THE JINKS ISLAND COMPLEX: MAGMA MIXING IN A HIGH-LEVEL INTRUSION FROM THE BISCOE ISLANDS, ANTARCTIC PENINSULA

A. B. MOYES

British Antarctic Survey, Natural Environment Research Council, High Cross, Madingley Road, Cambridge, CB3 0ET, UK

ABSTRACT. The Jinks Island Complex crops out in the northern part of the Biscoe Islands on the western coast of the Antarctic Peninsula and is characterized by numerous subspherical finer-grained and/or more mafic mineral-rich enclaves set in a leucocratic matrix. Many enclaves have crenulate margins and some have chilled margins, both indicative of liquid–liquid contact and strongly suggesting that the complex represents magma mingling. Some enclaves may be composite, formed by more than one episode of mafic magma injection into a high-level, possibly subvolcanic, magma chamber. The composition of the complex is tonalitic, although some enclaves (pillows) may be quartz diorite. Abundant mafic dykes associated with the complex are dominated by plagioclase and amphibole and suggest that mixing may be facilitated by the volatile-rich nature of the mafic magma. Cataclasite veins and dykes, pervasive throughout this part of the Biscoe Islands, are interpreted as the result of pneumatolytic activity associated with the development of the mixed-magma chamber. The Jinks Island Complex is significant because such a record of hypabyssal events within the Mesozoic–Cenozoic magmatic arc of the Antarctic Peninsula is rare, and also because it provides strong support for the concept of magma-mixing in the generation of the calc-alkaline orogenic suite as a whole.

INTRODUCTION

For many years there has been considerable debate in the literature on the origin of the calc-alkaline suite, and in particular, rocks of intermediate composition such as andesite or granodiorite. Recently, the recognition of the association between this suite and subduction processes at convergent plate boundaries has produced a variety of theories to explain the observed geochemical variations, such as crystal-liquid fractionation of parental basalt, partial melting of hydrated mantle or subducted oceanic crust, assimilation of continental crust by basalt, and magma mixing. The last two processes in particular may be very difficult to distinguish from each other. The complex magma genesis resulting from the variety of available source materials at convergent margins has given rise to controversy over which, if any, of the above processes is dominant in the genesis of the calc-alkaline suite (see review in Gill, 1981).

Magma mixing has been advocated recently as a viable petrogenetic process in many volcanic terranes where there is considerable field evidence for the contemporaneous existence of mafic and silicic magmas (mingling), and petrographical-geochemical data for their subsequent mixing (e.g. Eichelberger, 1975; Anderson, 1976; Eichelberger and Gooley, 1977). Recent experimental investigations into the fluid dynamical properties of magma chambers also suggest that magma mixing may be a significant contributor to volcanic processes (Sparks and others, 1977; Huppert and others, 1982). There is also considerable evidence to support the contention that mafic and silicic magmas coexist in many plutonic terranes (see reviews by Blake and others, 1965; Walker and Skelhorn, 1966; Yoder, 1973; Vernon, 1984), and the role of magma

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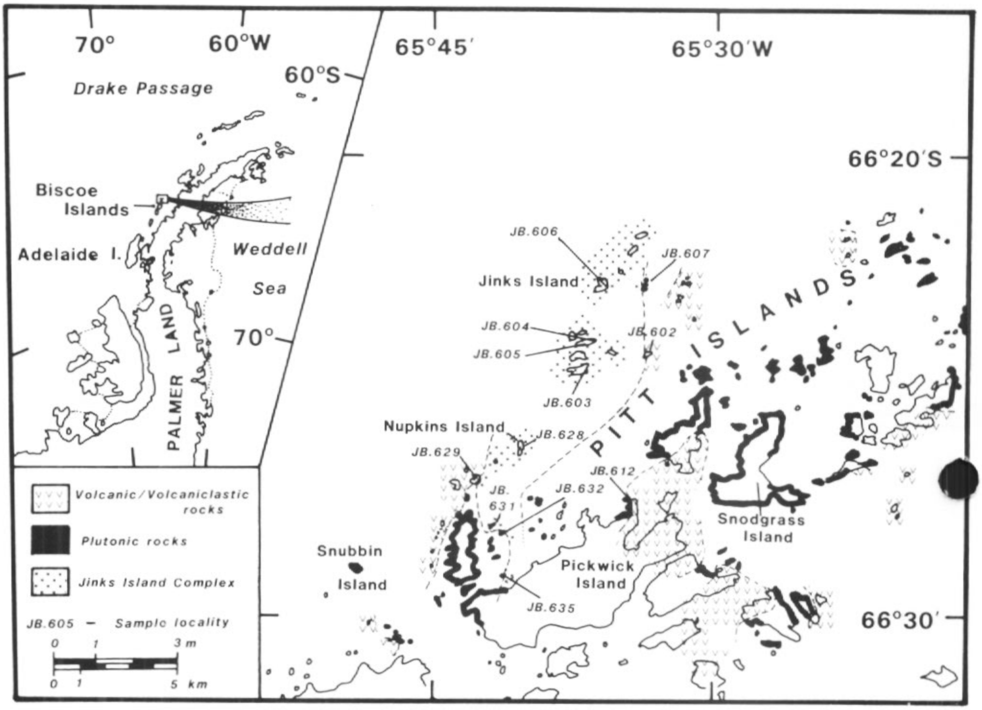

Fig. 1. Geological sketch map of the Pitt Islands, and the location of the Jinks Island Complex.

mixing in the production of relatively homogeneous intermediate magmas, particularly in the calc-alkaline suite, is currently the subject of much investigation (see Reid and others, 1983; Hill and others, 1985).

