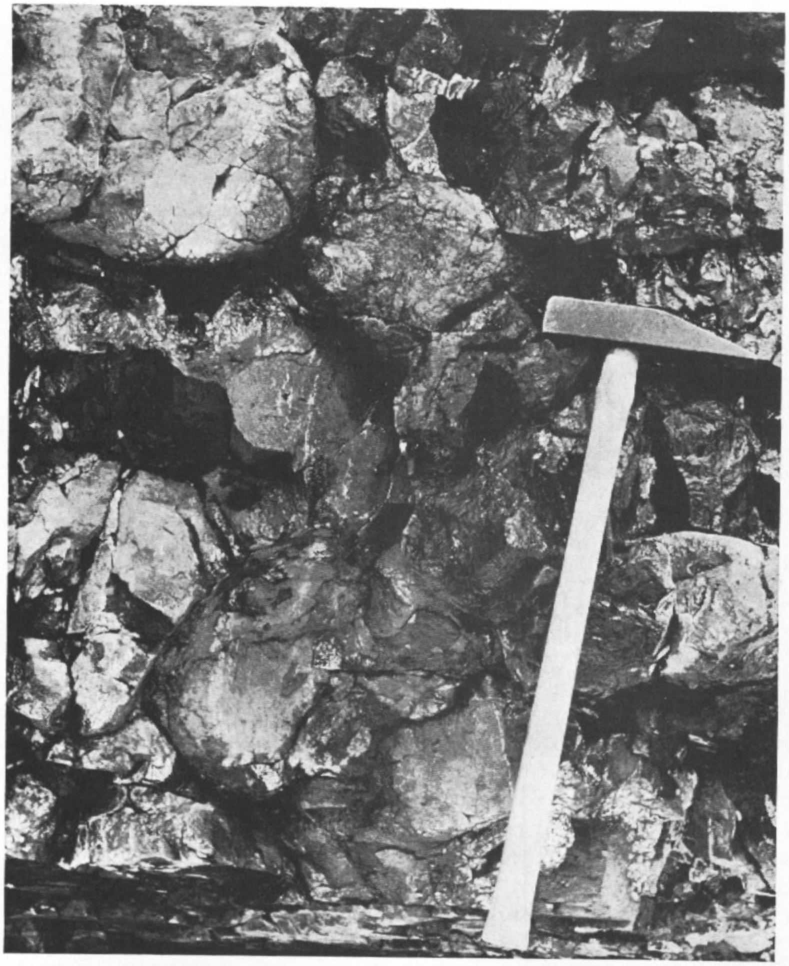

Fig. 4. Poorly sorted pillow lava; Larsen Harbour (Fig, 2, locality a). The hammer shaft is 60 cm long.

were originally described by Trendall (1959, figs 15 and 16), who recorded that they were part of a steeply dipping, apparently folded sequence but the field work reported here has established that they are in fact undeformed and dip gently towards the south-west. Flow planes are delimited by lenticular units of chert and volcanogenic sediment. Inter-pillow boundaries are sharp, each pillow existing as a separate unit usually characterized by a domed top and indented base produced during settling of the flow after extrusion. On average, the pillows measure 40 cm along their long axis and have a length:width ratio of approximately 5:2 (Fig. 4). Internally, the pillows are generally amygdaloidal and vesicular; a concentric arrangement of tubular amygdales reported by Trendall (1959, fig. 16b) is rarely seen but such amygdales found within pillows are usually at right-angles to the base of the pillow and transgress the concentrically banded interior. Generally, the pillows are dark grey-green in colour with a darker, almost black, chilled outer margin; subsequent alteration of the pillow may produce a bright lime-green core indicative of extensive epidotization (Fig. 5). Individual flows of pillow lava are up to 10 m thick and complete sequences have been estimated to be over 100 m in thickness.

Fig. 5. Tubular and spherical amygdales within the altered core of a pillow; col between Doubtful Bay and Larsen Harbour (Fig. 2, locality b). The hammer shaft is 60 cm long.

The pillow lavas have a fine-grained matrix of plagioclase laths, opaque minerals, alteration products and infilled vesicles or amygdales. Any remnants of former basaltic glass appear to have been altered completely. A variolitic texture is developed to a varying extent throughout the pillows but it usually consists of radiating clusters of small (< 0.5 mm) bifurcating plagioclase laths of square cross-section and compositionally zoned interior. Their small size precludes accurate determination of the variation in composition but average compositions obtained indicate that the feldspars are oligoclase-andesine. Where a variolitic texture is not developed, the laths are randomly dispersed throughout the matrix and tend not to show the typical fluidal arrangement seen in the amygdaloidal lava types. Larger atypical oligoclase-andesine and rarely more albite-rich phenocrysts are present, ranging from 0.35 to 0.75 mm within the matrix and they also have zoned margins. Their length : width ratio is of the order of ten times rather than 20 as for the laths in the matrix.

The matrix contains a high percentage of opaque minerals which show a specific concentration around amygdales and fractures in the rock and are generally larger in such zones. Pyrite is common as euhedral cubes throughout the matrix and it is usually visible both in the hand specimen and in thin section. Ilmenite forms skeletal intergrowths and irregular crystals, and may form the greater part of the opaque minerals present, although it is possible that the numerous minute opaque granules disseminated throughout the matrix are of magnetite.

Clinozoisite is a common matrix mineral and forms an interlocking mosaic of subhedral crystals around the plagioclase laths, opaque minerals and amygdales. Penninite, showing anomalous birefringence, is found in close association with the clinozoisite and commonly with acicular needles and subhedral crystals of actinolite. In some instances, the actinolite appears to be a pseudomorph after pyroxene. Irregular patches of a carbonate mineral occur in the matrix; minor quartz is present as irregular grains and is common as an amygdale infilling.

The amygdales are usually spherical (1.5–3.0 mm) and they are infilled with chlorite, epidote, quartz and actinolite in varying combination. The chlorite is either penninite or clinochlore, often overgrown by thin needles of actinolite. The epidote is pistacite in contrast to the iron-poor epidote of the matrix.

Mineralogy and feldspar composition of the pillow lavas suggest that they were originally basaltic but with a lower anorthite content than normal, and that they now display a spilitic assemblage. The pillow lavas from Larsen Harbour were first called spilites by Trendall (1959) and Pettigrew (1975) classified basalts on nearby Annenkov Island as spilites.

The term "spilite" implies a specific mineral association, that is, albite-chlorite in close association with epidote, calcite, pumpellyite, prehnite, sphene, actinolite and haematite (Battey, 1956, 1974; Coombs, 1974). Such minerals are also typical of low-grade zeolite- or greenschist-facies metamorphism and it has been suggested that such assemblages are produced by burial metamorphism of a submarine lava, presumably at low pressures and high temperatures deemed characteristic of oceanic crust in marginal basins (Packham and Falvey, 1971). Cann (1970, 1974) proposed a model for oceanic crustal structure with a layered sequence of metamorphic facies, increasing in grade with depth from unmetamorphosed pillows at the surface through clay-mineral to greenschist facies within the lower pillow lava units. In con-

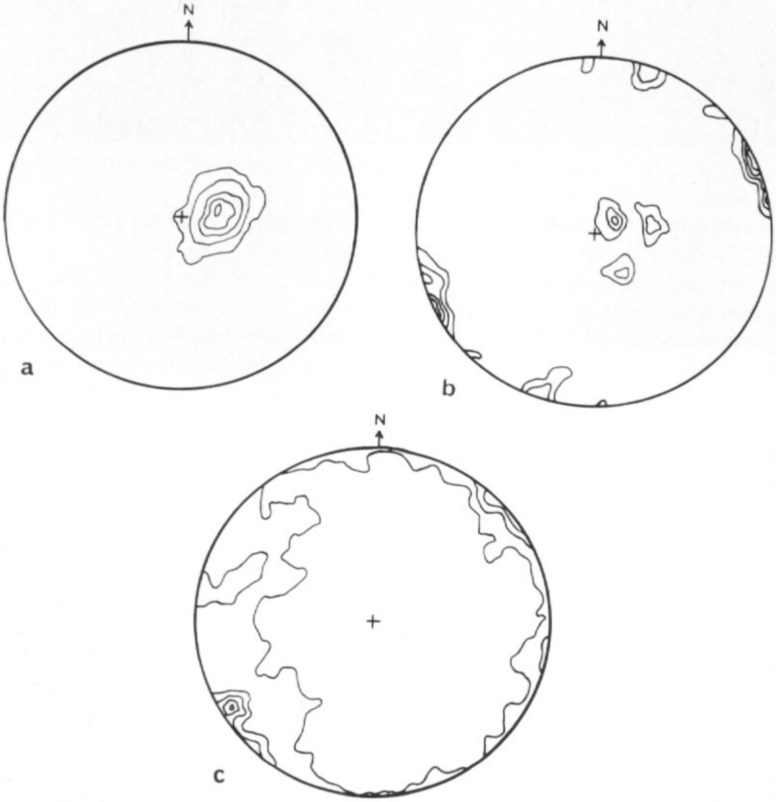

Fig. 6. Equal-area stereographic projections on the lower hemisphere of poles to: a. Bedding (150 points); b. Faults (45 points); c. Dykes (500 points).

