SYN-PLUTONIC ORIGIN AND TERTIARY AGE FOR THE (?) PRECAMBRIAN FALSE BAY SCHISTS OF LIVINGSTON ISLAND, SOUTH SHETLAND ISLANDS

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ABSTRACT. The False Bay schists are tabular enclave-like rocks, which occur within a 40 Ma tonalite pluton and a metagabbro pluton on the north-east side of False Bay, Livingston Island. The metagabbro was formerly regarded as an early dioritic phase of the tonalite but rhythmic layering is well developed at one locality and it is likely that two distinct plutons are present. The schists were previously interpreted as xenoliths of a (?) Precambrian metamorphic basement fragmented by the tonalite pluton during its emplacement. However, a mineralogical and textural gradation can be traced between the schists and a series of lamprophyric dykes, which intrude the plutonic rocks, and there are field relationships which suggest that the schists formed by injection as basic dykes. It is suggested that the mineralogy and textures of the schists are primary and that they evolved by injection and crystallization under conditions of stress during the emplacement of the tonalite pluton. Therefore, the schists are syn-plutonic and of Tertiary age.

LIVINGSTON ISLAND, the second largest of the South Shetland Islands, is situated at the south-western end of the island group (Fig. 1). In the False Bay area, Hobbs (1968, p. 12) discovered a sequence of metamorphic rocks, mainly hornblende- and hornblende-biotite-schists, which form screens and xenoliths within the foliated marginal zone of a major tonalite pluton. He interpreted these rocks (the False Bay schists) as fragments of a (?) Precambrian metamorphic basement incorporated by the pluton during its emplacement. Dalziel (1969) and Dalziel and Elliot (1973, p. 188) considered the origin and age of the schists as uncertain but they continued to refer to them as xenoliths in the "quartz-monzonite" pluton.

Detailed mapping by the author in the False Bay area, between Charity and Huntress Glaciers (Fig. 2), produced new evidence which suggests that the False Bay schists are best explained as metamorphosed and deformed basic dykes of a similar age to the tonalite pluton.

THE GEOLOGY OF SOUTH-EASTERN LIVINGSTON ISLAND

Hurd Peninsula (Fig. 1), situated on the north-western side of False Bay, is formed of essentially unmetamorphosed, isoclinally deformed sedimentary rocks of (?) Carboniferous–Triassic age (Miers Bluff Formation), whereas indurated metasomatized volcanic rocks of (?) Upper Jurassic age crop out at Mount Bowles and Renier Point (Hobbs, 1968; Dalziel, 1971).

A minor tonalite pluton intrudes the Miers Bluff Formation north of Johnsons Dock and two major plutonic intrusions, a layered gabbro (differentiated to (?) ferrodiorite near Renier Point) and a tonalite, crop out between False Bay and Renier Point. This is the first reported occurrence of a layered pluton in the South Shetland Islands. The tonalite has yielded Rb-Sr whole-rock and mineral ages of 40 Ma (Dalziel and others, 1973). Recent field work by British Antarctic Survey geologists indicates that the outcrop of these rocks is considerably more extensive than was previously thought (cf. Hobbs, 1968, fig. 2) and that the contact between the intrusions and altered volcanic rock lies within a narrow col 3.5 km south-west of Renier Point. Rhythmic layering was observed in the gabbro at one locality on the eastern side of False Bay (P.1257; Fig. 2). Individual layers are 4–10 cm thick, inverted and dip at 70° to the north-east, probably as a result of forceful intrusion by the tonalite which crops out in the surrounding exposures. Trough banding was observed in a thin-layered (1.5–2.5 cm) specimen (P.1257.1) collected loose at this locality. Despite the conspicuous layering, these rocks are dioritic in thin section, due to metamorphism by the tonalite, and no cumulate textures are preserved. Petrographically identical rocks, mapped by Hobbs