This paper presents the field observations of and petrographical evidence for the mingling of contrasting magma types at several localities within the Biscoe Islands area of the Antarctic Peninsula. The highly characteristic nature of the outcrop not only provides direct evidence of magma mingling within a calc-alkaline regime, but also affords an insight into the structure of a high-level magma chamber, a feature infrequently preserved and not recorded before in the Antarctic Peninsula region. In view of the geological significance and highly distinctive nature of the outcrop, the term 'Jinks Island Complex' is proposed here.

LOCATION AND GEOLOGICAL SETTING

The Biscoe Islands group consists of a large number of islands lying off the western coast of the Antarctic Peninsula (Fig. 1). The most northerly group of islands is collectively called the Pitt Islands, and the Jinks Island Complex crops out on a series of islands forming the western margin of this group (Fig. 1).

The geology of the Antarctic Peninsula is dominated by the calc-alkaline igneous rocks associated with subduction of easterly moving Pacific Ocean floor during much of the Mesozoic and Cenozoic, and is commonly represented by either the Antarctic Peninsula Volcanic Group (APVG, Thomson, 1982) or the Andean Intrusive Suite (AIS). The geology of the Pitt Islands consists of a suite of basic to intermediate plutons intruding volcanic and volcaniclastic rocks of uncertain age, which have

Fig. 2. Typical exposure of the Jinks Island Complex, showing abundant rounded enclaves in a leucocratic host. Locality JB.605. (Photograph by J. L. Smellie.)

been correlated with the APVG and coeval fore-arc sedimentary successions (Smellie and others, 1985). A range of volcanic and sedimentary rocks is present, including probable turbidites, poorly stratified water-lain sediments, non-stratified volcaniclastic rocks, massive and brecciated lavas and hypabyssal intrusions. Plutonic rocks are volumetrically dominant and are commonly gabbro or diorite, with associated quartz diorite and tonalite, more granitic rocks being conspicuously rare or absent. The plutons are interpreted as part of the AIS and commonly intrude the volcanic rocks, except for one volcanic neck observed cutting a pluton on Pickwick Island at locality JB.612 (Fig. 1). A characteristic feature of many of the outcrops in the Pitt Islands is the presence of dark-coloured anastomosing fractures, which locally coalesce to form cataclasite zones a few millimetres thick. There is no evidence of shearing or penetrative deformation within the host rock, and these veins are interpreted as resulting from cataclasis due to fracturing and volatile streaming (Smellie and others, 1985).

The complex is cut by mafic aphyric and phenocryst-rich dykes, and in places displays pneumatolytic fracturing. The margins of the complex are difficult to define due to the interrupted nature of the exposure, but it apparently intrudes both plutonic and volcanic rocks in the northern part of the Pitt Islands. At locality JB.607 (Fig. 1) the complex is juxtaposed against a medium-grained quartz diorite across a highly shattered and weathered zone, perhaps indicating a tectonic contact. The quartz diorite close to the contact contains dark-coloured enclaves, which become less abundant away from the contact. To the south of this locality, at JB.602 (Fig. 1), volcaniclastic rocks are intruded by a fine-grained leucocratic rock that may be related to the complex although it does not contain the characteristic mafic enclaves. Similar relationships are observed south of Nupkins Island at locality JB.629, where

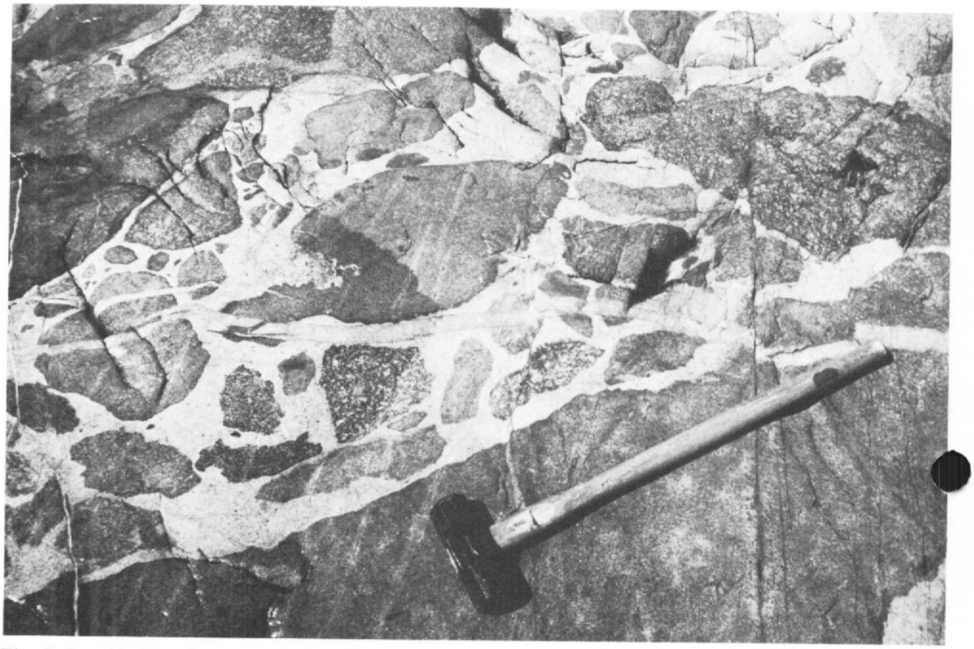

Fig. 3. Detail of enclaves, showing variable textures and grain size. Note that adjacent enclaves rarely impinge on each other, and the late, cross-cutting leucocratic dykelet. Hammer shaft is approximately 1 m long. Locality JB.605. (Photograph by J. L. Smellie.)