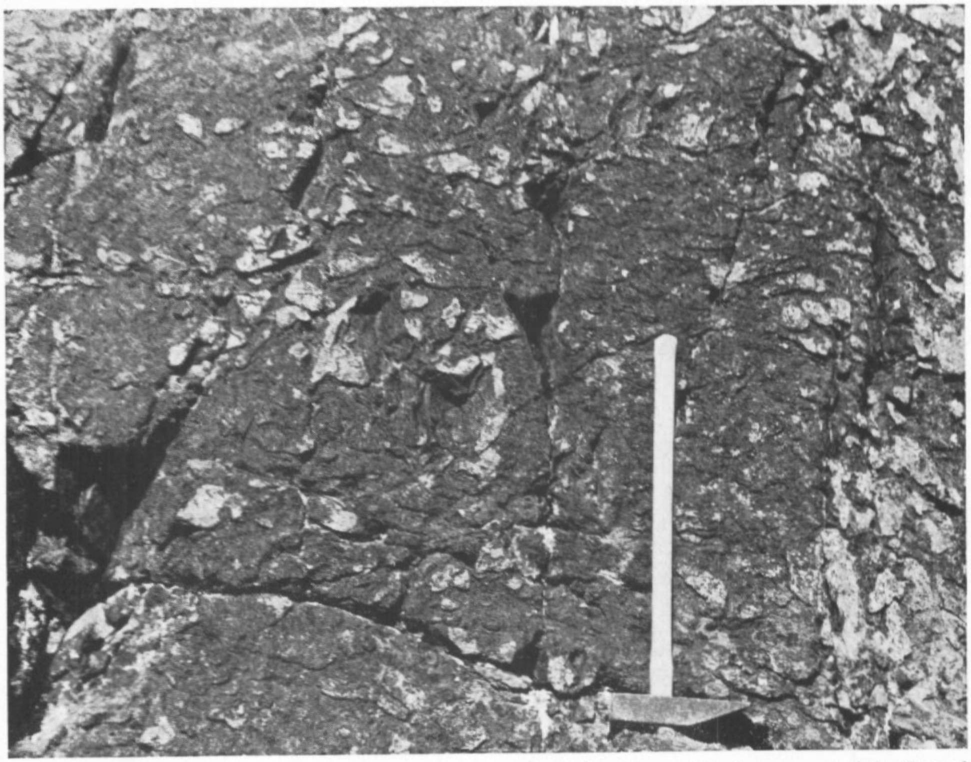

Fig. 7. Sequence of stratiform breccia; Smaaland Cove (Fig. 2, locality c). The hammer shaft is 60 cm long.

junction with entrapped fluids in the lava pile this "oceanic metamorphism" of basaltic pillow lava is thought to have produced the spilitic assemblage.

Feldspar compositions obtained from the pillow lavas of the Larsen Harbour Formation are mainly oligoclase-andesine and minor albite-oligoclase. Trendall (1959) recorded feldspars of albite-oligoclase composition from pillows within Larsen Harbour. The apparent deficiency of albite in the pillow lavas is atypical of a spilite assemblage; however, the presence of predominantly sodium-rich feldspar indicates that the process of spilitization, causing alteration of originally calcic feldspar to sodic feldspar has been arrested before completion. It is suggested that the spilites of South Georgia have a metamorphic origin and that they can be regarded more accurately as metabasalts. Further work is necessary before classifying the pillow lavas and associated rocks as spilites in the true sense.

Stratiform breccia

This rock unit, previously referred to as "breccia" by Bell and others (1977), forms an important part of the Larsen Harbour Formation and crops out over much of the promontory between Smaaland Cove and Doubtful Bay and within the pillow lavas west of Smaaland Cove (Fig. 2). Bedding-plane measurements from the stratiform breccia are consistent with those from the interbedded volcanogenic sediments recorded elsewhere in the formation (Figs 6a and 7).

The breccia consists of irregular, lensoid, dark amygdaloidal fragments of basaltic character, 2–15 cm long, set in a fine-grained or agglomeratic, massive or laminar matrix (Fig. 8). The basaltic fragments are amygdaloidal and unaltered, having an isotropic matrix of glassy character with no coloured silicates present and abundant zeolite, thought to be stilbite, infilling

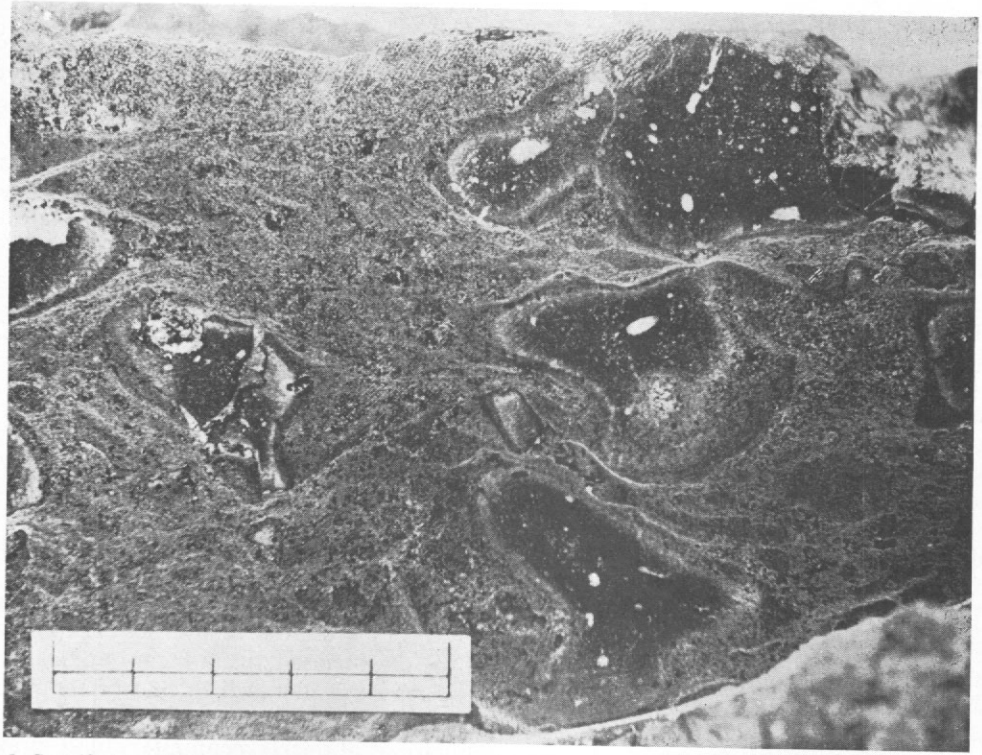

Fig. 8. Stratiform breccia containing dark, fresh amygdaloidal basaltic xenoliths with altered rims within an altered hyaloclastite matrix (Fig. 2, locality d). The scale is in centimetres.

the amygdales. The margins of the xenoliths are often altered and lose their original texture, gradually becoming incorporated into the enclosing matrix. In places, where the breccia overlies flows of pillow lava, it includes whole or fragmented pillows within its basal zone. The matrix, of prominent green coloration, appears to consist entirely of alteration minerals such as chlorite, epidote and clinozoisite, probably formed after the break-down of the enclosed unaltered xenoliths. Remnants of the original amygdaloidal xenoliths are seen to be thoroughly assimilated within the altered matrix. A crude flow structure is outlined in the matrix by the alignment of small plagioclase laths and elongation of the relict amygdales.

Assimilation of the xenoliths has taken place during their emplacement within the enclosing matrix, by chemical processes as well as by initial fragmentation on extrusion. Heat must have been retained by the magma following eruption to allow assimilation to take place. If the magma was erupted into wet unconsolidated sediment, it would have produced hyaloclastites on its peripheral surfaces which would thermally insulate its interior, thus maintaining temperature to assist flow and cause subsequent alteration (McBirney, 1963). Transport of the hot hyaloclastite debris within a fluid medium would produce a stratiform breccia, equivalent to the hyaloclastite breccia defined by Silvestri (1963). The presence of whole or fragmented pillows in the basal zones of the stratiform breccia represent local re-working of previously extruded pillow-lava flows by mobile hyaloclastite material. Such basal units can be referred to as pillow breccias after Silvestri (1963). The irregular occurrence of the stratiform breccia within the Larsen Harbour Formation is probably due to the uneven upper surface of earlier lava flows, on which the breccia would be produced and eventually deposited.

