THE GEOLOGY OF POURQUOI PAS ISLAND, NORTHERN MARGUERITE BAY, GRAHAM LAND

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ABSTRACT. The results of geological reconnaissance mapping are presented. No metamorphic complex rocks are seen on Pourquoi Pas Island, the oldest rocks being granodiorites, which are apparently overlain by a varied succession of volcanic strata totalling more than 1 500 m. The junction may be a pre-volcanic erosion surface. The full thickness of volcanic strata is referred to the Antarctic Peninsula Volcanic Group, and the possibility of older Palaeozoic volcanic activity there is refuted. Andean plutonic rocks form an intrusive complex in the western half of the island, with very varied lithologies and intrusive forms. Some molybdenite mineralization occurs in a granite. Post-Andean hypabyssal rocks are not common. A major, probably post-Andean, shear zone intersects the south-eastern corner of the island, with a substantial downthrow on its northern side. This is a major feature which can be traced some distance farther north and may be related to a fracture zone in the Bellingshausen Sea.

PHYSIOGRAPHY

POURQUOI PAS ISLAND (lat. 67°41′S, long. 67°30′W) is mountainous and heavily glacierized (Fig. 1). An approximately V-shaped system of glaciers diverges from Dalgliesh Bay, one arm running northward and isolating the high mountain massif of Perplex Ridge to the west; the other running eastward towards Nemo Cove and bounding another major mountain chain to the south which includes Mount Verne (1 633 m), the highest peak on the island. These valley glaciers afford access to a well-exposed though often precipitous inland area. The north-eastern quadrant of the island is less well exposed, being largely covered by the snowfields of Mount Arronax (see Fig. 2).

STRATIGRAPHY

Most of the eastern half of Pourquoi Pas Island consists of volcanic rocks of the Antarctic Peninsula Volcanic Group but some gaps still exist in the detailed geological mapping of this area and exposure is generally poor. The central and western parts of the island show a varied suite of plutonic rocks intruded into volcanic rocks. The general stratigraphy is summarized in Table I.

TABLE I. THE STRATIGRAPHY OF POURQUOI PAS ISLAND

Andean plutonic suite	Granite (veins and intrusions)
	Intermediate rocks
	Banded and basic rocks
Hypabyssal rocks	Basic dykes
Antarctic Peninsula Volcanic Group	Tuffs, agglomerates and lavas
"Older" plutonic suite	Granodiorite and diorite
Antarctic Peninsula metamorphic complex	Xenoliths in volcanic rocks

Antarctic Peninsula metamorphic complex

No rocks belonging to this group, or showing any metamorphic foliation, have been found *in situ* on Pourquoi Pas Island; this is an absence which may be significant. Some gneissic fragments have been found in the volcanic succession, particularly in basal strata (see below),

Fig. 1. Aerial view of Pourquoi Pas Island from the west. Dalgliesh Bay in the foreground (right). Mainland plateau of Graham Land under cloud in the background.

but no lithologies have been found that could be correlated with established types from elsewhere in Marguerite Bay.

"*Older*" *plutonic suite*

The main occurrence of suspected pre-volcanic igneous rocks is in the Lainez Point area, in coastal exposures. A coarse-grained heterogeneous white "granite" is exposed on the shore at station E.2347, which is similar in appearance to the "older" granite of the Mount Searle area of Horseshoe Island (paper in preparation by D. W. Matthews) and which contains similar irregular black crush lines and stringers.

In thin section the rock is a quartz-diorite, with pale greenish brown hornblende as a primary mineral, and as an alteration product of colourless clinopyroxene which is preserved as relics in some hornblende crystals. Chlorite and an opaque mineral are also commonly present as alteration products of hornblende. Plagioclase is the only feldspar and this is very strongly zoned but only moderately altered. Quartz is a common accessory as interstitial unstrained grains. An opaque mineral is scattered throughout the rock. In one part of the thin section of specimen E.2347.3, small clinopyroxene granules appear to have formed due to thermal metamorphism. The reason for this is uncertain but it is clear from this single thin section that considerable disequilibrium existed in the rock, due apparently to incipient

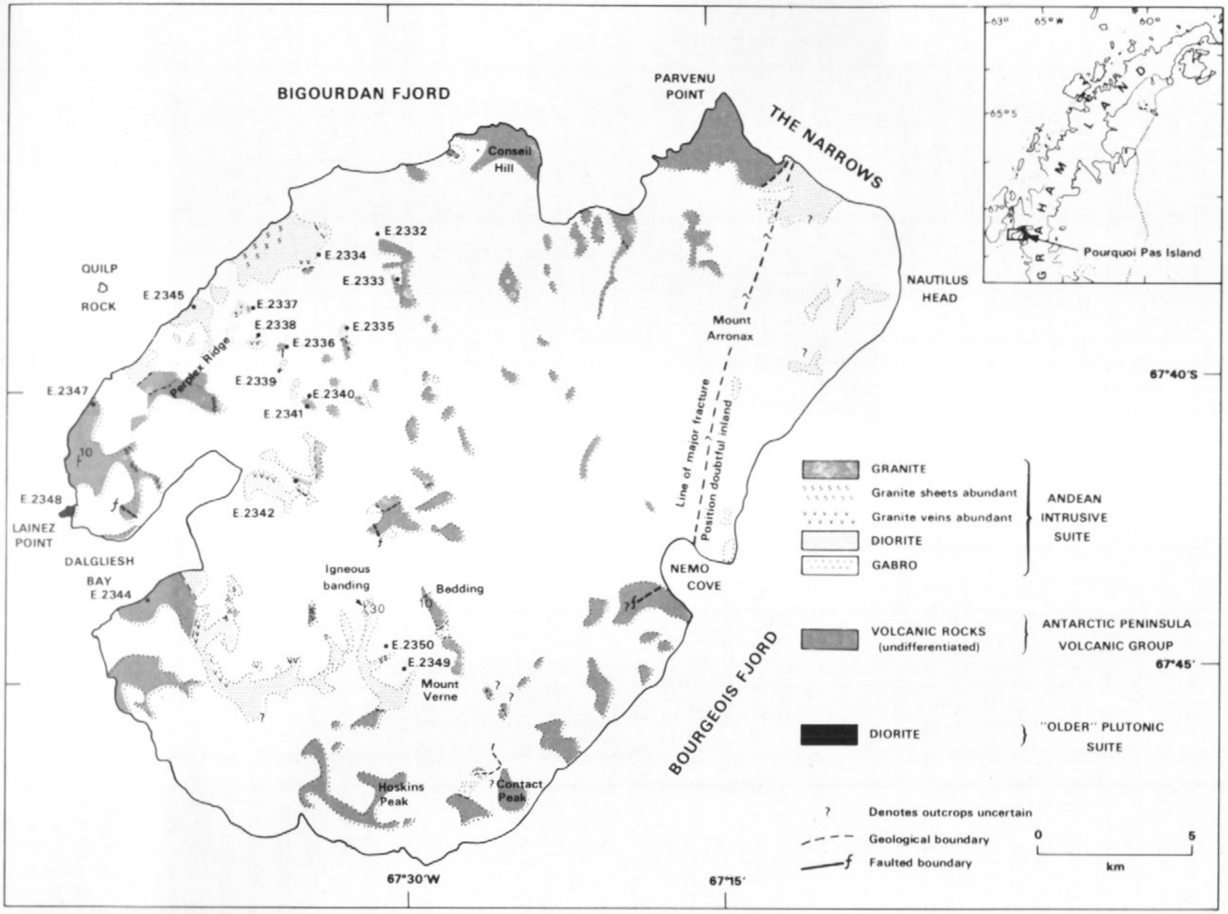

Fig. 2. Geological sketch map of Pourquoi Pas Island showing station numbers.

thermal metamorphism. This could be related either to volcanic or to later plutonic events.