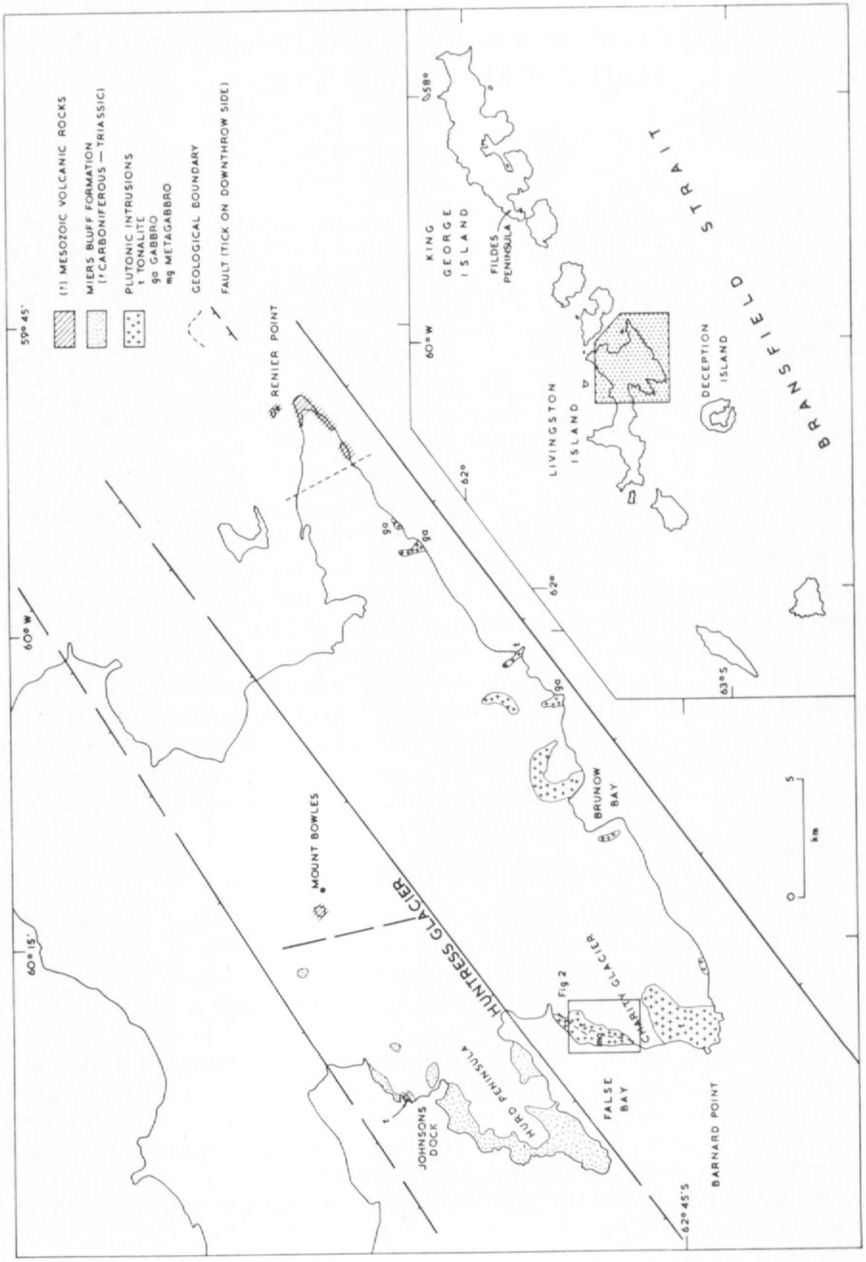

Fig. 1. Geological sketch map of south-eastern Livingston Island (modified after Hobbs (1968)), showing the area studied. The inset shows the location of Livingston Island in the South Shetland Islands.

(1968, p. 22) as diorite, crop out north of Charity Glacier and can probably be correlated with the layered rocks. They are collectively referred to here as metagabbro. Cumulate textures are prominent in thin sections of the gabbro–(?) ferrodiorite rocks east of Brunow Bay but layering was not observed. Apart from some variation in the biotite : hornblende ratio, the tonalite pluton is lithologically homogeneous. Hornblende-rich schlieren and biotitic or hornblendic enclaves are rarely present.