Massive and amygdaloidal lavas

Basic massive and amygdaloidal lavas comprise only a small part of the Larsen Harbour Formation and crop out sporadically in the pillow lava and stratiform breccia sequence. Both types cover insufficient area to be recorded as separate units on the geological map. They occur as thin flows within the pillow sequence, have indistinct boundaries and resemble sill-like intrusions. Total thicknesses are thought not to exceed several metres. The greater abundance of large well-defined amygdales is the main difference between the two types as their matrices are mineralogically similar.

The massive lavas resemble fine-grained dyke rocks in the hand specimen but they have a very different mineralogy. They are dominantly green, fine-grained and frequently agglomeratic, containing xenoliths of various basic lavas. In thin section they are microscopically amygdaloidal but on a much finer scale than the true amygdaloidal lavas. The groundmass is composed of abundant granular opaque minerals, lath-like feldspar, chlorite, actinolite, epidote and quartz. The feldspar laths average 0.3 mm in length and are of andesine (An$_{31-35}$). Each lath appears to be surrounded by an alteration rim of either sericite or epidote. A crude fluidal alignment of the laths is evident and this is also emphasized by the opaque minerals present. The epidote and chlorite of the groundmass form a felted aggregate, often nearly isotropic and cross-cut by acicular actinolite. Minor quartz is present, especially in the more altered rocks, and disseminated carbonate is common in close proximity to the opaque minerals. Euhedral apatite occurs in the matrix.

The amygdaloidal lavas are similar to the massive lavas except for the presence of numerous infilled amygdales, averaging 2.5 mm in diameter. They are often of a lensoid shape due to flow alignment and parallel the fluidal texture of the plagioclase laths in the groundmass. The laths (0.25–0.74 mm) are andesine (An$_{31-38}$). The matrix is identical to that of the massive lavas except for the irregular ragged sphene crystals found within it and in the enclosed amygdales. The amygdales contain various combinations of quartz, penninite, radial sprays of epidote and lath-like actinolite. It is thought that these minerals are replacements of former zeolites which occur in the fresh unaltered basaltic xenoliths of the stratiform breccia.

Rhyolite

The rhyolites are not confined to any particular level within the lava sequence and have an apparently random distribution (Fig. 2). They include the truly extrusive flow-banded rhyolites (Fig. 9), as well as massive acid intrusives (Fig. 10) but both have essentially the same mineralogy. Flow banding and associated flow folding is well defined in the extrusive rocks and is generally locally discordant with the regional bedding. Flow alignment of infilled amygdales is a common feature of both extrusive and intrusive rhyolites. Basal and peripheral regions of rhyolite bodies, where they are not flow banded, are often agglomeratic and consist of reworked, angular rhyolitic fragments of differing type and of xenoliths of earlier extruded basic lavas.

Rhyolite outcrops are up to 100 m wide but they are generally smaller and irregular in shape. The largest bodies, thought to represent centres of rhyolitic activity, crop out in Doubtful Bay and Smaaland Cove. Contact between the rhyolites and the enclosing basic lavas are diffuse and often obscured by later basic dyke intrusions. In general, the flow-banded and the massive rhyolites are light-coloured, porphyritic, of a dense cherty nature and often extensively discoloured by iron staining.

Massive rhyolite. In thin section the massive rhyolite is fine-grained, crystalline, porphyritic to varying degrees and amygdaloidal. Xenoliths within the agglomeratic types are distinguished by differences in grain-size, mafic content and phenocrysts from the surrounding matrix, which is composed of similar rhyolitic material. Quartz is the main constituent of the groundmass,

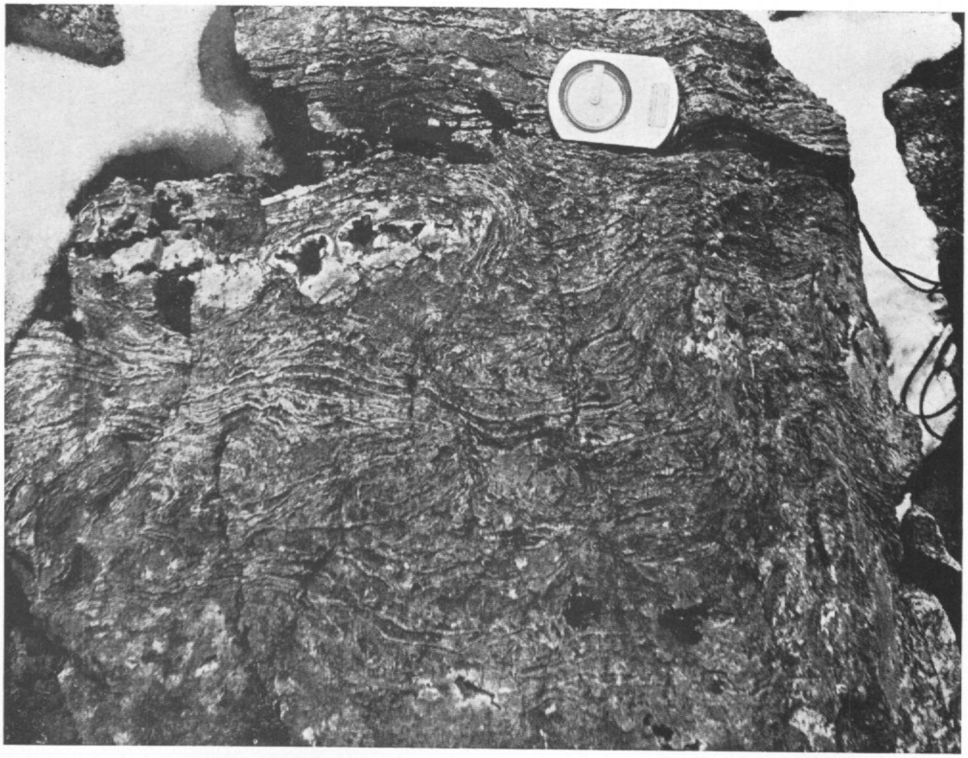

Fig. 9. Flow-folded and banded rhyolite; ridge above Smaaland Cove (Fig. 2, locality e). The compass is 7·5 cm long.

being present as euhedral phenocrysts in the porphyritic rhyolites and as granophyric intergrowths with alkali feldspar in the groundmass. The latter are less regular than those found in the coarser-grained tonalite body. The phenocrysts show recrystallized margins and are often embayed as though corroded but such cuspate forms have been attributed to irregular amoeboid growth of the quartz crystals (Moorhouse, 1959, p. 207).

Alkali and plagioclase feldspar occur both in the groundmass and as phenocrysts, often showing extensive alteration to sericite or epidote. No composition determinations were possible due to the fine grain-size, and the relative amounts of the different feldspars were not established. Microlitic laths of feldspar define flow alignment by fluidal arrangement around included xenoliths. Epidote is the most prominent ferromagnesian mineral, both as small irregular crystals in the matrix and as coarse crystal aggregates apparently pseudomorphing earlier mafic minerals. Chlorite, usually penninite in association with epidote, is dispersed throughout the matrix and infills amygdales in combination with epidote, carbonate and quartz. Carbonate is disseminated throughout the matrix as well as infilling amygdales. Well-formed cubes of pyrite and granular magnetite are common, often being concentrated around amygdales. Accessory apatite is present in small amounts.

Flow-banded rhyolite. These rocks are readily identified by their well-defined flow banding which consists of alternating, < 2 mm laminae of epidote and quartzo-feldspathic minerals (Fig. 11). The ragged crystal aggregates of epidote transgress from one lamina to another but they are concentrated in specific bands. The quartzo-feldspathic bands consist of a mosaic of finely disseminated calcite and sericite as well as quartz and feldspar; minute amygdales are