A great thickness of volcanic rocks overlies this diorite. At the base of the succession at Lainez Point, very coarse fragmental rocks containing large boulders of metamorphic complex gneisses and of pale quartz-diorite lie directly on the diorite surface. The remarkable feature of these boulders is that they are mainly well rounded and up to about 0.5 m in diameter. There is no evidence that the diorite has intruded the volcanic rocks, the boundary being an irregular surface with, apparently, a shallow dip to the north-east under the main mass of the volcanic succession. Rocks on either side of the boundary show very little alteration. It is therefore likely that the basal volcanic strata are here resting on an irregular pre-volcanic erosion surface (Adie, 1954) and that the diorite belongs to an older pre-volcanic intrusive suite which has been exposed by erosion. A considerable time interval is necessarily implied.

In the coastal exposures and islets around station E.2348 and Lainez Point itself, both diorite and volcanic (agglomeratic and extrusive) rocks occur but without an exposed contact between them. The pattern of outcrop is so irregular that faulting is assumed to be at least partly responsible. The diorite varies considerably but it is thought to be all part of the same original mass. In one place it shows a crude, thin, vertical compositional banding and in several outcrops it has a darker more basic appearance without banding.

A more doubtful and as yet imperfectly known occurrence of possible pre-volcanic plutonic rocks lies within the poorly exposed area between Parvenu Point and Nautilus Head. Pale diorite, not unlike the Lainez Point lithology, occurs here and is strongly sheared, particularly near Nautilus Head. Relations with adjacent volcanic rocks to the west are not known. The shearing is, however, likely to be related to a major structure through Scree Cove on Blaiklock Island to the east and of probable post-volcanic age. Therefore, there is only lithological evidence on which to classify this diorite and it could well be Andean.

The overall petrographical character of this postulated suite of pre-volcanic plutonic rocks therefore remains obscure. Limited but convincing field evidence from Horseshoe and Pourquoi Pas Islands argues strongly in favour of their existence as a distinct suite, although the lithologies do not differ greatly from Andean intermediate and dioritic intrusive rocks.

Antarctic Peninsula Volcanic Group

The whole of the eastern half of Pourquoi Pas Island consists of volcanic rocks, except for intrusive rocks in the Nautilus Head area. They are a varied sequence of tuffs, agglomerates and relatively few lavas, with a total thickness in excess of 1 500 m. There is no positive evidence of age on Pourquoi Pas Island but there are marked similarities with the thick volcanic sequence exposed on nearby eastern Adelaide Island (Dewar, 1970).

The western half of the island consists largely of plutonic rocks intruding volcanic rocks which remain as a screen along parts of the south and west coasts. Several of the spectacular mountains of this area consist entirely of volcanic rocks and thus show a continuous succession at least 1 500 m thick, the bedding being near-horizontal.

General characteristics of the volcanic strata on Pourquoi Pas Island are the great preponderance of fragmental rocks, the absence of any intercalated sediment and the scarcity of visible stratification over considerable areas and thicknesses. The alteration of the rocks is often extensive, with an abundance of epidote, limonite staining, etc. This can, on occasion, be seen to be confined to particular horizons, or simply to irregular patches several hundred metres in size. The main areas of volcanic rocks are described from west to east.

In the cliffs above Lainez Point, layering of grey and thicker yellowish bands is especially prominent at about 300 m above sea-level. The bands average an estimated 15 m in thickness, though this varies considerably both laterally and from one band to another. The base of the whole volcanic sequence is taken to be the "boulder agglomerate" (Adie, 1954) at station E.2347 and the irregular surface of diorite between stations E.2347 and 2348. The boulder deposit, a framework conglomerate, contains boulders mainly of crystalline gneisses and less often of diorite, from a few centimetres to 0.5 m in size. The boulders are mostly rounded to sub-rounded and the matrix is largely pyroclastic. The degree of rounding and relative lack of matrix suggest that flood-water transport could be a possible mechanism but the nature of the matrix is such that in places it looks like crystalline andesitic lava. Transport and erosion of boulders by a lava stream seems unlikely, as does inundating of an unconsolidated boulder bed by lava. It is possible that the matrix represents welded tuff material but it cannot be said with any certainty whether or not the boulders were transported within the welded tuff or whether subsequent recrystallization has obscured the original nature of the matrix.

In the Lainez Point area there is a great abundance of near-vertical basic dykes cutting the volcanic sequence, suggesting a feeder system for lavas higher in the succession. These features tend to suggest rapid accumulation of pyroclastic and extrusive rocks of essentially local derivation, with no great lateral continuity. They also suggest that the Lainez Point area may be close to a major eruptive centre, with an initial catastrophic outburst producing the basal boulder deposit followed by rapid accumulation of ejecta, effusive rocks becoming more common later on and better preserved further from the eruptive centres. The incipient metamorphism of the underlying diorite could be due to the high heat flow introduced by local vulcanicity, with rapid burial and proximity to hot eruptive centres contributing to the extensive alteration seen. Coarse agglomerate, with a vertical margin through volcanic lithologies but containing numerous fragments (often rounded) of pale diorite similar to the Lainez Point "older" diorite, is seen in the cliffs overlooking the point. This very probably represents an original vent margin.

The volcanic rocks on the north-west side of Dalgliesh Bay have a more altered appearance, being richer in pyrite and epidote, which give a yellow or rusty colour to weathered surfaces. The limit of this alteration seems to be a vertical line in the cliffs several hundred metres along the coast into Dalgliesh Bay, with relatively unaltered quartz-hypersthene-andesite beyond this to the north-east. In thin section, these more altered rocks contain abundant oligoclase phenocrysts, considerably altered, in a groundmass of plagioclase laths almost completely obscured by alteration products. A very pale green acicular amphibole is common in crystals up to 0.5 mm long and as much smaller needles; both habits are apparently secondary. Pale yellow pleochroic epidote is common as granules scattered throughout the rock, together with an opaque mineral. Several pseudomorph-like aggregates consist of coarse-grained epidote intergrown with chlorite, the whole aggregate surrounded with a rim of dense granular epidote. Although no primary mineral remains, these are thought to be pseudomorphous after pyroxene.

The degree of alteration of this rock is considerable but apparently local. Rusty-weathering volcanic rocks are seen at several horizons in the sequence on the south side of Dalgliesh Bay and it is suggested that these are comparable to the occurrences mentioned by Adie (1954). The presence of volcanic rocks of early Palaeozoic age in this area was inferred by Adie (1954) on the basis of their degree of alteration and their similarity to metamorphosed volcanic rocks of northern Alexander Island. However, no evidence of Adie's "stratigraphic or erosional break separating the lower from the upper volcanics" in Dalgliesh Bay was seen by the writer and it is thought to be very unlikely that such an older group exists.

Two areas of volcanic rocks on north-western Pourquoi Pas Island were examined in some detail:

i. The peak and buttresses near the north-west corner of the island (E.2332 and 2333).
ii. At station E.2344 in the south-west of the island.