agglomerates and tuffs are intruded by a fine-grained leucocratic rock, and the whole outcrop is extensively cut by mafic dykes and pneumatolytic veins. At locality JB.631 the complex appears to grade into a brecciated or agglomeratic rock, which may represent a disrupted portion of the complex formed through extensive volatile-streaming in, for example, a volcanic neck. Locality JB.635 is dominantly quartz diorite but contains a complicated enclave- or schlieren-zone, which may define the boundary with the complex, as it marks a transition from a heterogeneous diorite to rocks of the complex, the latter having a saccharoidal texture close to the contact. The observed field relationships suggest, therefore, that the Jinks Island Complex may intrude volcanic rocks of the APVG but is itself intruded and metamorphosed by younger plutons of the AIS. The complex, therefore, crops out as part of t calc-alkaline suite exposed abundantly throughout the Antarctic Peninsula, and does not appear to occupy any extraordinary structural or lithostratigraphical position.

MEGASCOPIC FEATURES

The Jinks Island Complex consists essentially of a leucocratic host containing abundant, darker-coloured enclaves, often forming up to 50% by volume of the exposed outcrop (Fig. 2). The colour contrast between host and enclave is due to both reduction in grain size and increase in mafic mineral content in the latter (see below), but the degree of contrast varies considerably from one enclave to another (Fig. 3). The enclaves vary in size from < 50 cm to > 2 m and are generally rounded, but with a highly variable degree of sphericity. Margins with the host are often crenulate in shape (Fig. 4) and may be distinctly finer-grained, suggesting chilling of mafic pillows against the host. The abundance of pillows varies considerably between

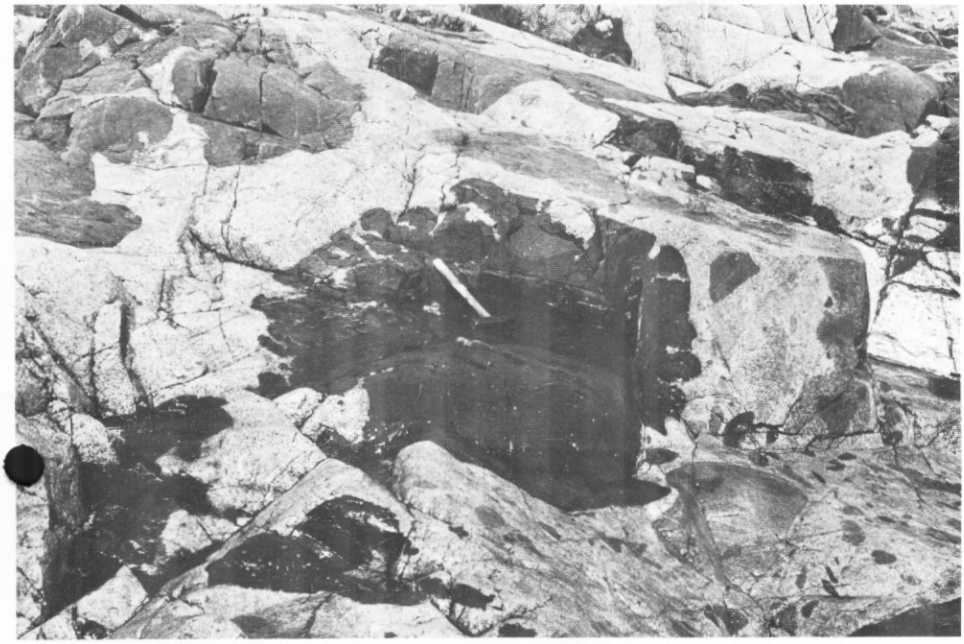

Fig. 4. Crenulate margin to a large enclave, indicating liquid–liquid contact. Note also the variability in the colour of different enclaves. Hammer shaft is approximately 30 cm long. Locality JB.606, Jinks Island.

outcrops but a true net-veined complex, where pillows are in far greater abundance than the host, occurs only rarely (Fig. 5). Megascopically there appears to be very little interaction between the host and pillows. Some enclaves are composite, comprising more than one pillow phase (Fig. 6) and suggesting that several episodes of pillow formation have occurred.