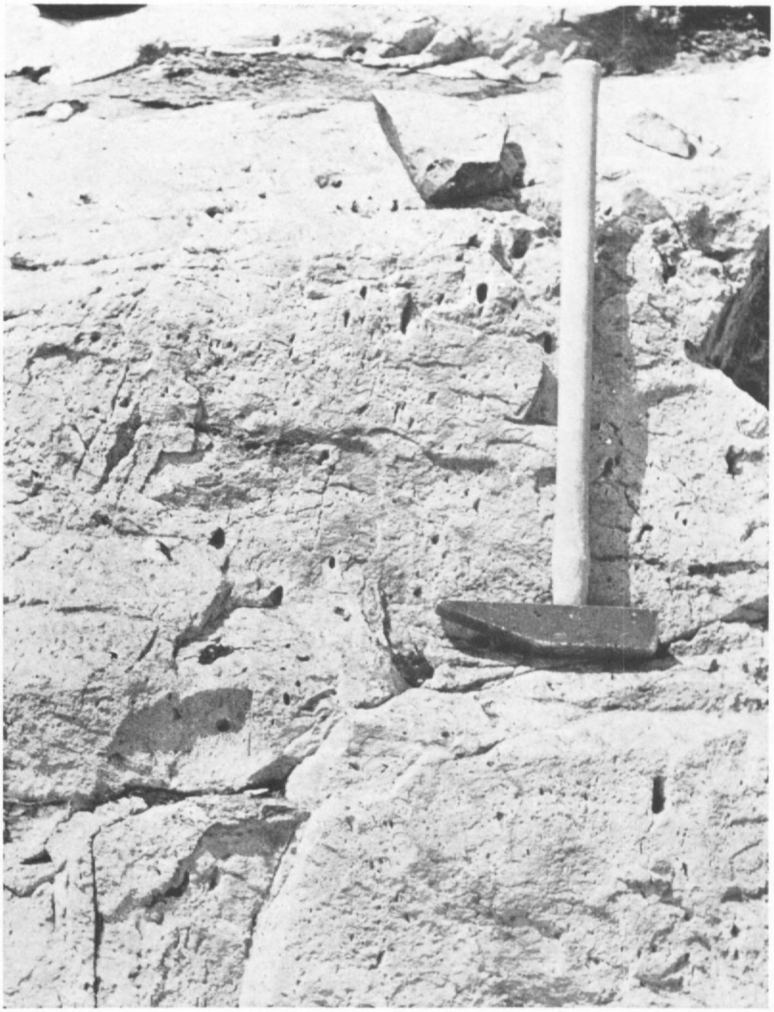

Fig. 10. Massive, flow-aligned amygdaloidal rhyolite; Doubtful Bay (Fig. 2, locality f). A basic dyke intrudes the rhyolite. The hammer shaft is 60 cm long.

infilled with calcite and chlorite, usually penninite. The lack of opaque and ferromagnesian minerals is a notable feature of the rhyolites in general.

The acid lavas were emplaced contemporaneously with the basic extrusive rocks of the Larsen Harbour Formation and are cut by the Smaaland Cove intrusion and by later basic dyke swarms. Their crystalline rather than vitreous nature indicates a slow rate of cooling and the abundance of fragmental material suggests that they were emplaced under a thin cover. By maintaining the temperature of the flow during extrusion, flow banding could be produced in a submarine environment. The irregular flow surface of basic lavas and water-saturated sediment, on to which the rhyolites were extruded, was responsible for local changes in their mode of emplacement. Some rhyolites were extruded normally giving concordant boundaries with the underlying lavas, whereas others may have been intruded as thin sills or dykes under a thin cover of unconsolidated sediment or lava, producing discordant contacts with the adjacent rocks. Such variation in the rhyolites occurs within spatially restricted areas. It is

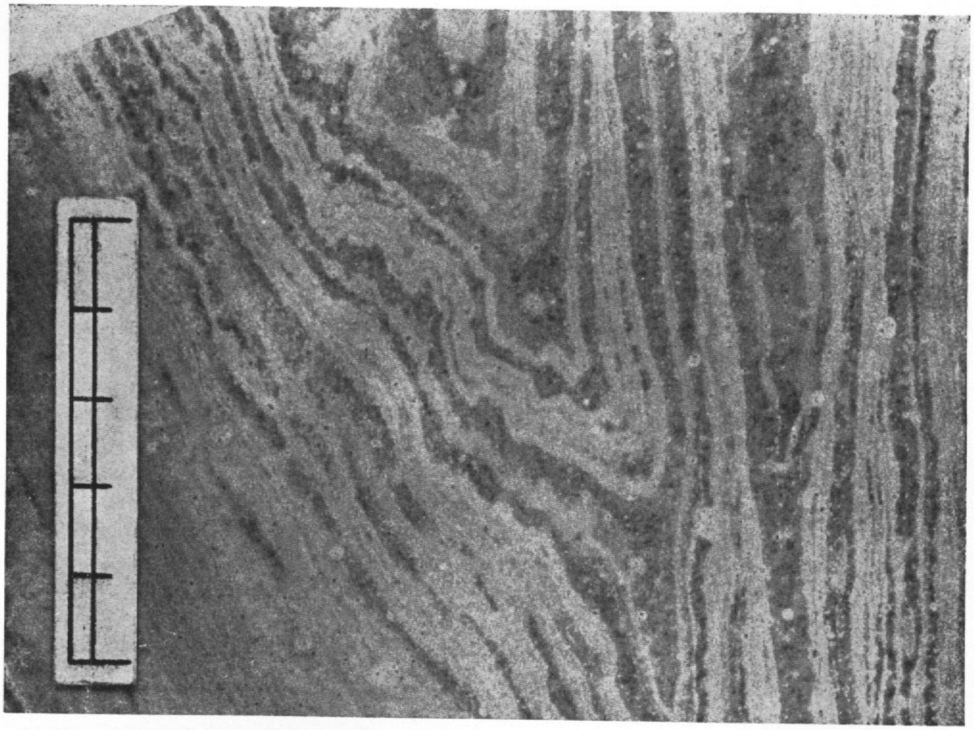

Fig. 11. Flow-folded and banded rhyolite; Smaaland Cove (Fig. 2, locality g). The scale is in centimetres.

suggested that the rhyolites are the near-surface or surface expression of the Smaaland Cove intrusion.

Volcanogenic sediments

Lenticular units of volcanogenic sediments are interbedded at infrequent intervals within the lavas of the Larsen Harbour Formation. The sediments, consisting of repetitive bands of interlaminated ash and chert deposits, range from a few centimetres up to 10 m in thickness and continue along strike for up to 20 m (Figs 12 and 13).

Well-bedded sequences crop out on the north-west side of Drygalski Fjord, on the southern shore of Larsen Harbour and west of Smaaland Cove (Fig. 2). They infill undulations within the pillow-flow surface and also occur as interstitial deposits between adjacent pillows (Fig. 14). In general, the sediments show impersistent stratification and lens out or terminates abruptly against flow-banded rhyolites or massive pillow units. Thin basic sills, averaging 75 cm in thickness, *intrude* the thicker sedimentary units, because such areas of unconsolidated water-saturated sediment would not support the extrusion of lava upon them (McBirney, 1963). Occasionally, flow-banded rhyolites are concordant with the stratification of the sediments and are interbedded with the various cherts and agglomeratic ash bands. The maximum thickness is 10 m within which individual bands attain a thickness of 2 m. The 2 m bands themselves commonly comprise 1–7 cm rhythmically repetitive units. Complete sequences are rarely homogeneous and variation in texture is common (Fig. 15). The interlaminated units consist of green and white chert bands and green to dark green alternating ash and agglomerate bands of differing thickness, colour and texture. Sedimentary structures are well developed, especially in the thinner fine-grained units (< 7 cm), which show sharp basal contacts with underlying beds and load casts and minor flame structures where coarse units overlie finer-

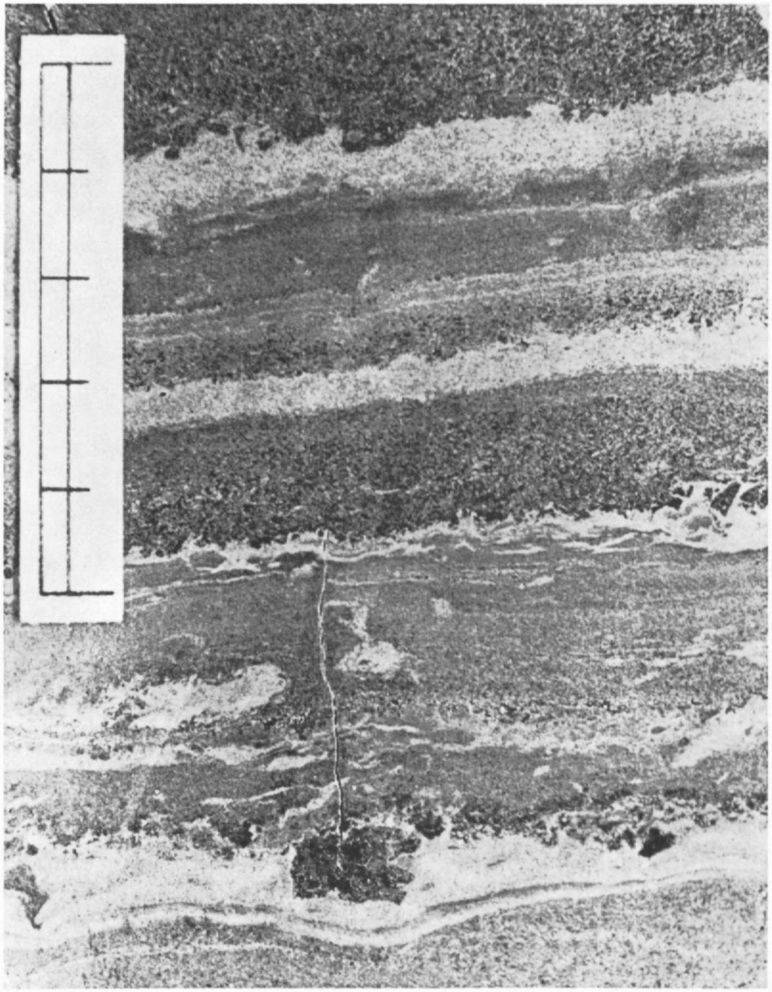

Fig. 12. Fine-grained repetitive units of inter-pillow sediment; Larsen Harbour (Fig. 2, locality h). The scale is in centimetres.

grained units. Graded bedding within individual bands is commonly developed (Fig. 12).