At the former, the lithology is decidedly variable but without regularity or bedding. The dominant type is a dark fine-grained porphyritic andesitic extrusive rock which, in thin section, is moderately to heavily altered so that the abundant plagioclase phenocrysts are obscured by carbonate and the groundmass is indeterminate. Rusty weathering is marked

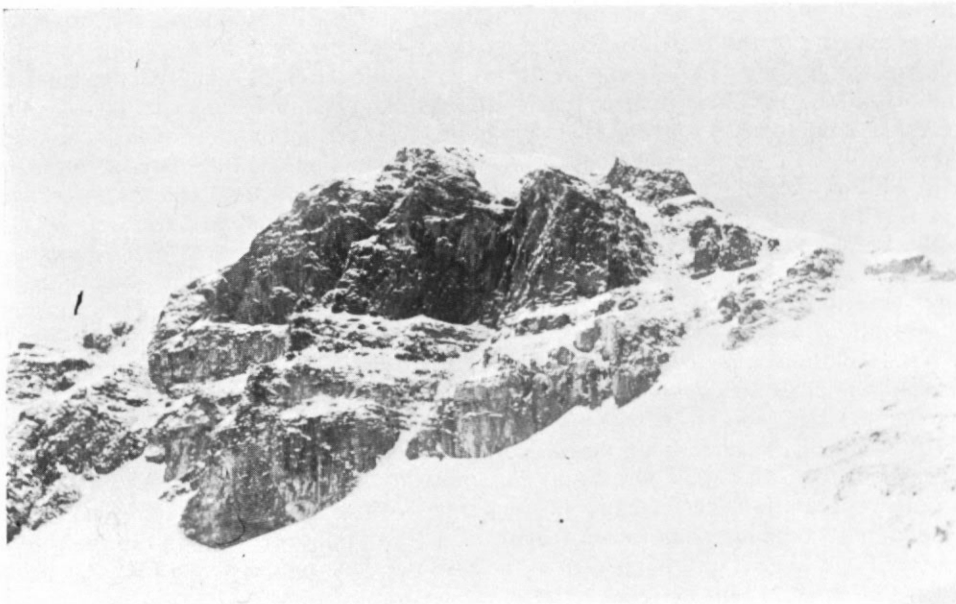

Fig. 3. Cliff section in volcanic rocks at station E.2333 (overall height 300 m approximately).

in places with macroscopic pyrite. Acid rocks are scarce but they are slightly less altered as also are the agglomerates which here contain no pre-volcanic fragment lithologies. One very unusual rock type occurs in an apparently vertical body without distinct margins; it is a fine-grained basic rock with large (5–7 cm) spherical yellow patches and many smaller less regular yellow patches. The patches themselves are homogeneous, except for an inner concentric dark shell in some larger examples, and they have sharp margins so that they can be detached easily and cleanly from the rock. In thin section, their host rock is unexceptional, containing abundant quartz and epidote, while the yellow blobs consist almost entirely of fine granular epidote. Their origin is unknown.

At station E.2333, the dark porphyritic extrusive rocks are confined to the upper half of the cliff, while the lower half (Fig. 3), below a prominent horizon with a slight south-westerly tilt, is more noticeably banded. One or two thick (2–3 m) greenish bands occur at this horizon but the lower part of the cliff consists of paler more acid volcanic rocks with a vague vertical jointing and a faint but definite banding which varies in dip from horizontal to moderate westerly or south-westerly. At the base of the cliff, which is approximately 300 m high, is a dark green extremely heterogeneous volcanic rock. It has irregular dark- and pale-coloured patches whose origin is uncertain but possibly primary. The base of this unit becomes homogeneous and fine-grained against coarse agglomerate underlying it at the very lowest exposures. It could therefore be a product of ignimbritic eruption with a pronounced chilled base.

Although these rock types are varied, scree and moraine debris at these localities in north-western Pourquoi Pas Island shows an even greater variety of lithologies, presumably derived from areas to the east and south. Almost every common volcanic lithology is represented, from ultra-fine-grained near-glassy types, through spherulitic, porphyritic and coarser-grained rocks, to breccias and agglomerates. It must be assumed that these are all represented in the volcanic sequence.

The second area of more detailed observation was the ridge above station E.2344 along the south side of Dalgliesh Bay, approximately 8 km south-east of Lainez Point. The lower south-west end of the ridge is formed of fine-grained andesitic to basaltic lavas, mainly non-porphyritic, with some tuff and agglomerate. The groundmass of these lavas is moderately altered and plagioclase phenocrysts are often heavily altered. Primary ferromagnesian minerals are rare, nearly always being replaced by calcite, chlorite and epidote. The middle section of the ridge is formed of more weathered rocks with wide scree gullies; some rusty-weathering acid volcanic rocks (probably lavas) are almost totally eroded away but dark flinty lava horizons and patches of greenish agglomerate remain. At approximately 700 m above sea-level, the ridge steepens abruptly into great towers and cliffs of fresh massive agglomerate resting on an horizon of fine-grained purple tuff above yellowish rusty-weathered rocks. This may possibly be an horizon of regional extent. The upper parts of the mountain, which are largely inaccessible, show broad near-horizontal banding wedging out laterally and are thought to consist mainly of agglomerate. Plutonic igneous fragments are conspicuously scarce in these higher agglomerates, porphyritic volcanic lithologies being predominant, and this is consistent with the fact that eruption in this area must already have had to penetrate approximately 1 km of volcanic strata.

Along the south and south-east coasts of Pourquoi Pas Island, near-horizontal, moderately well-stratified volcanic strata are exposed in mostly inaccessible faces such as Contact Peak. Intrusion by later plutonic masses is seen in several places as far as Nemo Cove, where crystal tuffs and fine agglomerates on the east side of the cove show a strong gneissic foliation and dip approximately 70° to the north-west. This is interpreted as an extension of the same shear zone that has affected plutonic rocks farther north-east and is linked to the same structural event.

On the north coast of the island, the volcanic succession contains a preponderance of tuffs with andesites and basalts, some of which show marked red bole tops. At the north end of the ridge east of Moider Glacier, individual tuff horizons vary down to a few centimetres in thickness. A prominent massive purple tuff is also overlain by purple agglomerate but, although the colour is unusual, its cause is not known and only a tentative correlation can be made with the similar horizon above Dalgliesh Bay.

Andean Intrusive Suite

The majority of the intrusive rocks of Pourquoi Pas Island are exposed in a belt trending north–south across the west end of the island from the north end of Perplex Ridge to Contact Peak. A wide range of plutonic rocks is represented from gabbro to granite. The overall impression is that there is a single sequence of intrusion from basic to acid and that all the rocks in the belt may belong to a single igneous complex. A few isolated intrusions elsewhere may be unrelated. The level of exposure is generally rather high.

Where seen, the contact between plutonic intrusions and volcanic rocks is very brecciated and veined, usually by diorite or granite. Granite, in particular, is often intruded into volcanic strata or Andean diorite in the form of large regular sheets, or as complex veins and brecciation. Relationships within the igneous suite are even more complex and in many places are not yet understood. The sub-divisions described below may therefore prove somewhat arbitrary when details of their chemistry and genesis are known.