The host rock is usually more leucocratic and coarser-grained than the pillows, and also commonly displays an acicular texture except where recrystallized. Internal contacts within the host rock marked by contrasting grain-size have been noted (Fig. 7), which also suggest that more than one episode of magma mixing has occurred, earlier phases of both host and pillow gradually assuming similar characteristics. At [illegible]me outcrops (e.g. JB.603) the host has a 'pseudobrecciated' appearance (Fig. 8), with relatively large (up to 50 cm) rounded areas separated by a finer-grained matrix of essentially similar but paler-coloured material. At these localities, the host is also cut by cataclastic fractures (Fig. 9). Several veins (1–2 m) of leucocratic material indistinguishable from the general host rock cut some outcrops of the complex (see Fig. 3) but no chilling is observed at their margins, and their grain-size is often greater than that of the host. More commonly, mafic aphyric and phenocryst-rich dykes cut the complex, and their abundance suggests that dyke intrusion has a particular relevance in the generation of the complex, although not necessarily at the currently exposed level.

With the exception of very localized areas of foliated rock a few metres in extent at locality JB.631, there are no penetrative structures within the complex apart from late joints, which cut all rock types, although the lack of observed vertical section and horizontal extent of the outcrops makes interpretation difficult. There are no indications of 'way-up' structures within the complex, as crenulate versus

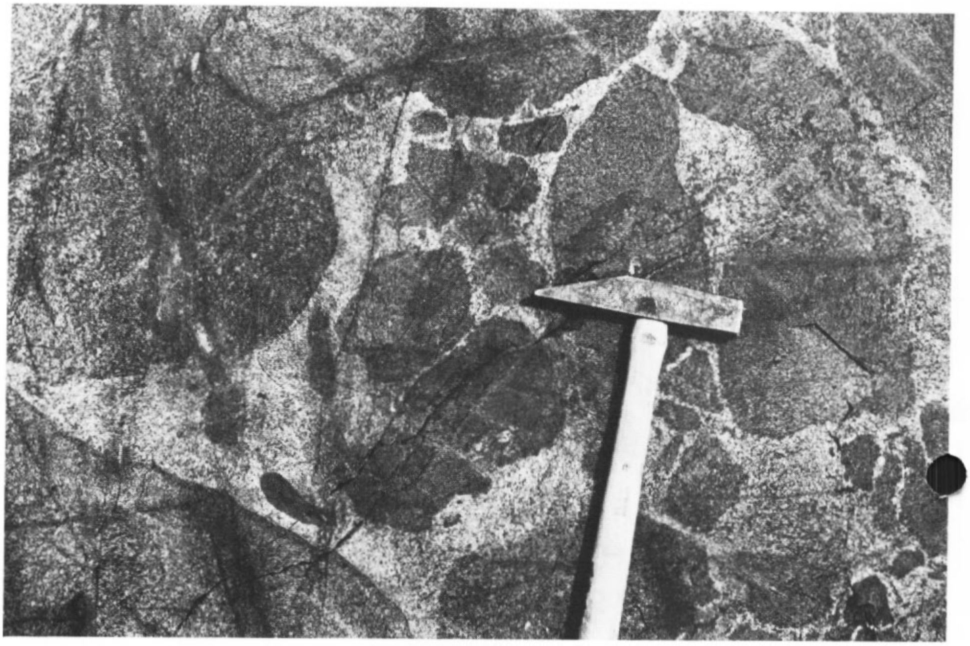

Fig. 5. Net-veined area within the complex, with a high concentration of pillow material. Hammer head approximately 15 cm long. Locality JB.6 03.

curvilinear margins on the pillows vary considerably in distribution and do not appear to indicate the lower and upper surfaces of the pillow respectively. The maximum exposed width of the outcrop is approximately 1 km, suggesting that the complex is too wide to be considered as a dyke, sill or cone-sheet. The linearity of the outcrop, however, might indicate a structural control on a high-level magma chamber.

MICROSCOPIC FEATURES

Host rock

The host rock is most commonly a tonalite, although one granodiorite and one quartz-rich granitoid have been observed (Fig. 10). In general, the host is richer in quartz and poorer in mafic minerals than the pillows. Plagioclase crystals are 1–2 m[illegible] (occasionally 4–5 mm) long, subhedral and frequently very turbid or altered. They may show continuous zoning and have an overgrowth of more sodic plagioclase, and occur as a porphyritic phase at some localities. Quartz is interstitial to the feldspar, and is typically anhedral with undulose extinction and sutured sub-grain boundaries indicating minor recrystallization. The ferromagnesian phases are most commonly biotite and an opaque oxide, although amphibole does occur rarely as a fibrous secondary mineral with low (1st-order) birefringence. Biotite may occur as relatively large (1 mm) subhedral crystals, often partially or wholly altered to chlorite, epidote and granular sphene, but it most commonly forms as aggregates of small (< 0.5 mm) crystals that appear to have replaced an earlier mafic phase. An opaque oxide is commonly associated with the biotite as anhedral or subhedral equidimensional crystals that appear unaltered despite the associated chlorite or secondary amphibole. Accessory phases include zircon and allanite, the latter occurring as radiating,