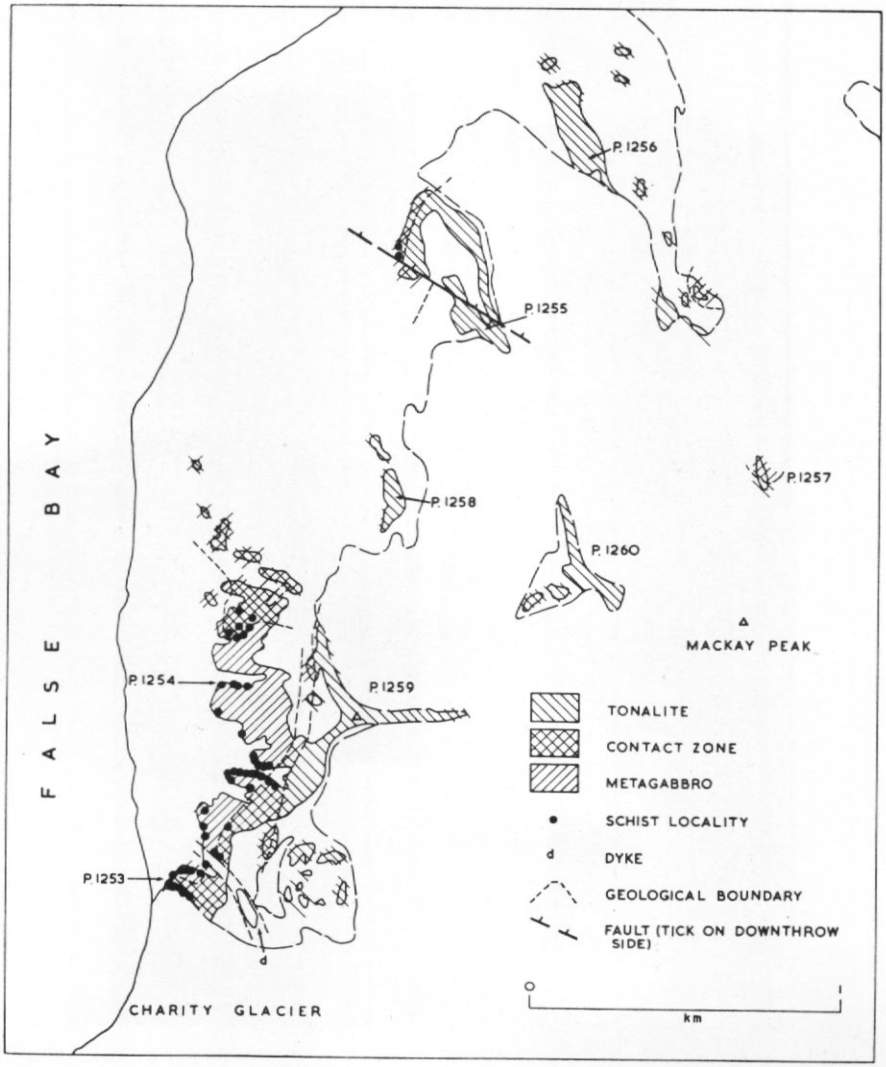

Fig. 2. Geological sketch map of north-eastern False Bay, Livingston Island. For clarity, the numerous east-south-east-trending lamprophyre dykes have been omitted.

The junction between the two plutons is exposed in the crags which extend north from Charity Glacier (Fig. 2). In many respects, the contact area closely resembles the "protoclastic border" of the Colville batholith (Washington, USA) described by Waters and Krauskopf (1941). In a zone up to 200 m wide, screens of net-veined (*s.l.*) metagabbro alternate with foliated microtonalite and zones rich in metagabbro enclaves (xenoliths (*s.s.*), not "autoliths" (Hobbs, 1968, p. 22)). The microtonalite becomes more intensely foliated as the contact with the tonalite pluton is approached and in places the gneiss-like foliation is puckered into small folds with a wave-length of a few centimetres. Steep jointing sub-parallel to the margin of the tonalite is conspicuously developed and there are local shear zones close to the contact (Fig. 3), in which protoclastic blastomylonites (e.g. P.1253.16) are formed (terminology after Higgins (1971, p. 13)). Aplite and pegmatite veins intrude all rocks but

Fig. 3. Sheared (protoclastic) rocks in the zone of contact between the tonalite pluton and metagabbro. The field of view is approximately 5 m across.

they are noticeably scarce within the tonalite.

The plutons are intruded by many predominantly east-south-east-trending lamprophyric dykes (Fig. 4).

The False Bay schists

Field relationships

The False Bay schists are tabular sheets and enclaves of hornblende- and hornblende-biotite-schist and semi-schist, which crop out exclusively within the metagabbro and the foliated marginal phase of the tonalite pluton. The outcrop extent of the schists is greater than was mapped by Hobbs (1968, fig. 4) and schists were observed along the entire length of the crags extending north from Charity Glacier and in foliated microtonalite exposed near station P.1255 (Fig. 2).