The thicker units lack the more delicate sedimentary structures of the thinner bands but they possess coarse bases and fine-grained upper zones, although grading between the two is seldom developed. Agglomerate horizons are generally matrix supported and consist of angular fragments up to several centimetres in length of re-worked rhyolite, sediment and detached lava pillows in a coarse-grained ash-type groundmass. Such well-formed agglomerates occur at intraformational breaks between pillow-lava flows and bedded units of stratiform breccia (Fig. 14).

In thin section the sediments have an overall dusty appearance, are usually fine-grained and composed of volcanic fragments or detritus, and contain the silicified remains of Radiolaria. Pettigrew (1975) described the occurrence of Radiolaria in volcanogenic sediments from Annenkov Island, lying to the south-west of South Georgia. Alteration of the sediments, possibly related to the regional metamorphism which has affected the lavas of the formation, has been extensive and epidote is disseminated throughout. All former glass fragments have

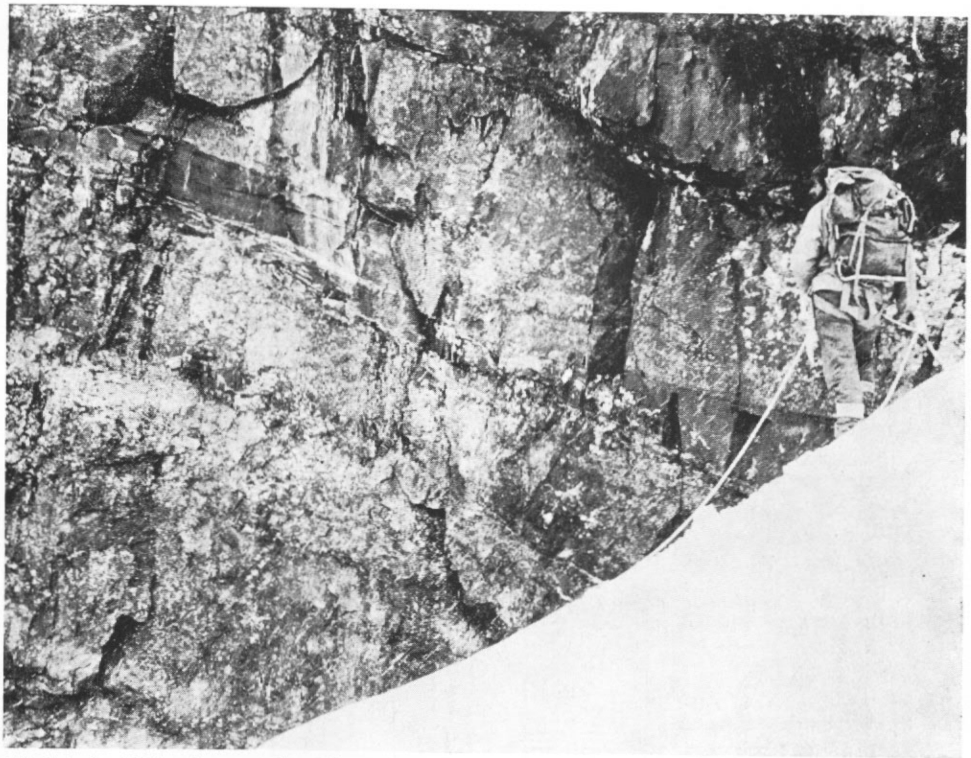

Fig. 13. Interbedded volcanogenic sediment within stratiform breccia above pillow sequence; glacier above Larsen Harbour (Fig. 2, locality i).

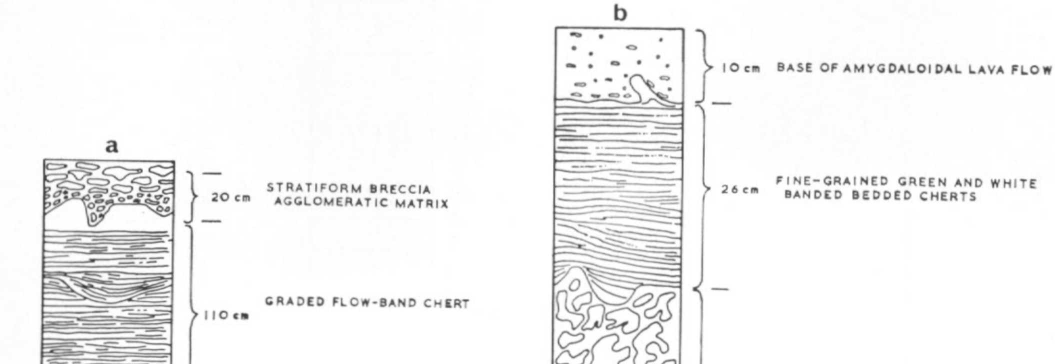

Fig. 14. a. Intraformational sediment between pillow lava and stratiform breccia; col between Larsen Harbour and Doubtful Bay (Fig. 2, locality j).

b. Interbbeded volcanogenic sediment within pillow lava; Larsen Harbour (Fig. 2, locality h).

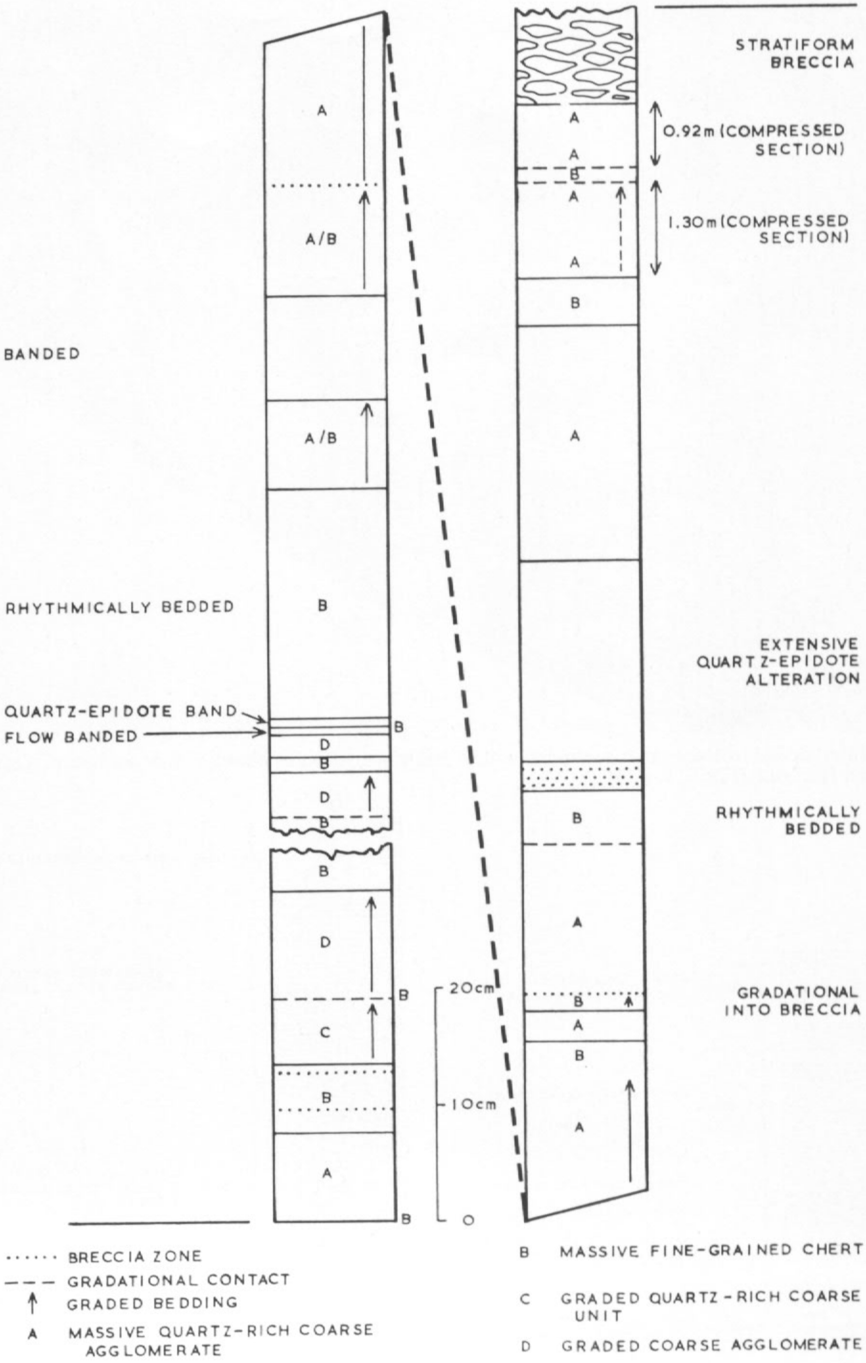

Fig. 15. Vertical section through rhythmically banded volcanogenic sediment within pillows; Larsen Harbour (Fig. 2, locality k).

been devitrified but they have retained their shard-like form. Sub-rounded fragments of detrital feldspar occur in the groundmass. The chert horizons are ultra fine-grained with an amorphous texture occurring as green- or white-coloured bands and containing remains of former radiolarian tests.