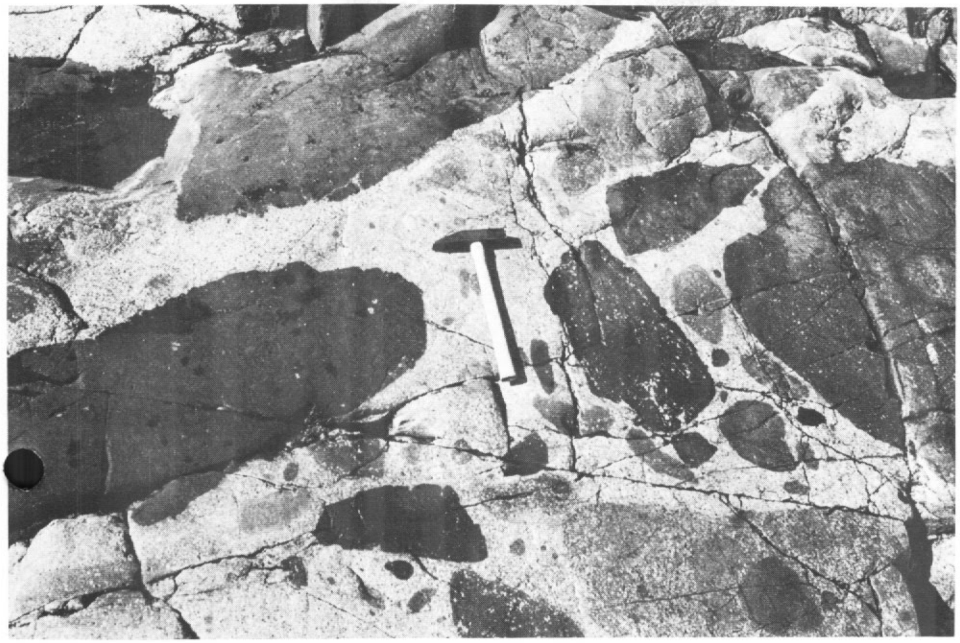

Fig. 6. Typical variation in pillows within the complex. Note the composite pillow (bottom, right) and the variation in host-rock grain-size. Hammer shaft approximately 30 cm long. Locality JB.606.

interstitial crystals. Apatite is also present as small acicular needles, and may be very abundant locally.

At some localities (e.g. JB.628) there is a very distinctive graphic intergrowth between quartz and plagioclase, suggesting that the latter is not more calcic than oligoclase in composition. The alkali-feldspar content also increases in these rocks but, in general, there is very little petrographical indication of its presence. The host rock is medium-grained (1–5 mm), but may increase to coarse-grained (> 5 mm) in the leucocratic dykes, which are otherwise petrographically indistinguishable. No drusy cavities have been observed in the host rock, but two samples are unusual in containing small areas (2–3 cm across) where the quartz and plagioclase grains have been physically disaggregated and the interstices filled with biotite. Each affected area contains a single central grain of opaque oxide surrounded by a clay mineral, biotite and garnet (?hydrogrossular). Such features are interpreted here as possible fluid and volatile pathways, perhaps the initial stages of pneumatolytic activity. Throughout the entire exposure of the complex, but particularly at its southern extremity, there is petrographical evidence for metamorphism, consisting of granoblastic textures between quartz and plagioclase. This recrystallization is related to the proximal intrusion of a quartz diorite as discussed above.

Pillows

The principal distinctions between the host rock and pillows are that the latter are finer-grained and have an increased proportion of plagioclase, apatite and ferromagnesian minerals, particularly amphibole (Fig. 10). The pillows are commonly tona-

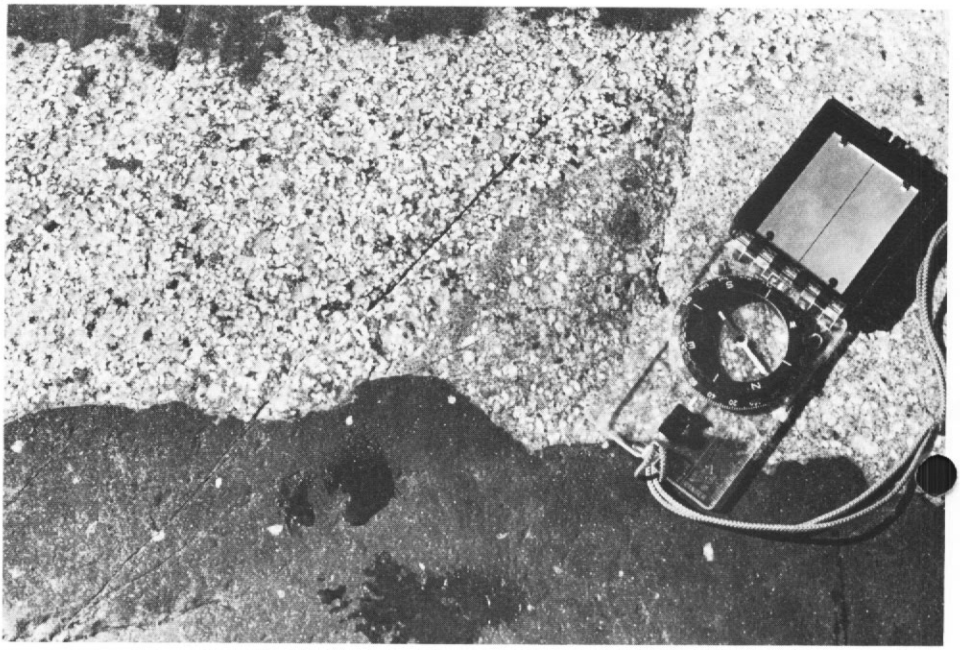

Fig. 7. Detail from part of Fig. 6, showing an internal contact between host rock of different grain-size and texture. Note also the contrast between the crenulate margin in the upper pillow compared to the curvilinear margin in the lower one. Locality JB.606. Jinks Island.