Basic rocks

Several distinct occurrences of gabbro represent the earliest magmatic event and they are clearly intruded into the volcanic sequence. First, at the extreme northern end of Perplex Ridge, a coarse dark uniform gabbro is intruded by granodiorite on its south side along a plane contact dipping at 70° to the north-east but it is not itself in contact with volcanic strata. In thin section, it shows labradoritic plagioclase, very slightly clouded by sub-microscopic inclusions and rimmed by more sodic plagioclase. Colourless clinopyroxene is the dominant ferromagnesian mineral, also containing fine inclusions, but altered extensively to pale blue-green actinolitic hornblende. Minor but significant constituents are orthoclase, quartz and brown biotite, which make this gabbro decidedly acid and potassic.

Secondly, south of station E.2335, a similar gabbro crops out in two masses on the east side of the long north-westerly trending ridge, apparently intruded and locally modified by granite on the west side and with unknown contact, probably intrusive, against volcanic rocks on the east side in a small spur at the col between the two glaciers. In thin section this gabbro is markedly similar to that from Perplex Ridge and may be part of the same mass. It differs from the former rock in containing a small percentage of hypersthene, more clinopyroxene and no potash feldspar.

Other occurrences of gabbro are at station E.2342, forming the summit of a prominent

Fig. 4. Banded gabbroic rocks at station E.2341. A "large-feldspar" band shows just below centre at the left of the picture. Ramifying acid bands and veinlets are abundant.

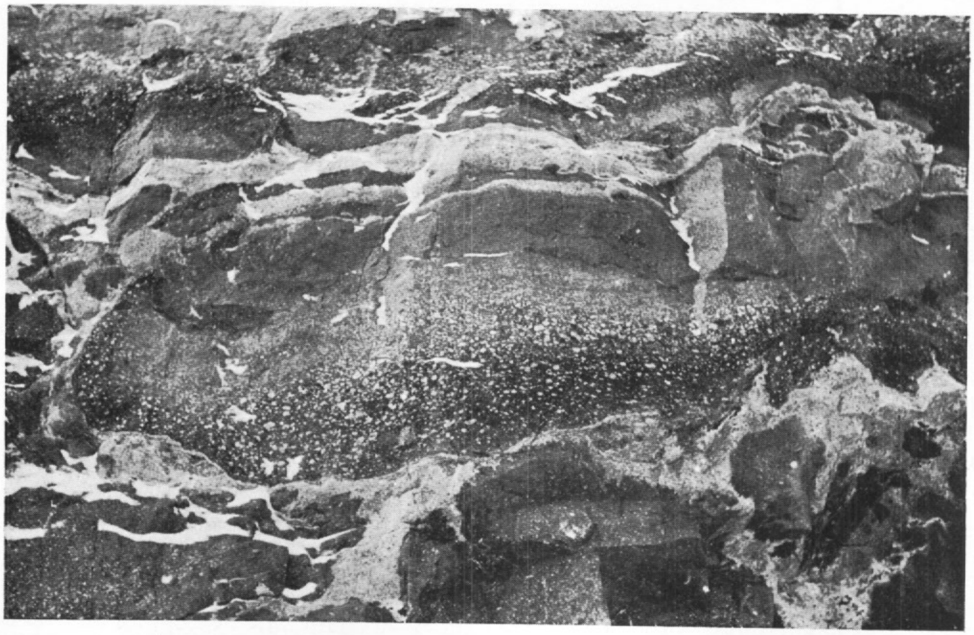

Fig. 5. Detail of a porphyritic "large-feldspar" band at station E.2341.

pyramidal shaped peak, on the north ridge of Mount Verne as a vertical sheet between granitic and volcanic rocks, and in the south face of Contact Peak, where the volcanic rocks turn over to a steep northerly dip adjacent to gabbro. A dolerite or microgabbro occurs along the north side of Dalgliesh Bay but its field relations are not known and it could be related either to nearby volcanic rocks or to the Andean intrusive rocks seen to the north.

Banded rocks

There are several occurrences on Pourquoi Pas Island of conspicuously banded rocks, intermediate to basic in composition, and apparently limited in extent. They may be related to some of the unusual rock types found elsewhere in isolated exposures, for instance, on Horseshoe Island (paper in preparation by D. W. Matthews) and Quilp Rock.

The most striking form of banding is that resulting from concentrations of large feldspar crystals and this has been examined at two particular localities (E.2338 and 2341). At the latter, an elevated and completely isolated buttress shows the following pattern. The lower part of the cliff is a virtually unbanded medium-grained grey gabbro which forms the host lithology for the banding. The banded sequence starts in the middle of the buttress with one thick dark band (approximately 1 m) overlain by three thin paler bands (less than 0.5 m), alternating with intervening layers of grey gabbro, all contained in a height of approximately 5 m (Fig. 4). In the upper part of the buttress the dark bands predominate. They are coarse-grained, have a shallow north-easterly dip and show exceptionally porphyritic coarse margins up to 15 cm thick with the upper margin usually being thicker than the lower (Fig. 5). Porphyritic bands without a coarse dark centre also occur in the gabbroic host rock. The spacing of these bands is not regular and some are not continuous laterally but gradually pinch out. Many thin pale-coloured acid bands also occur, often seeming to divide the cliff face into repetitive units of banded rock each containing an upward sequence from basic to acid. This appears, however, to be an oversimplification and, although the acid bands usually occur at the boundaries between other banded lithologies, they are irregular and ramifying, and have relatively sharp margins. They are considered to be later than the basic banding and possibly controlled by it but not necessarily related to it.

In thin section, the assemblages and textures of these banded rocks are decidedly unusual. The darkest banded lithology consists essentially of hornblende, olivine and biotite, in order of decreasing abundance, but only the olivine is normal in appearance; it has a composition in the range 20–50% fayalite and is present as large fresh crystals showing only marginal alteration to carbonate, chlorite and actinolite. The hornblende occurs as large (approximately 1 mm) fresh crystals showing the vivid red-brown to pale brown pleochroism of a kaersutite, with some blue-green actinolite as marginal alteration, and it forms more than half the volume of the rock. The biotite also has pleochroism of a very reddish tinge, from red-brown to almost colourless, and often has margins in which the pleochroism is only very weak though of the same colour. The overall texture is not primary, crystals of the three principal minerals existing in a felted mass of secondary carbonate and fibrous amphibole, with no quartz or feldspar present.

The porphyritic rock immediately above the dark band consists mainly of very large (3–5 mm), fresh composite plagioclase crystals separated by smaller amounts of a matrix of olivine with green-brown hornblende together with some colourless clinopyroxene and an opaque mineral, neither of which is present in the dark band. These large plagioclase crystals show characteristic albite and Carlsbad twinning and often consist of several orientations intergrown within a single crystal with a markedly rectangular outline. They are composed of labradorite (An_{60-65}) and are uniform in composition except for an occasional thin zoned rim. In the border between the dark and the porphyritic bands, both the olivine and the plagioclase show locally increased cracking and alteration, and the size of the plagioclase phenocrysts increases upwards away from the dark band to reach a maximum of 1 cm.

The upper margin of the porphyritic band is slightly diffuse like the lower margin and gives way to a dark grey medium-grained lithology with a normal gabbroic texture and assemblage. Olivine and slightly pleochroic orthopyroxene are present in minor amounts but colourless clinopyroxene is the dominant ferromagnesian mineral. It is only slightly altered and has a granular texture. Some green-brown hornblende is present and also a little biotite. Fresh plagioclase laths form the bulk of the rock and are heavily zoned in the labradorite-andesine range. An opaque mineral is an abundant accessory. At the junction with underlying porphyritic rock the large plagioclase phenocrysts are almost completely altered, decreasing in size upwards towards the gabbro, but remaining heavily altered for some distance into it. Coarse brown hornblende is very abundant at this junction but it becomes finer-grained into the gabbro. Coarse-grained epidote is abundant, probably as an alteration product of plagioclase, and sphene is a prominent accessory mineral.