SMAALAND COVE INTRUSION

An igneous body covering about 6 km^2 in surface area crops out on either side of Smaaland Cove and this has intruded the basic lavas of the Larsen Harbour Formation (Figs 2 and 16). The intrusion lenses out within 1 km on either side of the cove, is fault bounded to the south and continues northward to re-appear at the head of Larsen Harbour. This body was tentatively described as a quartz-diorite (Bell and others, 1977) and later re-classified as a tonalite (Storey and others, 1977) but it will be referred to as the Smaaland Cove intrusion throughout this paper. No mention of this body was made by earlier workers on South Georgia.

A contrast in colour index between the basic lavas and the pluton emphasizes the sharp non-diffusive contact which exists between them (Fig. 16). The intrusion has a massive light-coloured aspect and shows no internal fabric but it has brecciated the country rock in places and caused loss of bedding structure. No metamorphic aureole is developed. The breccia screens contain angular, little altered xenoliths of basic lava intruded by thin stringers of massive quartz and coarse fractions of the body. Assimilation of the xenoliths has occurred to varying amounts in the breccia screens; in places only a relict shape indicated by a concentration of mafic minerals outlines a former xenolith. Small-scale variations in grain-size and colour of members of the intrusion are a common feature but no distinct boundaries between such

Fig. 16. Western roof contact of lighter-coloured intrusion and darker basic lavas, intruded by later dykes; Smaaland Cove (Fig. 2, locality 1). The dark area in foreground is cloud shadow.

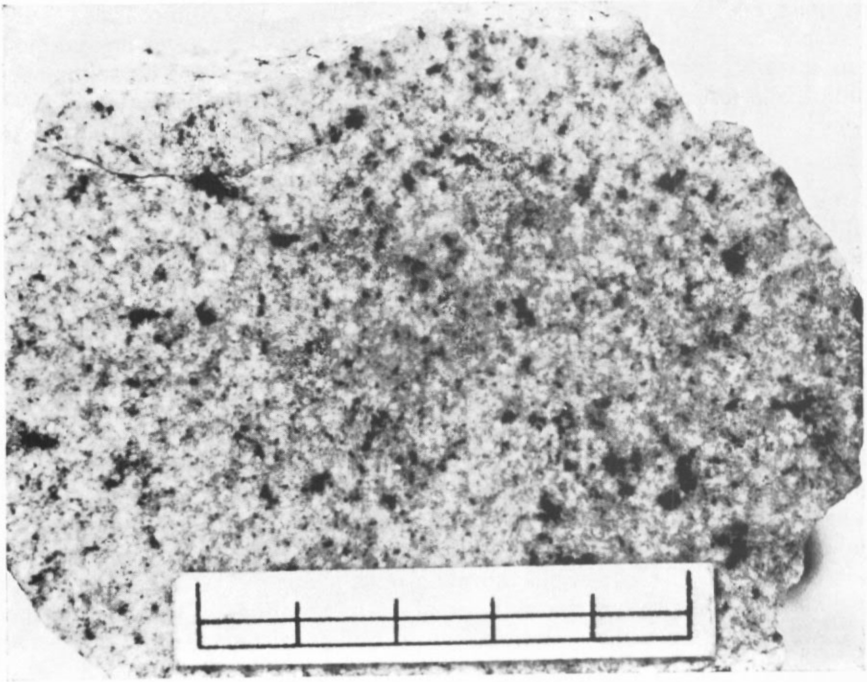

Fig. 17. Typical aspect of a tonalite (Fig. 2, locality m). The scale is in centimetres.

different phases are evident and it is inferred that they represent different fractions associated with multi-phase intrusion of the body. The earlier phases of the intrusion are more basic and less common than the later more acidic fractions. The main pluton is intruded by a minor aplitic phase and numerous basic dyke swarms.

In the hand specimen, the average tonalite is coarse- to fine-grained, light-coloured, holocrystalline and has a granular texture (Fig. 17). Both hornblende and epidote are recognizable within the quartzo-feldspathic groundmass in the field and euhedral cubes of pyrite are distributed throughout. Modal analyses (500 points) of the different phases of the body reveal that it is non-uniform and that the percentage of quartz present varies from 3 to 50 (Fig. 18). Quartz is present as subhedral 2 mm phenocrysts in a dominantly quartz-rich matrix where it forms interstitial grains with feldspar and hornblende. It also occurs as myrmekitic and granophyric intergrowths involving alkali feldspar, plagioclase and quartz. Both types of intergrowth can be found in the same rock but there is no gradation between them. The presence of myrmekitic intergrowths is common in rocks of a granodioritic habit (Moorhouse, 1959, p. 270) and the high content of granophyric intergrowths indicates a high level of intrusion at moderate temperatures (Barker, 1970).

Staining demonstrates that relative amounts of alkali and plagioclase feldspar vary but that plagioclase is dominant (Fig. 18). The modal percentage of plagioclase increases slightly within the more gabbroic members and shows an indefinite relationship to apparent decrease in the quartz content (Fig. 18). Both feldspars are susceptible to incipient alteration by epidote and sericite. No microcline was observed and the alkali feldspar noted is tentatively named orthoclase, although it gives a positive rather than a negative interference figure. This anomalous characteristic has been noted in other Andean intrusive rocks in the Antarctic Peninsula (personal communication from R. B. Wyeth). Plagioclase occurs in three compositional ranges, namely An_{0-10}, An_{27-35} and An_{43-55}, both as subhedral crystals and minor laths. Albite

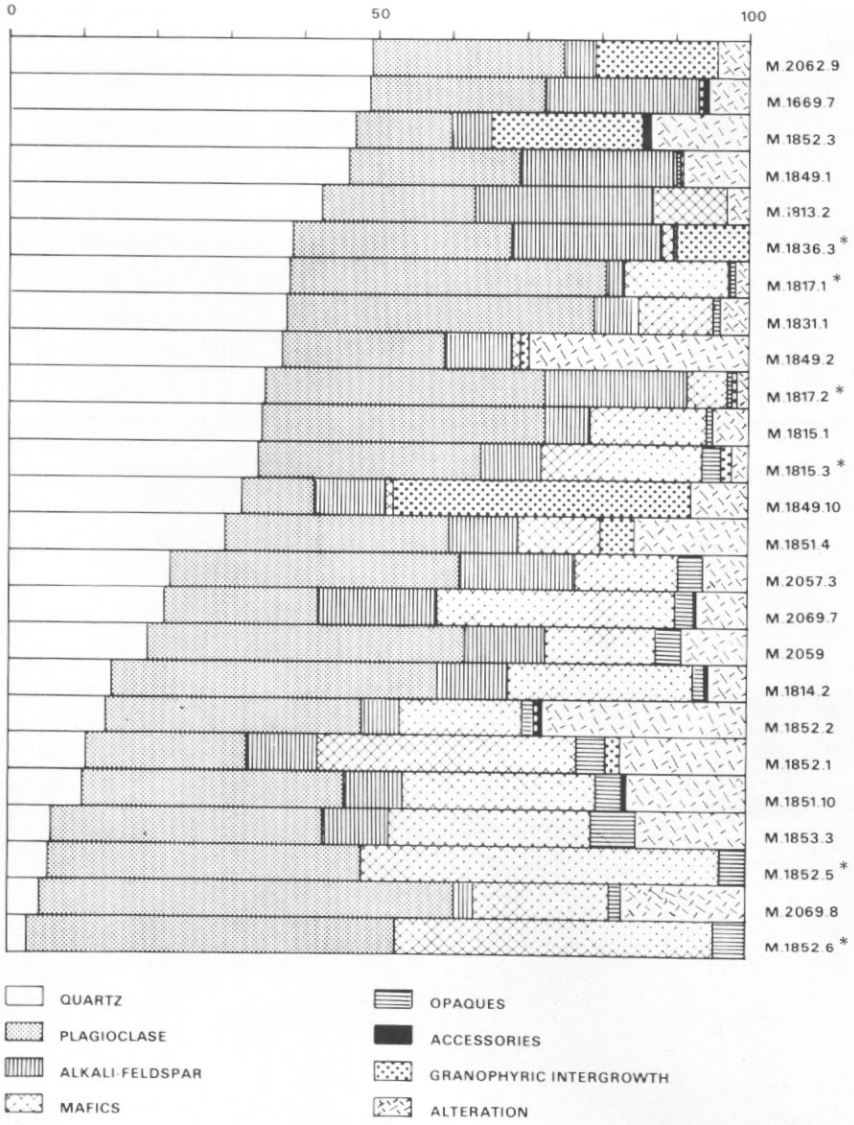

Fig. 18. Modal analyses showing petrographic variations within the Smaaland Cove intrusion. The analyses are arranged in increasing percentage of quartz.