lite, but some are quartz diorite. Plagioclase is subhedral and occurs as lath-shaped or elongate crystals often with a radial or variolitic texture. Examples of spherulitic texture are also present. The feldspar is highly altered and turbid, and may have an overgrowth of more sodic plagioclase. Amphibole occurs as subhedral to anhedral crystals with a variety of compositions reflected in different pleochroic schemes. A magnesio-hornblendic variety (α = yellow-brown; β = olive-green; γ = dark-green) is most frequent although a tschermakitic amphibole (α = pale-yellow; β = reddish-brown; γ = dark reddish-brown) has been observed, and some acicular crystals are probably of secondary ferro-actinolitic amphibole (α = pale-yellow; β = green; γ = deep greenish-blue). In many samples, primary amphibole is pseudomorphed by small crystal aggregates of secondary biotite or chloritized biotite; primary subhedral crystals of biotite are rare. An opaque oxide occurs as small (< 0.5 mm) subhedral equidimensional crystals, and accessories include zircon and apatite. The latter mineral occurs abundantly as acicular crystals, often with hollow cores, included in the plagioclase and quartz. Some pillows contain phenocrysts of plagioclase. Many pillows appear to have undergone a recrystallization similar to that observed in the host rock, but the generally finer-grained nature of the pillows makes textural assessment of this difficult.

Towards the margins of many pillows the radial texture of the plagioclase crystals is particularly well-developed but a significant decrease in grain size is not always apparent. Instead, the proportion of biotite in the pillow decreases outwards, and the contact with the host rock may be marked by a zone of fine-grained quartz and plagioclase which may belong either to the host or pillow.

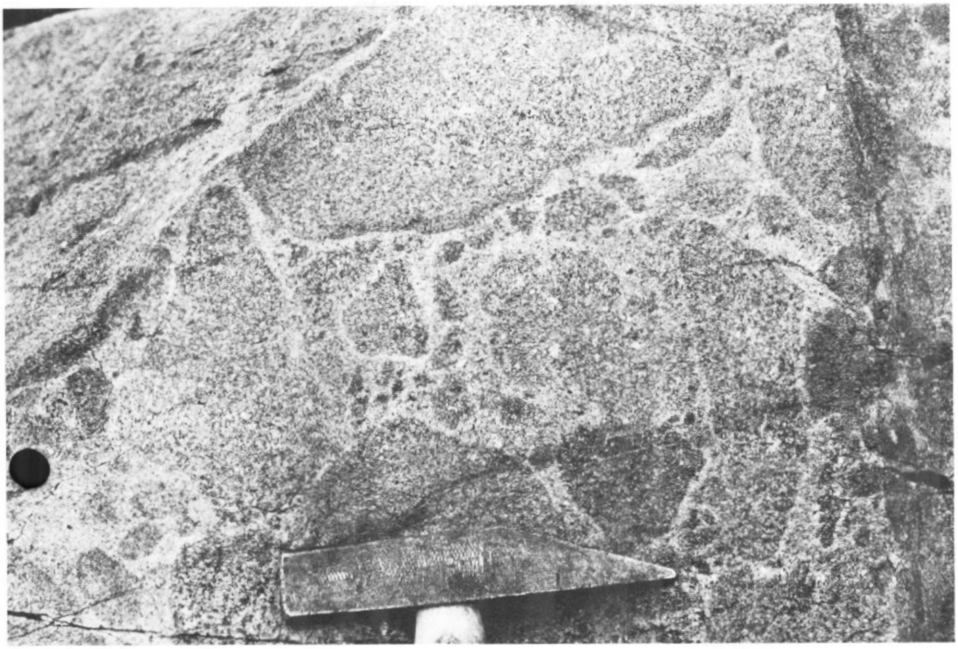

Fig. 8. 'Pseudobrecciated' appearance of host rock at locality JB.603. Hammer head is approximately 15 cm long.

Dykes

Three different types of mafic to intermediate dykes can be recognized: aphyric, trachytic-textured, and phenocryst-rich. The aphyric dykes are generally fine-grained with an intergranular texture of plagioclase and amphibole, and a variable proportion of biotite and opaque oxide. There is no petrographical evidence of any pyroxene in these rocks, although the fibrous amphibole does in part appear to be actinolitic in composition and therefore is probably secondary. These dykes are commonly 1–2 m wide with no consistent strike direction.

The trachytic-textured dykes are mafic or intermediate in composition but may be heavily altered: they have a characteristic alignment of the groundmass plagioclase. Small phenocrysts (1 mm) of plagioclase are present, and the rock often appears to be seriate-textured. Phenocrysts of (?)amphibole are pseudomorphed by epidote and actinolite, and again there is no evidence for the rock having originally contained pyroxene.