Finally, the very pale acid rock invading the banded sequence shows an unusual texture in thin section. It consists mainly of plagioclase crystals with irregular margins and patchy twinning, more resembling a metamorphic than an igneous texture. The plagioclase is albite-rich, is slightly altered to granular epidote and often encloses larger crystals of slightly pleochroic epidote. Very pale green hornblende is present as scattered subhedral crystals, some having cores of a slightly darker green colour. Epidote is the only other mineral present in any amount and it forms 10–20% of the rock.

The second important occurrence of banding, at station E.2338, covers the whole of a large buttress on the west side of the same pass. A variable grey basic rock lithology is extensively brecciated and invaded by granite which forms about 30% of the cliff face. The basic host rock shows no regular structure in the upper part of the cliff apart from some dark raft-like xenoliths, possibly gabbroic, several metres long. In the lower part of the cliff, however, there is one discrete darker mass about 30 m long and 10 m thick with near-horizontal banding; this is very similar in appearance to that at station E.2341 and, like it, includes a highly porphyritic type. The spacing of the bands differs from that at station E.2341, the units being thicker, and there is only one well-developed dark band; apart from this, the similarity between the two occurrences is remarkable and the abundance of similar scree specimens at station E.2338 suggests that there may be more examples higher in the cliffs.

In thin section, the relations between zones is not as clear as at station E.2341 but the lithologies are essentially similar. The hornblende and biotite in the dark band are less highly coloured and of a more normal less reddish pleochroism, while the amount of olivine present is very much less and it has reached a more advanced stage of alteration.

The acid rock invading this cliff face and cutting across the mass of banded rock has some hornblende and plagioclase as well as orthoclase and quartz, and is granodioritic. In its contact facies, it is chilled and slightly porphyritic with coarse plagioclase and therefore it may be related to the plagioclase-rich type at station E.2341.

These two occurrences of banded rocks may indicate the presence of a distinctive rock series within the Andean group, and a few isolated outcrops of hitherto unknown affinity can be correlated with them with some certainty in view of the unusual lithologies involved. On Horseshoe Island (near station E.2324) (paper in preparation by D. W. Matthews), there is an occurrence of an extremely porphyritic rock apparently as sheets in a more even-grained grey gabbroic host, the whole occupying an isolated outcrop surrounded by foliated granites. In thin section, the porphyritic rock consists of slightly clouded and altered basic plagioclase crystals, often forming well over 50% of the volume of the rock, as on Pourquoi Pas Island, with a matrix that differs slightly in being more acid with greenish brown hornblende, plagioclase, orthoclase and quartz (showing well-developed graphic intergrowth) but without olivine or biotite. The distribution of the more acid parts of the matrix is irregular and patchy, and it is possibly due to later contamination. The non-porphyritic rocks are also slightly different from the Pourquoi Pas Island types and are more dioritic than gabbroic, with hornblende, plagioclase, biotite and orthoclase but no pyroxene.

Quilp Rock, an isolated group of islets about 3 km off the west coast of Pourquoi Pas Island, consists of heterogeneous basic rocks, for the most part only slightly porphyritic, but containing apparently random patches of the coarse "big feldspar" lithology very similar to that on Pourquoi Pas Island. In thin section, besides the usual large labradoritic plagioclase crystals moderately altered in this instance, there is common olivine altering to fibrous amphibole and an opaque mineral, and a little almost colourless clinopyroxene with slightly pleochroic pink hypersthene. Colourless to pale blue-green amphibole is very abundant, often in large crystals enclosing plagioclase, olivine and biotite, and in places showing a reddish brown core in company with reddish biotite.

These occurrences all have in common the distinctive labradorite-rich rock. Their age is uncertain but, although the occurrence on Horseshoe Island is associated with older foliated rocks, the associations on Pourquoi Pas Island are decidedly Andean. Banding, where seen, is within 10° of the horizontal at both of the important localities on Pourquoi Pas Island, and this suggests strongly that the banding has formed *in situ* and is undisturbed except in the more patchy occurrences like Quilp Rock. The occurrences on Pourquoi Pas Island are only 11 km apart at the maximum but that on Horseshoe Island is approximately 25 km from the nearest locality at station E.2341 on Pourquoi Pas Island. The genesis of this group of rocks is problematic and has not yet been studied chemically. That they are a type of igneous cumulate is almost certain but any explanation of their origin must take into account the following general observations. No simple sink or float mechanism is adequate to explain the banded features but the bands must indicate quiescent evolution of a magma in a terrain which is otherwise notable for the complexity of its intrusive events. There are strong signs of late-stage alteration localized at certain horizons, particularly the boundaries of bands. The mineralogy suggests a slightly alkaline and hydrous magma, possibly near

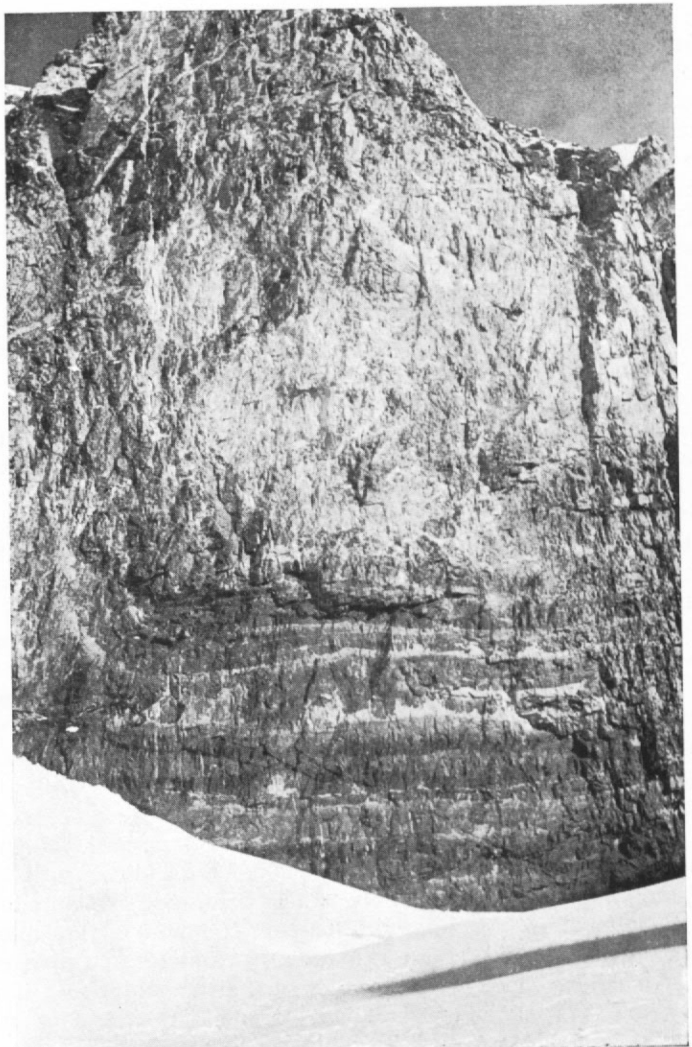

Fig. 6. Banding in basic rocks at station E.2349.

gabbroic in composition, with a kaersutitic hornblende in places. The mineralogy also suggests a substantially contaminated magma with olivine, two pyroxenes, hornblende and biotite all appearing though with as yet uncertain overall disposition. The unbanded gabbros described above are not dissimilar and could well be related. Closely associated plagioclase-rich acid rocks may also be genetically related but they show signs of emplacement at a slightly later stage.