(An_{0-10}) is present in the rocks of a more typical tonalitic habit in association with oligoclase-andesine (An_{43-55}). Many of the twinned feldspars are compositionally zoned and show differential alteration between their cores and margins.

Green hornblende (α = brown, yellowish green; β = brownish green; γ = dark green) is the only major mafic constituent and comprises over 40% of total minerals in the gabbroic phases (Fig. 18). These more basic phases are characterized by a crude sub-ophitic texture involving the hornblende and plagioclase laths. The hornblende forms irregular subhedral crystals with ragged margins within the quartzo-feldspathic matrix of the tonalitic parts. Epidote, clinozoisite and penninite are common alteration products found throughout but

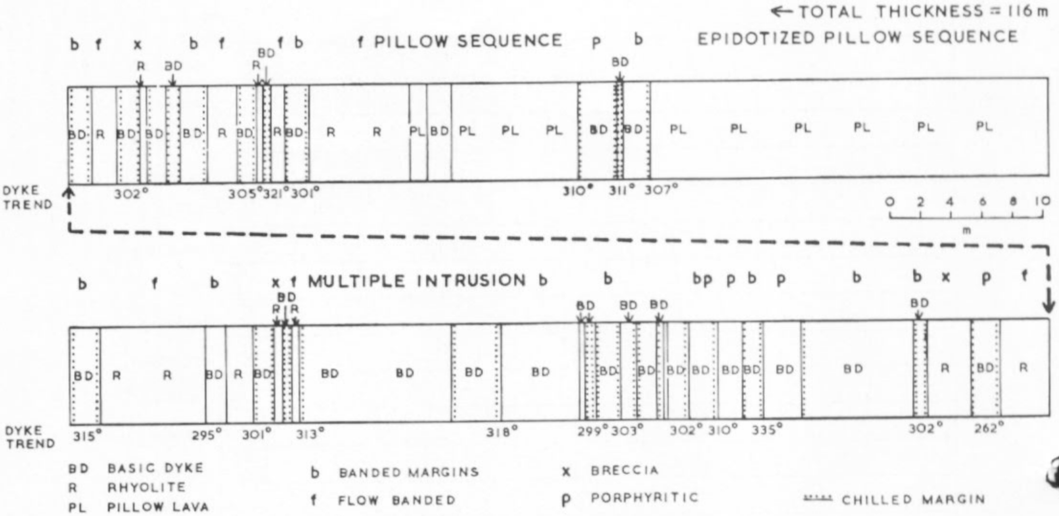

Fig. 19. Horizontal measured section across intensive dyke swarms; Doubtful Bay (Fig. 2, locality n).

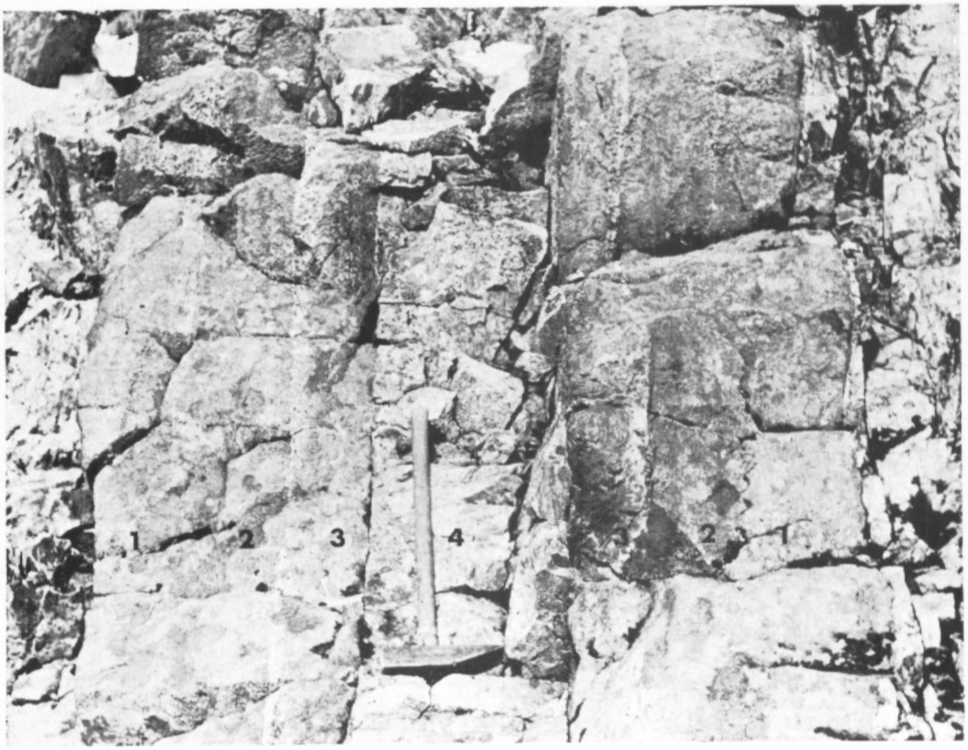

Fig. 20. Composite dyke intruding rhyolite; ridge between Smaaland Cove and Doubtful Bay (Fig. 2, locality o). Successive phases are indicated. The hammer shaft is 60 cm long.

they are more prolific in the more mafic-rich gabbroic phases. Opaque minerals include magnetite, ilmenite and pyrite, and accessory sphene, zircon and apatite are abundant in all phases. The sphene occurs as ragged crystals, and the zircon and apatite as euhedral prisms. Most of the optical characters of the apatite are the same as those outlined by Deer and others (1966) and other reference texts, but the interference figure was found to be biaxial positive rather than biaxial negative. Further work is necessary to clarify this situation but this unusual apatite has also been recorded in rocks from the Antarctic Peninsula (personal communication from R. B. Wyeth).

DYKE SUITES

The Larsen Harbour Formation and the Smaaland Cove intrusion are cross-cut by a series of complex basic dyke swarms (Fig. 3). A minor group of acidic dykes intrudes the sequence but these are correlated with the rhyolite bodies of the formation and are described above. Cross-cutting relationships of the different dyke sets have proved to be ambiguous and no definite pattern has been established, although Trendall (1959) reported that the north-east-trending dykes traverse the north-west-trending set east of Drygalski Fjord outside the area described here. Main trends recorded west of Drygalski Fjord in the Larsen Harbour Formation are 311° and 294° true, and a minor trend follows 352° true (Fig. 6c). These correspond to the north-west-trending dykes of Trendall (1959) and the lack of a north-east set within the formation may be a fundamental difference between it and the Drygalski Fjord Complex of South Georgia. Basic dykes cross-cut all rocks south-west of Drygalski Fjord but they show a specific concentration around Doubtful Bay (Fig. 3). A pattern of fault planes parallel to the main dyke trends is present (Fig. 6b and c).

The dykes form single or multiple units. The single dykes average 2 m in width and have a prominent chilled margin; in areas such as Doubtful Bay the profusion of dykes has almost completely removed the former country rock (Fig. 19). The multiple dykes are subdivided into those where re-intrusion of similar magma has taken place and those wherein subsequent phases are of differing mineralogy; the latter intrusions are more correctly termed composite dykes. The multiple and composite dykes represent re-intrusion of magma along a previously established plane of weakness, successive phases being emplaced in the centre of the preceding dyke, thus producing repetitive and identical sequences of chilled margins at either side of the final central intrusion (Fig. 20). These dykes are up to 7 m in total width and can involve up to four separate intrusions. The change in magma composition within the composite dykes (which become more acidic with time) is readily visible as a colour change, although the chilled margins between successive phases are not as clearly defined as those of the multiple or single dykes.

Single dykes

The single dykes are medium- to fine-grained and, although altered, they have a fresh appearance compared with the basic lavas. Their chilled margins appear as darker zones, 3 cm in width and of slightly finer grain. Some alignment of the larger plagioclase laths is visible close to the margin but no other internal structure is present.

In thin section, the dyke rocks show a well-defined ophitic to sub-ophitic texture involving clinopyroxene and euhedral plagioclase laths. The plagioclase, in laths up to 0.5 mm long with a length:width ratio of 8:1, has a uniform labradorite composition ranging from An_{48} to An_{61}. The feldspars show little alteration and are well twinned. The colourless clinopyroxene with moderate relief, biaxial positive interference figure and small 2V is pigeonite. Chlorite and acicular actinolite are present throughout, especially in the more altered dykes where penninite, epidote and sericite replace feldspar and pyroxene. Euhedral pyrite is the most abundant opaque mineral but minor haematite and ilmenite are also present. Irregular sphene is a common accessory mineral in the dykes but quartz was recorded in less than 5% of the sections examined.