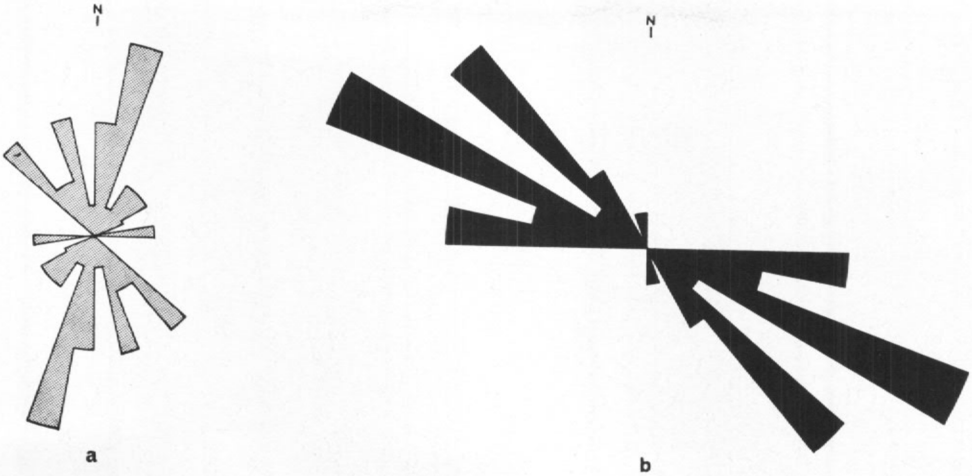

Fig. 4. Rose diagrams showing (a) the overall trends of the schist bodies (stippled) and (b) the trends of the lamprophyric dykes (solid black).

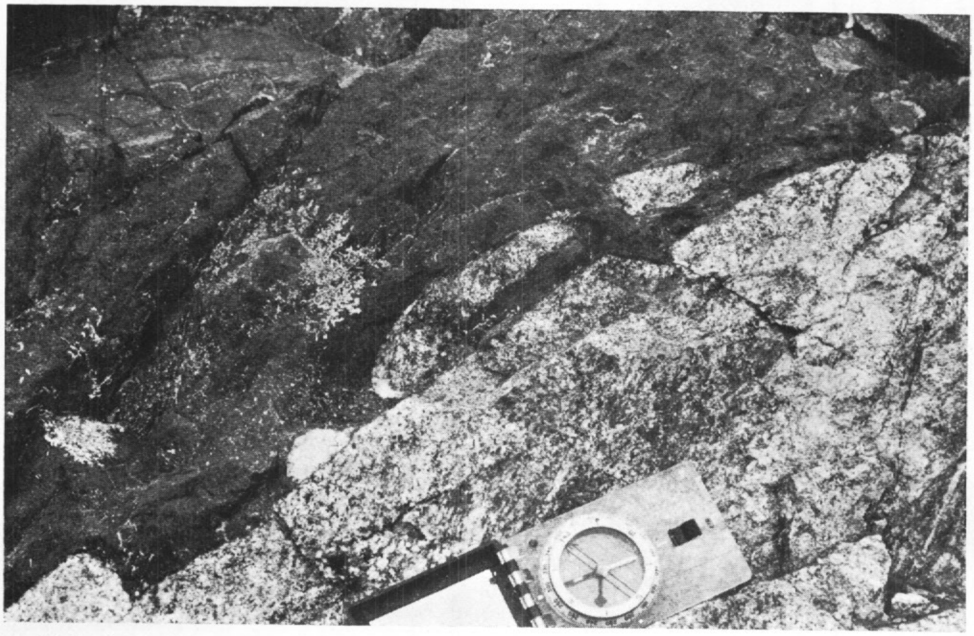

Fig. 5. (?) Enclaves of metagabbro in a False Bay schist in the crags north of Charity Glacier. The compass dial is 4 cm in diameter.

The schists are dark grey or dark green fine-grained rocks, which often have a gneiss-like appearance due to a thin "felsic" foliation parallel to the schistosity. The schistosity and/or gneissosity are orientated sub-parallel to the margins of the schists with dips generally 50° (mainly to the west) to near-vertical. The schist bodies are thin (ranging from 3 cm to 2 m) and sinuous, and can be traced for several tens of metres roughly parallel to the tonalite pluton. Closely spaced jointing is commonly developed parallel to the schistosity and there is a tendency for the joints and/or the schistosity to be more pronounced along the margins

Fig. 6. *Lit-par-lit* injection of microtonalite into a False Bay schist in the crags north of Charity Glacier. The pencil is 17 cm in length.

Fig. 7. False Bay schist (arrowed) in a zone of flow-orientated metagabbro enclaves enclosed by microtonalite at station P.1253. The rucsac is 36 cm in width.

or where the sheets exhibit a type of "pinch and swell" structure. The contact between schist and metagabbro is usually sharp and in rare instances the schist has developed a fine-grained margin. (?) Enclaves of metagabbro were observed within schist at two localities (Fig. 5) but the relationships are ambiguous and the "enclaves" may also be interpreted as apophyses of the metagabbro. Weak (?) flow banding was rarely observed in the metagabbro; at these localities, the schist bodies are orientated at a moderate angle to the banding. In contrast, the microtonalite frequently shows clear intrusive relationships towards the schists and considerable disruption, *lit-par-lit* injection (Fig. 6) and exfoliation of the outermost schistose layers have occurred where schists and microtonalite are in contact. Schistose enclaves, variably biotite- and/or hornblende-rich, are common in the foliated microtonalite. They probably represent the disrupted remnants of schists which were originally sheet-like in form. Some schists occur in zones of metagabbro enclaves enclosed by microtonalite but they have not suffered the fragmentation shown by the metagabbro (Fig. 7).