At station E.2349, on Pourquoi Pas Island, further banding was seen but of a different character and lacking the spectacular porphyritic rock types. A repetitive upwards variation in colour from dark to pale grey is associated with prominent white "granite" which occurs as layers between some of the more basic bands. The acid layers normally have a sharp (though it is sometimes gradational) lower margin and a characteristically sharp though irregular and blebby upper margin (Figs 6 and 7). Thicker acid sheets with a purplish core sometimes cross the normal banding which, at this locality, is folded through a right-angle

Fig. 7. Detail of Fig. 6.

in a cliff face about 100 m high. In the angle of the fold, several large irregular masses of a similar granite show in the cliff face with purplish centres but white margins.

In thin section, these banded rock types show moderate to heavy alteration, particularly of the plagioclase, and have a very confused and irregular texture. The darkest lithology is gabbro, with a little olivine, abundant colourless clinopyroxene altering to hornblende and a moderate amount of brownish hornblende usually associated with grains of an opaque mineral. The plagioclase is basic and strongly zoned, and shows a very irregular texture. As the rock becomes paler grey in colour upwards, hornblende increases in amount, the alteration of pyroxene to hornblende becomes more extensive and olivine disappears. Quartz appears as rare interstitial grains and then in the pale grey upper part of the bands, quartz and potash feldspar become significant in amount, with some graphic intergrowth of the two. The discrete acid bands are granodioritic in composition but they are very altered and heterogeneous. Hornblende is pale green in colour and is mostly altered to chlorite; it is the only ferromagnesian mineral present. Plagioclase is present as large cracked and altered crystals which seem to be invaded by potash feldspar along cracks in some crystals. Quartz and potash feldspar, with graphic intergrowth, are present mainly as aggregates interstitial to the plagioclase.

Other possible examples of a similar though fainter banding were seen at station E.2350 and in cliffs near the south-east corner of Dalgliesh Bay. In both of these cases the banding appears nearly horizontal without any structure comparable to the large fold at station E.2349.

This second group of banded rocks has some similarities with the non-porphyritic parts of the banding described from stations E.2338 and 2341, but it is much more widely developed and shows a greater number of bands in a more regular pattern. The large fold, approximately monoclinal, at station E.2349, could be due to some large displacement of the mass before solidification of the rock was complete. The purple-white granite in bands and in the angle of the fold is probably related to the nearby Mount Verne granite, to which, also, the high degree of alteration of these banded rocks may be attributed. They are assumed to be magmatic in origin and are similar in many ways to the feldspar-rich banded rocks described above. The main difference may be in the composition and abundance of the parent magma, in this case giving rise to a type of igneous banding more widespread in occurrence.

Intermediate rocks

On Pourquoi Pas Island, diorites and other intermediate plutonic rocks are abundant, often closely associated with acid rocks, and many inaccessible areas have been mapped as "diorite" only on the basis of two main characteristics observable from a distance: a medium grey colour similar to normal diorite and intrusion or veining by later granite. Further sub-division on lithological and genetic differences is not yet practicable, the rocks themselves showing such great variability on both a large and small scale. This heterogeneity and the great abundance and variety of xenoliths of volcanic, gabbroic and other igneous rock types suggest that, in any case, there is not likely to be much constancy or simplicity in evolution of the magmas. It is thought likely that the whole suite of rocks may form an intrusive complex with a distinct outer limit such as the huge xenolith screen in the southern mountains of Pourquoi Pas Island. Within the complex, which occupies most of the western half of the island, a number of closely spaced intrusive events with extensively hybridizing and contaminating magmas is suspected, quite distinct from the more static cooling which allowed coarse crystal cumulates to form. Age relations with the banded rocks are not clearly displayed but consistent evidence shows that the gabbros were earlier and the granites (described below) always later than the dioritic rocks.

The largest mass of intermediate rock forms the northern and central parts of Perplex Ridge and shows a number of interesting features. At station E.2334 it is a variable grey diorite, considerably altered, but with some clinopyroxene remaining as cores in pale blue actinolitic hornblende. It is veined and intruded by granite at the southern end of the cliffs with a conspicuous granite boss over 100 m high. Numerous angular and rounded diorite (?) xenoliths can be seen in the granite, the latter type in "whorls". At the northern end, the diorite appears to grade into fresh granodiorite, pale grey in colour and containing abundant small dark xenoliths. The same granodiorite occupies a tract of gentler angled mountainside approximately 1 km long and intrudes gabbro at the north end of Perplex Ridge. Also at station E.2334, in the middle of the diorite cliff, a large vertical body about 10 m wide appears to consist of igneous breccia with masses of coarse dark porphyritic rock, which, in thin section, is only slightly more basic than the host diorite. It has a higher proportion of unaltered pyroxene but has a definite ophitic texture that is inherited by the hornblende which has replaced pyroxene. Interstitial material in this breccia is more normal diorite but it contains an abnormal number of epidote-filled vugs. Breccia of this kind suggests complex emplacement of successive dioritic magmas at shallow depth, possibly related to each other.

The west side of this same part of Perplex Ridge, in cliffs overlooking the coast, shows large regular granitic sheets from 10 to 30 m thick, dipping shallowly westward, intruded into diorite. Farther south along Perplex Ridge, at station E.2345, the rock is dioritic to granodioritic with small dark xenoliths which, as at station E.2334, are apparently volcanic rather than gabbroic. At station E.2337, diorite is the main rock type, intruded by only one granite sheet and some granitic veins. The diorite itself is variable throughout this western-facing area, having in places a highly xenolithic or a brecciated appearance.

Two other major masses of diorite occupy the north-east corner of Dalgliesh Bay and the northward-trending spurs to the west of Mount Verne. These also show extensive granite veining and intrusion, and in places a faint banding of unknown nature. In thin section, the variability of this rock becomes even more apparent. The commonest type is a quartz-diorite with some relict clinopyroxene and with interstitial quartz as a significant modal constituent but it is exceptional in showing moderate zoning of the hornblende (a pale brown variety) in the cracked and corroded state of the plagioclase and in the abundance of micrographic intergrowth of quartz and potash feldspar. Varieties of this assemblage include types with porphyritic plagioclase (resembling the highly porphyritic banded types described above) and with a smaller percentage of ferromagnesian minerals, particularly hornblende.