The phenocryst-rich dykes are often wide (7–10 m) and are typified by abundant phenocrysts of plagioclase and amphibole. The plagioclase occurs as euhedral or subhedral crystals (up to 5 mm in length), commonly glomeroporphyritic, and may be heavily fractured and altered. It frequently displays continuous, oscillatory or patchy zoning, commonly with a well-defined zone of inclusions near its margin. Amphibole phenocrysts are generally smaller (1–3 mm), subhedral or euhedral, although acicular crystals are also present. Lamellar twinning is common, and the composition appears to be magnesio-hornblendic, but many crystals are highly altered to secondary fibrous amphibole and biotite. Pyroxene phenocrysts have been observed only rarely, but it is interesting to note that they are generally smaller than coexisting amphibole phenocrysts. The groundmass is usually an intergrowth of plagioclase,

Fig. 9. Cataclasite vein cutting leucocratic host rock at locality JB.628, Nupkins Island. Hammer head is approximately 15 cm long.

amphibole and opaque oxide, with varying proportions of quartz, accessory biotite and apatite.

At locality JB.605, samples of a phenocryst-rich dyke show evidence of syn-magmatic pneumatolytic activity. Amphibole and plagioclase phenocrysts appear fragmented in outline, the latter with oscillatory zoning intersecting the crystal boundary. Small clastic veins cut some plagioclase phenocrysts but not the groundmass, suggesting that a high initial volatile content has ultimately led to gas release during crystallization.

Cataclastic veins

These veins are characterized by a cataclastic texture with dynamic recrystallizati[illegible] no planar fabric has been observed except for small, late-stage shears. Transport of material has taken place along these veins with no relative movement between adjacent blocks of host rock, as indicated by the inclusion of exotic fragments and by the observation that the veins cut enclaves without relative displacement. There also appears to have been considerable metasomatism along these veins, with abundant epidote, (?) hydrogrossular garnet, ferro-actinolitic amphibole and opaque oxide being present. Whether this metasomatism accompanied pneumatolysis or post-dated it is unknown.

Discussion

The concept that mixing of two contrasting magma types could ultimately result in intermediate compositions has been advocated for many decades, but has always been regarded as somewhat of a localized or minor modifier of other more fundamental

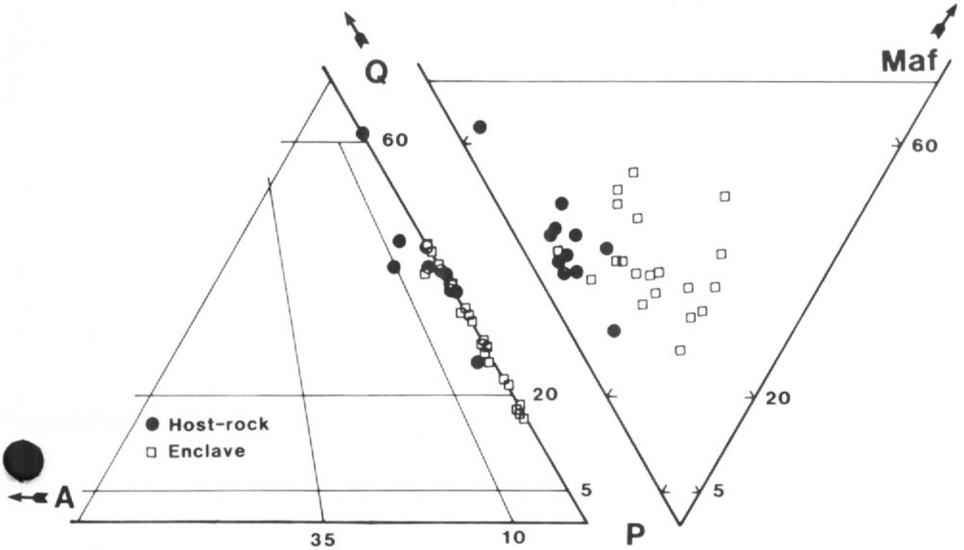

Fig. 10. Modal proportions of quartz (Q), alkali feldspar (A), plagioclase (P) and total mafic minerals (Maf) in samples of host rock (filled circles) and enclaves (open squares).

processes such as partial melting or fractional crystallization. This is usually a result of the recognition of the great differences in the physical properties that two contrasting magmas would have to overcome, such as temperature, viscosity, density and the very slow rate of chemical diffusion, all of which combine to inhibit mixing. Despite these objections, there are numerous documented cases where two different magmas have coexisted (magma mingling), thus providing at least the initial requirement for mixing (see reviews by Blake and others, 1965; Walker and Skelhorn, 1966; Yoder, 1973; Vernon, 1984). The contemporaneity of two or more magmas has been clearly demonstrated in many high-level situations such as composite dykes and ring-dyke complexes (Wiebe, 1973; Vogel and Wilband, 1978) and net-veined intrusions (Didier, 1973; Marshall and Sparks, 1984). Recent investigations into many calc-alkaline volcanic areas have resulted in detailed petrographical and geochemical data to support the hybrid nature of many of these rocks (e.g. Eichelberger, 1975; [illegible]derson, 1976; Sakuyama, 1981; Grove and others, 1982; Gerlach and Grove, 1982). Convincing evidence for magma mixing has come also from many plutonic terranes, where interpretation of textures and chemistry is necessarily more difficult, e.g. the Nain anorthositic complex (Wiebe, 1980; Wiebe and Wild, 1983), the Cape Breton Island diorite (Wiebe, 1974), the Tichka Massif, Morocco (Vogel and Walker, 1975) and at numerous localities throughout the British Tertiary Province (Vogel, 1982; Vogel and others, 1984). Much of the evidence for magma mixing in plutonic rocks centres on the interpretation of 'microgranitoid enclaves', which are a characteristic feature of many orogenic granitoids. Such enclaves have been interpreted as representing xenoliths of country-rock, the restite phase from partial melting, and as the product of magma mingling. Current opinion strongly favours the last possibility (Vernon, 1983; Cantagrel and others, 1984).