Petrography

The petrography of the False Bay schists has been described by Hobbs (1968, p. 13). Four specimens are described here in order of increasing injection by microtonalite to illustrate the mineralogical changes which have occurred.

Specimen P.17.1 is a dark green hornblende-schist which forms a screen within the metagabbro. It is composed of nematoblastic prisms of pale green hornblende, plagioclase ($An_{\sim 50-75}$) and isolated opaque ore anhedra, which show pronounced segregation into felsic and hornblende-rich bands (Fig. 8a). Specimens P.17.3 (a schistose enclave of hornblende-biotite-semi-schist from the microtonalite) and 17.4 (a finely gneiss-like grey-coloured hornblende-semi-schist from a sheet within the microtonalite) are composed of anhedral green hornblende and granoblastic plagioclase ($An_{\sim 40-50}$). Brown biotite occurs in thin (1 mm) schlieren-like trails parallel to the hornblende crystals (P.17.3) and as scattered unorientated flakes (in both specimens). Minor opaque ore, quartz, apatite and sphene are also present. Thin (1–2 mm) stringers of microtonalite intrude both rocks parallel to the hornblende-rich layers. They are coarser-grained than the semi-schists, quartz-rich and include plagioclase, hornblende, biotite, minor opaque ore and accessory sphene. K-feldspar occurs in specimen P.17.4 (Hobbs, 1968, p. 13). Sericite alteration of plagioclase, rarely associated with epidote (*s.s.*), is well developed in the microtonalite stringers in specimen P.17.4 and prehnite and

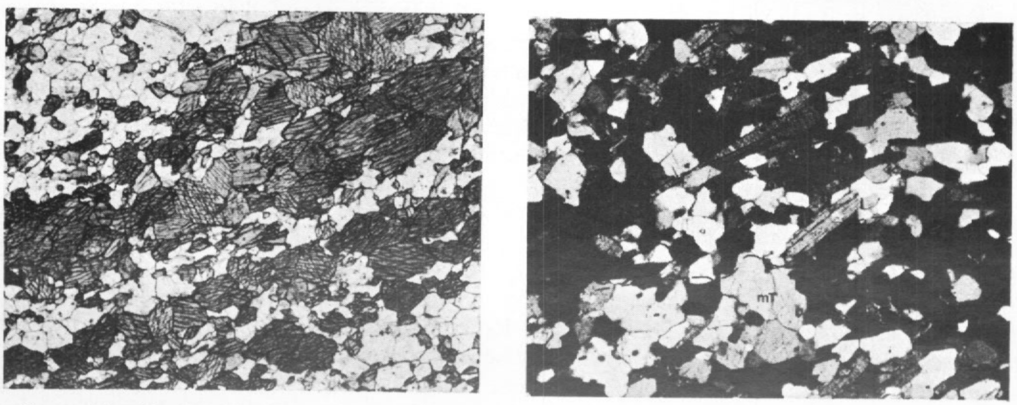

Fig. 8. a. Hornblende-schist from the north side of Charity Glacier, showing segregation into hornblende- and plagioclase-rich bands (P.17.1; ordinary light; ×50).
b. Biotite-schist from the crags north of Charity Glacier, composed of dark brown biotite, plagioclase and quartz. The schist is intruded by a thin stringer of microtonalite (mT) (P.1253.12; X-nicols; ×50).

clinozoisite occur in a thin ($\sim$0.2 mm) vein which cuts both the semi-schist and microtonalite in this rock. In the schists which have suffered more intensive *lit-par-lit* injection of microtonalite, conspicuous trains of brown biotite crystals are set in a fine-grained ($\sim$0.06–0.18 mm) granoblastic mosaic of quartz, plagioclase ($An_{\sim 20-40}$) (P.1253.12) and accessory apatite (Fig. 8b). The broad ($\sim$1–10 mm) bands of microtonalite are mineralogically identical to the schist but they are more coarsely crystalline (up to 1 mm) and the biotite crystals are randomly orientated.

In addition, Dalziel and Elliot (1973, p. 188) have reported minor garnet in the False Bay schists.