Trendall (1959, p. 39) referred to dolerite dykes from the Drygalski Fjord Complex and western side of the island as being either albite or non-albite bearing. The above single dykes are classified as dolerites and correlated mineralogically with the non-albite-bearing type described by Trendall.

Multiple dykes

In the hand specimen the multiple dykes are similar to the single dykes and adjacent phases of the multiple dykes tend to differ only in grain-size. They have a poorly developed sub-ophitic or aphanitic texture of medium to fine grain and the coarser varieties are usually porphyritic.

The plagioclase present in the groundmass as laths (to 0.45 mm in length) and phenocrysts (to 1.5 mm) is labradorite (An_{52-54}). No fresh pyroxene was recorded, the matrix surrounding the plagioclase laths consisting entirely of epidote, penninite and actinolite, presumably alteration products after the original pyroxene. The amount of alteration is greater than that within the single dykes. Carbonate infills vugs and fissures, often in association with opaque minerals. Small amygdales, 0.4–1.0 mm across, are infilled by various combinations of penninite, carbonate and epidote overgrown by acicular actinolite. Pyrite is present throughout.

The chilled margin between adjacent phases of the multiple dykes is clearly defined by a concentration of opaque minerals. Fluidal alignment of feldspar microlites is clearly displayed in the chilled margins of the finer-grained intrusions. Infilled amygdales are the only other textural features visible in the aphanitic parts of the multiple dykes. The mineralogy of the finer-grained intrusions is essentially similar to that of the coarser dykes.

Composite dykes

The amount of quartz present in adjacent phases of the composite dykes increases with successive intrusions. Early phases are coarse-grained and contain a greater amount of coloured silicates than the later, more quartz-rich phases, and have a mineralogy similar to that of the multiple dykes. The chilled margin is more diffuse and is outlined by a zone of epidote alteration across which textural and colour changes occur. The later acid phase has a quartzo-feldspathic groundmass of less than 0.5 mm grain-size with included ragged 1.0 mm crystal aggregates of either epidote or penninite. The texture and mineralogy of the quartz-rich phase are almost identical to that of the rhyolitic rocks that crop out sporadically within the formation.

Trendall (1959, p. 38) recorded multiple dykes of quartz-dolerite within the Drygalski Fjord Complex but he made no mention of composite dykes which may be characteristic only of the Larsen Harbour Formation.

CONCLUSIONS

The Larsen Harbour Formation is a strip of oceanic crust formed during the emplacement of a marginal basin within continental crust, and it is thought to represent the upper level of an ophiolite complex (Bell and others, 1977). The occurrence of single, composite and multiple dykes as intensive swarms, completely removing the former country rock in places, is taken as evidence of spreading centres within the oceanic floor. This floor, consisting of abundant pillow lavas, hyaloclastite and stratiform breccias, and interbedded radiolarian sediments was subsequently affected by a regional, oceanic metamorphic event. The dominantly basic nature of the Larsen Harbour Formation is contrasted by the presence of contemporaneous rhyolites and a later tonalite intrusion. This suggests that the marginal basin environment, although essentially oceanic, has continental affinities.

The sharp contact of the intrusion with the surrounding rocks, its lack of a distinctive chilled margin and high content of granophyric intergrowths indicate that it was intruded at high level in the crust. Lack of a sufficient temperature gradient between the lavas and the pluton during emplacement, due to high heat flow in the marginal basin, may have prevented the formation of a distinct chilled margin (Packham and Falvey, 1971). It is suggested that the Smaaland Cove intrusion is more closely related to the granodiorites which crop out near Annenkov Island rather than to the granites of the Drygalski Fjord Complex. It may have been derived from material subducted on the trenchward side of the island arc and carried below the marginal basin by plate movement rather than by *in situ* melting of deformed continental sediments, a process which is thought to have produced the granites of the Drygalski Fjord Complex (Bell and others, 1977; Storey and others, 1977).

Further work is necessary to evaluate the cross-cutting relationships of the numerous dyke swarms. No consistent age relationships between the single and multiple or composite dykes have been established but it is thought that only single dykes intrude the later Smaaland Cove intrusion. An extensive geochemical programme is being undertaken at present in order to verify the oceanic nature of the Larsen Harbour Formation and to establish its relationship to the "island-arc" type rocks of Annenkov Island and to the gabbros and granites of the Drygalski Fjord Complex. It will also provide data for more local comparisons and correlations: between the differing dyke suites, between the lavas and the dykes, and between the Smaaland Cove intrusion and the rhyolites.

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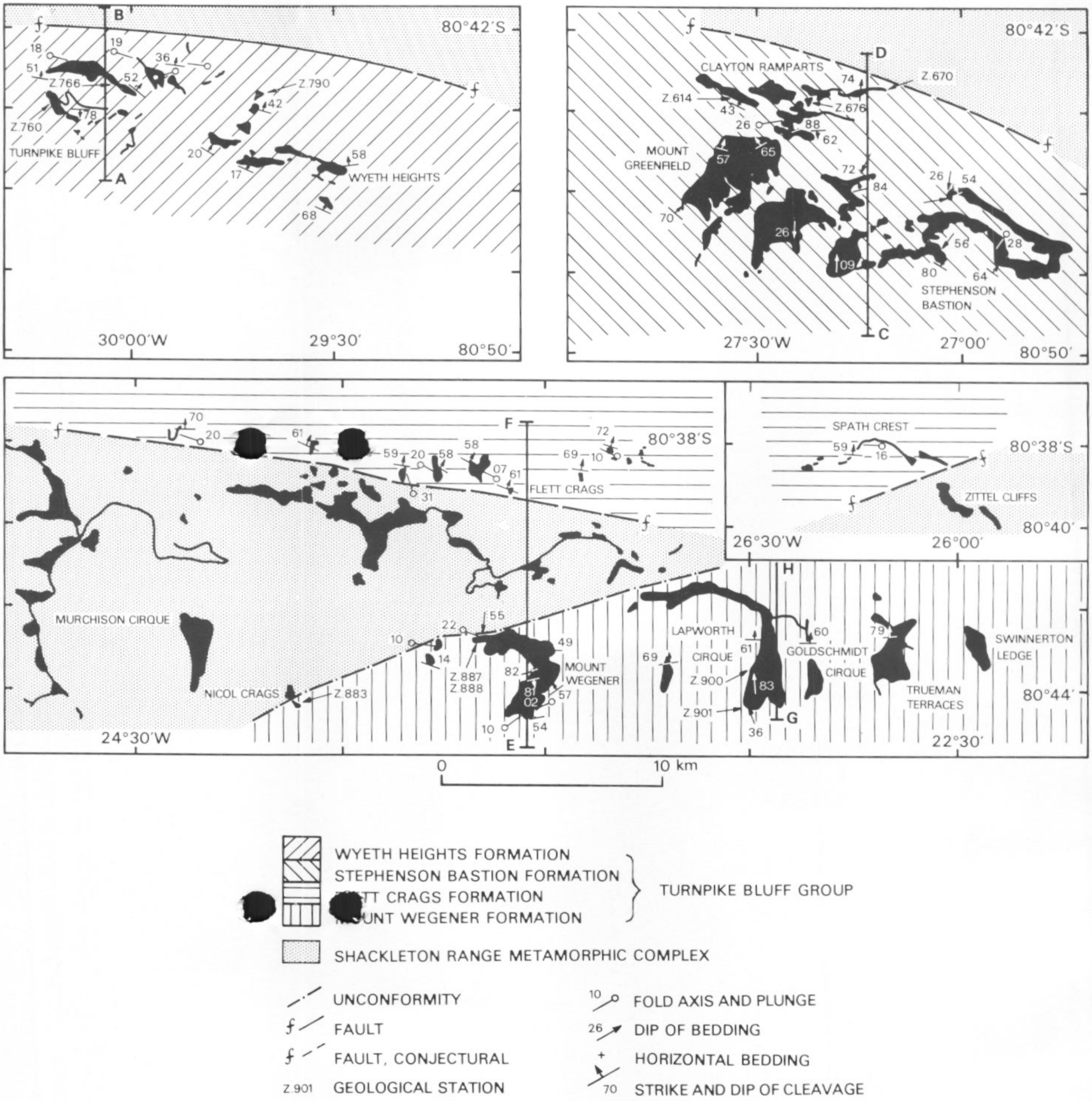

Fig. 1. Geological sketch map showing the distribution of the formations comprising the Turnpike Bluff Group. The positions of the four cross-sections in Fig. 8 are shown.