As a prerequisite to magma mixing, it is important to establish the coexistence of contrasting magmas, and in this respect the Jinks Island Complex offers several lines of evidence. The sub-spherical or rounded shape of all the enclaves is unlike that of wall-rock or accidental inclusions, and suggests that they are not xenoliths. The crenulate margins of many enclaves is particularly characteristic of liquid–liquid contacts (Wager and Bailey, 1953) and the presence of finer-grained margins to some 'pillows' reinforces this, suggesting chilling of the mafic magma. The elongate crystal forms in the pillows, in particular the radial- or spherulitic-textured plagioclase, suggests crystallization under rapidly cooling conditions (Logfren, 1974; Eichelberger, 1980) and the acicular, hollow apatite crystals have also been reproduced experimentally through quenching in the presence of a volatile-phase (Wyllie and others, 1962).

The relatively sharp contacts observed between the host and pillows in the Jinks Island Complex suggest that little interaction has taken place, and that mingling occurred at a relatively shallow level, where heat loss is more rapid than in deeper-seated complexes (Bishop, 1963). However, the wide variety of pillow types observed within the complex, and the moderate variability of the host rock (see Fig. 10) suggest that more intimate mixing has occurred, though not necessarily at the currently exposed level. The wide range of compositions also suggests that the comp[illegible] has suffered several episodes of mafic magma injection, as would be expected in a high-level or sub-volcanic chamber (Didier, 1973). The cataclastic veins prevalent throughout the Pitt Islands are interpreted here as resulting from volatile release during mixing, and possibly reflecting volcanic eruption (Sparks and others, 1977). Earthquake activity or similar movement associated with volcanicity may have caused disturbance in a quasi-solid magma chamber, resulting in the 'pseudobrecciated' appearance of some of the rocks.

There is a growing acceptance that many intermediate rocks may be produced via magma mingling and mixing, particularly in orogenic areas. It should be noted, however, that some investigations into net-veined complexes specifically reject the contemporaneous nature of the magmas, preferring models in which a later silicic magma utilizes and invades a pre-existing mafic dyke feature (e.g. Chapman, 1962; Windley, 1965; see also McBirney, 1980). Recent experimental investigations suggest that two contrasting magmas will rapidly attain thermal equilibration, and their subsequent ability to mix more thoroughly then depends on the resultant differences in their other physical properties (Furman and Spera, 1985). Sparks and Marshall (in press) suggest that complete hybridization (i.e. mixing) will occur when both magmas behave as liquids at the same temperature. Enclave formation resulting in pillow complexes (i.e. mingling) results when the proportion of mafic magma is small or when it is effectively a solid due to a high crystal content. Also, although chemical diffusion between magmas is too slow to produce intermediate mixes before cooling, Kou[illegible] & Sunagawa (1982, 1983) have demonstrated that vigorous convection could promote mixing in, for example, a volcanic neck. Modelling of the fluid-dynamical properties of a high-level magma chamber has also shown that the injection of hotter, denser material into the base of a cooler, lighter one may result in mixing by convective overturn after crystallization and cooling have reduced temperature and density contrasts (Huppert and Sparks, 1980; Huppert and others, 1982). The role of volatiles in promoting equilibration of initial density contrasts and thus intimate mixing has also been advocated in this respect (Eichelberger, 1980; Huppert and others, 1982), to the point where volatile build-up may be the trigger for volcanic eruption (Sparks and others, 1977). If a large viscosity contrast exists between the two magmas, then viscous stresses almost inevitably lead to significant mingling (Huppert and others, 1983). In a recent review, Sparks (1983) suggested that magma mixing was an inevitable consequence of the recharge and eruption process operative in a high-level magma chamber, although during long periods of quiescence fractional crystallization and partial melting could contribute significantly to chemical diversity. Therefore, the occurrence of magma mixing and its significance in the genesis of the calc-alkaline suite would appear to have been firmly established, although its relative importance with respect to other petrogenetic processes will continue to cause debate.

In summary, the following model for the generation of the Jinks Island Complex is proposed:

(i) Hot, mafic magma was injected into a relatively high-level (possibly sub-volcanic) siliceous magma chamber, possibly as a series of dykes.

(ii) The resulting rapid cooling and crystallization of the mafic material produced a pillow complex, with limited reaction between the two magmas.

(iii) Periodic injection and mixing of fresh mafic material gave rise to a series of pillow types, whereas the host rock showed only limited variability.

(iv) The volatile-rich nature of the complex, which may have initially facilitated mingling, ultimately resulted in venting of the magma chamber; this is reflected now by the cataclastic veins pervasive throughout the area.

The Jinks Island Complex provides the first record in the Antarctic Peninsula region of a high-level association between plutonic and volcanic rocks, and it also demonstrates that magma mixing may have been an effective process in the generation of some intermediate members of the calc-alkaline suite.

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