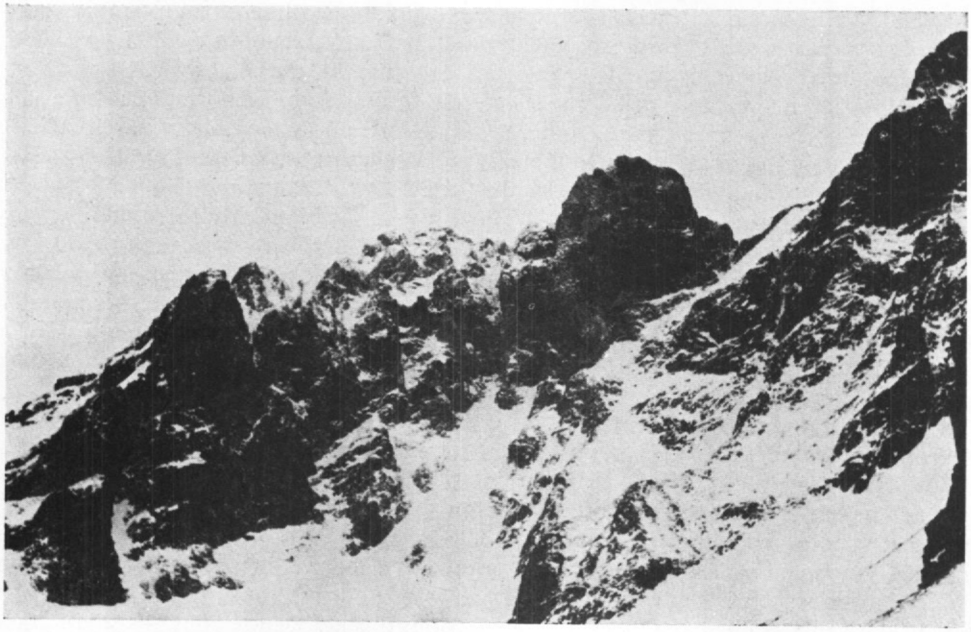

Fig. 8. Large-scale brecciation of volcanic rocks by granite on southern Pourquoi Pas Island.

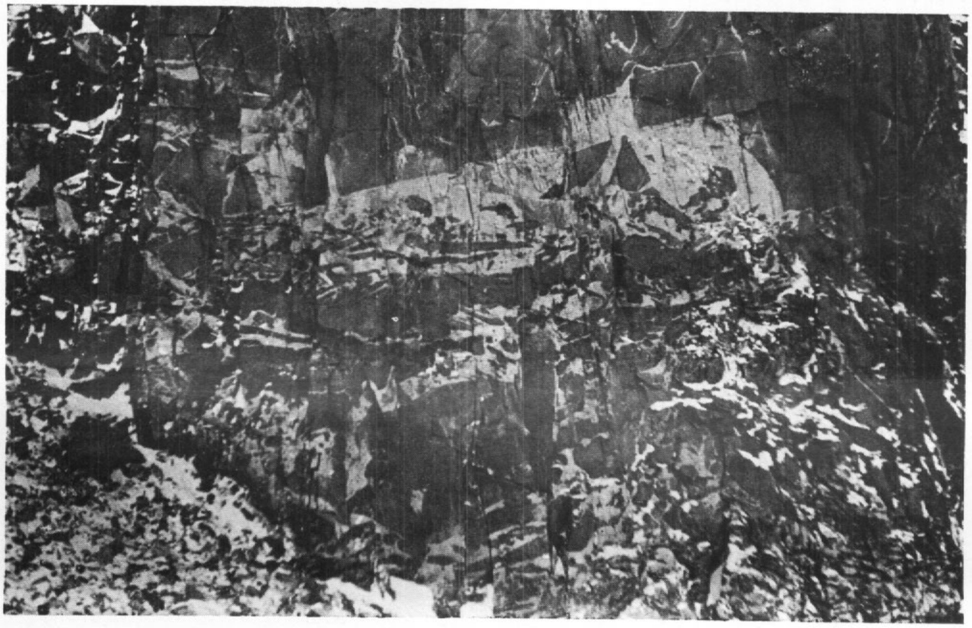

Fig. 9. Detail of stoping of diorite by granite at station E.2341.

Acid rocks

Granites occur on Pourquoi Pas Island in several distinct intrusive forms, as veins and infilling of brecciated older rocks (usually diorite or volcanic rocks), often on an immense scale (Figs 8, 9 and 10); as large regular sheets up to 30 m thick, near-horizontal and sometimes with a faintly banded aspect; and as large masses of plutonic dimensions, possibly sheet-like in form, two in particular showing spectacular and distinctive xenolithic contact zones.

Granite occurring in veins and breccias is largely altered and slightly contaminated due to its proximity to more basic rocks. The sheet granites have a more normal petrography and are coarse-grained and pale pink in outcrop. They are particularly well developed in the Perplex Ridge area and in the spurs to the east of Dalgliesh Bay, where their dip is generally less than 20° to the south. In thin section, they consist predominantly of quartz and potash feldspar, with chlorite and some plagioclase. They are usually altered. Micrographic intergrowth of quartz and potash feldspar is very well developed in a granophyre sheet in the Mount Verne area and the lithologies in this area tend to be purplish in colour and sometimes porphyritic. The overall distribution of the sheet and vein forms of intrusion in the western and southern parts of the island shows some regularity, suggesting emplacement at a shallow level with a definite relation to intrusive activity farther east or south. The full significance of this outcrop pattern is not yet understood.

The larger plutonic granites of western Pourquoi Pas Island have much in common petrographically with the sheet intrusions but they are more variable, particularly in their relations with other rocks. The boss intruding diorite at station E.2334, for example, is a simple adamellite, while farther south at station E.2335 the long ridge at the head of the glacier is formed of granodiorite with a pronounced granophyric texture. At station E.2336, adamellite is intruded over grey xenolithic diorite with a sharp contact dipping approximately 20° to the north-east. It is slightly vuggy and shows a band just above the contact containing abundant dark fine-grained xenoliths. In thin section, this adamellite contains small amounts of biotite, hornblende, chlorite and microperthitic orthoclase, while the xenoliths consist of plagioclase laths crowded with small granular crystals of clinopyroxene and biotite, and are probably of basic volcanic rock.

Fig. 10. Irregular, often sheet-like, intrusion of granite into diorite at station E.2354.

At station E.2340 nearby, the situation is similar, with pink granite overlying heterogeneous intermediate rocks on a near-horizontal contact but the xenolithic zone in this granite above the contact is here extremely well developed (Fig. 11). For approximately 10 m above the contact, the granite is coarsely xenolithic and contains sub-rounded fragments up to 30 cm in diameter; above this is a zone approximately 1 m thick containing uniformly smaller xenoliths less than 8 cm in diameter. These zones are remarkably regular and sharp margined, and the size and spacing of the xenoliths is extremely regular, the size decreasing gradually upwards away from the contact except for an abrupt change at the boundary between the two zones. Below the contact, the more basic rock is extensively veined by pale grey "granite" and itself contains large elongated, probably volcanic, xenoliths up to 1 m long of dark fine-grained rock with conspicuous phenocrysts.

In thin section, this pink granite at station E.2340 is normal though with a smaller

Fig. 11. Highly xenolithic contact at margin of granite (above) at station E.2340.

plagioclase and ferromagnesian content than elsewhere. The xenoliths are dioritic to gabbroic in composition but, except for the raft-like xenoliths at the base, all are marginally recrystallized to a finer grain-size. The phenocrysts visible in the hand specimen are relics of large plagioclase phenocrysts, now heavily altered and corroded, and groups of coarse epidote (?) porphyroblasts have the appearance of pseudomorphs after original phenocrysts. Epidote is very abundant in the plagioclase of all the xenoliths, as coarse-grained aggregates and as prismatic intergrowths with pale green acicular hornblende, possibly indicating its derivation from diopsidic pyroxene. The precise origin of the xenolithic material remains unknown but the presence of large plagioclase phenocrysts suggests the banded series which crops out nearby, rather than volcanic rocks, as a probable source.