Metamorphism

The mineralogy and textures of the False Bay schists suggest that they are metamorphic rocks. The commonest mineral assemblage is: plagioclase (generally sodic andesine, varying from calcic oligoclase to sodic bytownite)–green hornblende–brown biotite–(quartz–opaque ore–apatite). This is typical of a basic igneous rock metamorphosed under amphibolite or hornblende-hornfels facies conditions (Turner, 1968; Miyashiro, 1973), although the virtual absence of epidote suggests that hornblende-hornfels facies conditions prevailed (Turner, 1968, p. 223). There is no evidence which suggests that any of the False Bay schists formed from rocks of pelitic or psammitic composition.

With the exception of local areas of diaphthoretic rocks (actinolite-bearing), the commonest mineral assemblage in the metagabbro is identical to that of the False Bay schists and it is clear that the mineralogy of the schists and the metagabbro evolved under a similar metamorphic regime.

The origin and significance of the False Bay schists

Several features suggest that the False Bay schists are fragments of regionally metamorphosed rocks:

i. The rocks are generally schistose. This contrasts with the non-schistose metagabbro (in which the majority of the schists occur) and with non-schistose dykes which are also present.
ii. The schists occur mainly as sub-vertical planar sheets without chilled margins. They have a regular orientation which led Hobbs (1968, p. 22) to consider that this was the original attitude of the rocks, into which the tonalite intruded in a *lit-par-lit* manner.
iii. No traces of relict igneous or sedimentary features are present and the schists have the mineralogical and textural characteristics of metamorphic rocks with mineral assemblages which conform to the hornblende-hornfels facies.
iv. Pegmatite/aplite veins and microtonalite stringers frequently intrude the schists and the microtonalite contains abundant schist-like and biotite- and/or hornblende-rich enclaves derived from the schists.

There are considerable problems involved in distinguishing between thin, elongate tabular relics of country rock (xenoliths, skialiths or "pseudodikes" (Goodspeed, 1948, 1955; Didier, 1973)), pre-plutonic relict dykes (Goodspeed, 1955) and syn-plutonic dykes (Allaart, 1967), and many authors have suggested criteria by which distinctions can be made (e.g. Grout, 1937; Miller, 1945; Goodspeed, 1948, 1955; Roddick and Armstrong, 1959). Hobbs' (1968) interpretation of the origin of the False Bay schists as regionally metamorphosed xenoliths is consistent with the criteria suggested by these authors.

However, there is considerable new field evidence which suggests that the False Bay schists are not enclaves but may have formed as basic dykes.

It is likely that a considerable period of convective cooling was required to create the layering in the gabbro (Wager and Brown, 1968, p. 210). This implies that the emplacement of the tonalite did not take place until this (ill-defined) period had elapsed. The predominance of *angular* enclaves of metagabbro enclosed by microtonalite in the contact zone also indicates that the gabbro had cooled and solidified before the forcible intrusion of the tonalite.

The field relationships between the schists and metagabbro are generally ambiguous. This is unusual because the emplacement temperature of the metagabbro was almost certainly greater than that of the tonalite and a hot basic magma should assimilate basic enclaves (the schists) more easily than a cooler acid magma (the tonalite). However, metagabbro was not seen to intrude any schists; contacts are sharp and fragments of schist in the metagabbro are absent. Three localities in the crags north of Charity Glacier are important in this context. At two of these, (?) enclaves of metagabbro occur within dark grey semi-schists (Fig. 5). At the third locality, thin stringer-like apophyses of semi-schists apparently intrude the metagabbro. In addition, there is the evidence of flow banding oblique to schist trends at two other localities; a tabular enclave would be orientated by magmatic flow and would become sub-parallel to the flow banding. These observations suggest that the schists were emplaced into the metagabbro as basic dykes rather than passively incorporated as sheet-like enclaves.

A progressive change can apparently be traced from unmetamorphosed non-schistose dykes with prominent chilled margins, through dykes with both metamorphic and relict igneous (mainly porphyritic) textures and narrow schistose margins to completely schistose and gneissose rocks (the False Bay schists (*s.s.*)). The dykes occasionally contain tonalite or metagabbro enclaves and they are locally injected by palingenetic stringers of tonalite. Epidote and/or metalliferous mineralization related to a late stage in the cooling history of the tonalite affect virtually all of the dykes mainly along joints. Petrographically, the dykes are distinctive and similar rocks have not been observed elsewhere in the South Shetland Islands. They are composed of euhedral to subhedral phenocrysts of hornblende (usually pale brown but occasionally pale green (P.19.2) with striking colour zoning from pale cores to dark margins), plagioclase, augite and olivine (in specimen P.1255.4 and possibly P.1260.2). Prismatic brown hornblende is abundant in the groundmass, accompanied by a sub-equal amount of plagioclase, minor augite, opaque ore and rare accessory apatite. Calcite, chlorite, epidote, (?) serpentine and sericite have variably affected plagioclase, olivine (totally pseudomorphed) and augite, whereas hornblende is unaltered. Microgranular sphene has commonly replaced opaque ore in specimen P.19.1.

Many features of these rocks are characteristic of lamprophyres (camptonites) (Turner and Verhoogen, 1960, p. 251; Hatch and others, 1972, p. 416). In true lamprophyres, feldspar is restricted to the groundmass (Turner and Verhoogen, 1960, p. 251), whereas plagioclase phenocrysts are usually present in the rocks under discussion. However, lamprophyres (camptonites) from Alexander Island also contain plagioclase phenocrysts (Horne and Thomson, 1967, p. 17), which suggests that this cannot be regarded as a rigid criterion.

Many dykes show characteristics intermediate between the lamprophyric dykes and the False Bay schists (*s.s.*). In some (e.g. P.1260.1), a fabric is defined by parallel lenticular aggregates of green hornblende and/or brown biotite, which are distributed in a granoblastic (P.1260.1) or relict pilotaxitic (P.1254.1) groundmass composed of plagioclase (sodic andesine in specimen P.1254.1), minor opaque ore and accessory apatite. Relict euhedral and subhedral phenocrysts of plagioclase (andesine in specimen P.1260.1), showing complex polysynthetic twinning and oscillatory zoning, are common and together with the field relationships provide unambiguous evidence for the igneous origin of these rocks. Alteration is minimal and consists of flecks of sericite in plagioclase and rare yellow epidote in biotite (P.1254.1). Minor secondary quartz is also present.

Whereas the field relationships suggest that many of the schists were emplaced prior to the tonalite pluton, there is evidence that at least some schists are younger than the tonalite. This is illustrated by a thin (12 cm) slightly sinuous schist which cuts metagabbro enclaves and microtonalite in an enclave zone at station P.1253 (Fig. 7). The metagabbro enclaves show textural variation and crude flow alignment, which indicate that some transport and mixing occurred due to intrusion by the microtonalite. Despite its thinness, the schist can be traced many metres laterally and vertically. If the schist was a tabular enclave of metamorphic rock which was present in the gabbro before intrusion by the microtonalite, it is difficult to visualize a mechanism whereby the gabbro could be fragmented by the microtonalite, yet the fragile schist with its large vulnerable surface area remains preserved intact. Roddick and Armstrong (1959, p. 608) have described "dykes which are less than 2 ft wide and more than 100 ft long and which are partly replaced by the enclosing plutonic rocks. Applying the magmatic stoping concept to such examples, one can hardly fail to conclude that the dykes, being little different in composition, must surely be brecciated and assimilated at roughly the same rate as the country rock. . . . Probably no magmatic mechanism could be so selective as to cut away all the country rock and leave a brittle tenuous dyke floating in it immune to the enormous stresses which must be operative in plutonic flow." The most feasible explanation for the relationships observed at station P.1253 is that the formation of the schist post-dated the formation of the zone of enclaves. Consequently, the schist is younger than the tonalite.

The margins of the schist at this locality have suffered minor injection by microtonalite. Kahma (1951, p. 23–30) has described a similar relationship in which the intrusion of dolerite into a granite pluton caused fusion of the granite which was then back-injected into fractures in the dolerite.

Experimental studies (Yoder and Tilley, 1962; Hamilton and Anderson, 1967; Cawthorn, 1976) have demonstrated that a hydrous magma will crystallize hornblende-bearing rocks which, in a stress environment, may crystallize as primary amphibolites (Windley, 1970, p. 79). In view of the close association between the hydrous magmatic suites (e.g. the lamprophyres) and plutonic intrusions (Turner and Verhoogen, 1960, p. 251), Allaart (1967, p. 100) and Rock (1977) suggested that much of the water required by the basaltic magma may be supplied by penecontemporaneous plutonic rocks. In the False Bay area, there is abundant evidence for the presence of hydrothermal fluids evolved by the cooling tonalite pluton, including areas of diaphthoretic rocks (composed of actinolite and saussuritized plagioclase (Hobbs, 1968, p. 22)) in the metagabbro, abundant epidote and/or metalliferous mineral veins, pegmatite and aplite veins, and the ubiquitous alteration of the lamprophyric dykes. Hamilton and Anderson (1967, p. 449) suggested that a hydrous basic magma may also crystallize a dense phase such as garnet. This may explain the occurrence of garnet in the False Bay schists reported by Dalziel and Elliot (1973, p. 188).

Yoder and Tilley (1962, p. 469) stated that "under equilibrium conditions it would not be possible to distinguish amphibolite and hornblende gabbro formed at the same pressure and temperature. Only the presence of non-equilibrium (relic) features may make it possible to determine whether or not such rocks came from the metamorphism of igneous (or sedimentary) rocks or were precipitated directly from a liquid." This is very similar to Eskola's (1921, p. 146) definition of a mineral facies. Therefore, extending these arguments to the False Bay schists in the manner in which Allaart (1967, p. 99) applied them to similar dykes in Greenland, the schists could simply be described as basic rocks crystallized in the lamprophyre facies as opposed to the basalt facies.

Dykes analogous to the False Bay schists crop out widely in south-western Greenland (Watterson, 1965, 1968; Allaart, 1967). They are composed largely of plagioclase and amphibole, and a large proportion are foliated. Watterson (1968, p. 27) suggested that the foliation in the dykes was caused by shearing and he considered that "the absence of cataclastic effects shows that the movement was paracrystalline with respect to that crystallization of the dyke during which the foliation was formed." Cataclastic effects have not been observed in the False Bay schists. Windley (1970, p. 90) presented convincing field evidence, which indicates that the foliation in the Greenland dykes developed contemporaneously with their intrusion and crystallization during periods of compressive stress, and Nicolaysen (cited by Rast (1970, p. 357)), on the basis of hydraulic experiments, suggested that schistosity can originate by "crystal growth in a medium which is transmitting stress". In the False Bay area, this process is possibly illustrated by the foliation of the tonalite in the contact zone. The presence of protoclastic rocks in this zone indicates that strong laterally directed stresses were operative along the margins of the pluton during its emplacement and these are probably responsible for the orientation of the hornblende and biotite crystals in the foliated microtonalite. If the False Bay schists were injected as dykes penecontemporaneous with the tonalite, they would be subjected to the same physical conditions responsible for the foliation in the microtonalite and an internal foliation would similarly result. Watterson (1968, p. 10) concluded that "although many features of the (Greenland) dykes are those more usually associated with metamorphic rocks, all were developed either during or immediately after consolidation of a magma and are to that extent primary features." It is suggested that this is also true of the False Bay schists.

Although the schistose dyke at station P.1253 apparently post-dates the tonalite, its age need not be dissimilar to that of the pluton and it is suggested that the schistosity formed in a similar manner to that in the other schists. This raises the problem of the rheomorphic state of the tonalite pluton at the time of injection of the dyke. There are many descriptions of "granitic" (*s.l.*) magmas with "embryonic" fractures which subsequently healed by flowage and recrystallization (e.g. Grout, 1937, p. 1549; Roddick and Armstrong, 1959, p. 612; Pitcher and Read, 1960, p. 59; Watterson, 1965, p. 99). Walker (1969, p. 166) compared the properties of magma with those of pitch "which flows like a liquid (though very slowly) under its own weight, but breaks with a conchoidal fracture when struck with a hammer" and he suggested that a viscous magma (e.g. the partially crystalline tonalite) can sustain fractures and dyke intrusion "provided that the stresses preceding and leading to the injection of the dyke are applied rapidly enough to break the acid magma" (Walker, 1969, p. 171).

The south-south-west-trending (early) fractures (occupied by the schists (Fig. 4)) may have been created by a stress field set up by the tonalite pluton during its emplacement, whereas the later-formed south-east-trending fractures (occupied by the lamprophyric dykes) may reflect a return to regional rather than local tectonic stresses as the pluton crystallized and ceased to exert strong lateral pressures. On Fildes Peninsula, 90 km to the north-east (Fig. 1), dykes possibly of a similar age to the lamprophyric dykes are predominantly north-east to south-east-trending; south-south-westerly trends are extremely rare. The overlapping trends in Fig. 4 are consistent with a progressive rotation of the stress field in the False Bay area.

Conclusions

It has been shown that there are close mineralogical similarities between the False Bay schists and a series of distinctive east-south-east-trending lamprophyric dykes present in the False Bay area and it is considered likely that the mineralogy of the schists is primary. A textural gradation is also apparent between the dykes and schists, and it is suggested that the schistose textures are a direct result of crystallization under conditions of stress related to the emplacement of a tonalite pluton, around the margins of which the schists crop out. The schists are interpreted as basic dykes with lamprophyric affinities which were intruded over a period of time immediately prior to, during and immediately following the tonalite. Dykes intruded later in the cooling history of the pluton show little or no evidence of metamorphic textures but they are affected by hydrothermal alteration caused by late-stage fluids evolved by the pluton.

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