Mount Verne, the highest peak on the island, consists largely of a prominent pink granite-porphyry stock with an irregular outline. A similar lithology is seen in minor intrusions nearby and at station E.2342, so that a distinct magmatic type seems to have evolved and been emplaced separately from the coarser pink granite of north-west Pourquoi Pas Island. Granite of a similar appearance but not definitely correlated is also found as a sheet near Conseil Hill and more doubtfully near Nautilus Head, where it must post-date the strong shearing affecting diorite in that area.

Hypabyssal rocks

Distinct late dykes are rare in the Andean rocks of Pourquoi Pas Island compared with the abundant basic dykes seen cutting the volcanic formation. Occasional basic dykes cut granite-porphyry on Perplex Ridge. Numerous vein, dyke and sill complexes of acid material cut diorites and other rocks, for instance, on Perplex Ridge, but these are closely related lithologically to the plutonic granites (which they do not cut) and are most probably marginal effects of the larger intrusions. The form of the latter is not known with certainty but it may be laccolithic in north-west Pourquoi Pas Island.

STRUCTURE

In the absence of folding and of normal faulting on anything other than a local scale, the only major structure on Pourquoi Pas Island is the apparently major shear zone which intersects the south-east corner of the island. At Nemo Cove, a cataclastic foliation, locally intense and mylonitic, trends north-east with a near-vertical north-westerly dip. Epidote and limonite appear in later cross-cutting veinlets (unpublished notes of P. H. Grimley). In plutonic rocks, feldspathic augen are left between foliae but in volcanic rocks the mineralogy is largely or entirely destroyed.

The structure is interpreted as a major shear zone, continuing with slight curvature across the centre of Blaiklock Island, where it clearly divides massive batholithic granite from volcanic strata similar to those of north-eastern Pourquoi Pas Island. While the horizontal displacement along the shear zone is unknown, it is clear that at least 1 000 m of vertical displacement are involved, bringing down volcanic strata to the north. It is assumed that the same structure must continue south-westward down Bourgeois Fjord and separate Horseshoe Island from Pourquoi Pas Island, while its northward curving extension lies clearly through the physiographic trough of the Heim–Antevs Glaciers system to Lallemand Fjord. LANDSAT-1 imagery shows the shear zone as a pronounced feature.

The major shear zone intersecting the central isthmus of Horseshoe Island (paper in preparation by D. W. Matthews) has a near-parallel trend and may well be a related structure, although its north-easterly extent is not known. It, too, shows an inferred downthrow on its north side, though of unknown magnitude, but on the other hand it is more precisely dated in being apparently earlier than the brick-red granite (one of the latest of the Andean granites).

The occurrence of major shear zones in this area of Marguerite Bay is interesting in that they may be related to the Tula fracture zone in the Bellingshausen Sea (Herron and Tucholke, 1976). The trends of the structures do not, however, appear to be compatible and the eastern end of the oceanic fracture, although still imperfectly located, cannot yet be traced through the submarine edge of the shelf.

Mineralization

Occurrences of metalliferous mineralization on Pourquoi Pas Island are confined to two types on surface-outcrop evidence. First, the volcanic rocks contain concentrations of pyrite visible in the hand specimen, for instance, at station E.2332 near the north end of Perplex Ridge, which are presumed to be secondary in origin. Alteration of the lavas has to some extent oxidized the pyrite and limonite staining is very widespread. Secondly, Andean granite in the centre of the island (E.2336) is slightly vuggy just above its contact with diorite and the vugs show quartz, epidote and molybdenite. This granite and the Mount Verne porphyry are potentially the most likely sources of metalliferous mineralization, and the alteration and postulated high level of erosion suggest that Pourquoi Pas Island is potentially at least as important in this respect as Horseshoe Island, although it does not show comparable copper mineralization at the surface. The area, in general, is one of suspected earlier Andean igneous activity, not particularly alkaline in character, and is therefore not the most likely area for large concentrations of metals (Sillitoe, 1976). The alteration needs more detailed examination before it can be related to the type of alteration zoning associated with metalliferous mineralization common in the younger igneous rocks of the Andean Cordillera.

Discussion

The absence of metamorphic complex gneisses on Pourquoi Pas Island and the substantial thickness of volcanic rocks preserved suggest a relatively shallow level of erosion compared with the rest of Marguerite Bay but a comparable level to that seen on Arrowsmith Peninsula and Adelaide Island to the north and west. The major dividing structure between Horseshoe and Pourquoi Pas Islands is almost certainly represented by the major shear belt intersecting the south-east corner of Pourquoi Pas Island and is apparently late or post-Andean. The level of exposure within the plutonic complex centred in western Pourquoi Pas Island should therefore be correspondingly shallow.

The occurrence of a basal boulder bed to the volcanic strata imposes some further constraint on erosion level and it seems probable that the pre-volcanic erosion surface in this area dips shallowly eastward. It is cut into quartz-diorites and similar lithologies, superficially similar to postulated pre-volcanic intrusive rocks on Horseshoe Island. This contrasts with the more pronounced topography of the pre-volcanic erosion surface cut in metamorphic complex gneisses on Millerand Island approximately 60 km to the south (Fraser, 1962). The existence of a distinct suite of pre-volcanic plutonic rocks in northern Marguerite Bay is strongly supported by evidence from Pourquoi Pas Island, although petrologically the suite is still obscure. No radiometric data are yet available and superficial comparisons with other localities in Graham Land are unproductive because of the variability of the rocks. What is significantly shown by the Pourquoi Pas Island exposures, if the interpretation in this paper is correct, is the existence of a substantial time interval between emplacement of the "older" suite and eruption of the volcanic formation. At least 1 km of overlying strata must have been eroded away in this interval.

In excess of 1 500 m of volcanic strata are exposed, massive and relatively poorly bedded near the base, and predominantly fragmental throughout but extremely varied as might be expected in an island-arc situation. Major eruptive sources in the Lainez Point and south-west Perplex Ridge areas are suspected on the grounds that the lower half of the succession is extremely massive and poorly bedded, and is cut by numerous dykes. Some evidence of actual vent margins is also seen. Alteration of the volcanic strata is patchy but extensively developed and hydrothermal in character. Its age is not known. No systematic evidence was seen of alteration confined to a lower and possibly older suite of volcanic rocks and the existence of such a suite is not supported by any other evidence.

Physical conditions during eruption of the Pourquoi Pas Island volcanic rocks are not known but the presence of some boles in the eastern half of the island and the apparently complete absence of water-lain tuffs supports the idea of mainly subaerial eruption with at least a few breaks in activity long enough to permit lateritic weathering.

Andean plutonic rocks range from an early rather potassic gabbro to a variety of late granites and granodiorites. Two types of banded complex are particularly interesting, it being relatively rare to see well-developed banding in the Andean province. The more extensively developed is a normal basic to acid banding from diorite to granodiorite but of great interest is a banding involving formation of a coarser plagioclase-rich lithology and rather potassic hydrous ultramafic assemblages. The genesis of these rocks is uncertain but the latter type may be related to early contaminated gabbro and probably includes isolated occurrences of similar "big feldspar" rocks seen elsewhere on Horseshoe Island and Quilp Rock.

Dioritic and related granodioritic rocks are the major rock types in the western half of the island and these are very variable and heterogeneous both on a large and a small scale. Banding is seldom seen but breccias and xenolithic masses are extremely common, suggesting extensive contamination and high-level emplacement of very variable and rapidly evolving magma. Acid intrusive rocks form both vein and sheet complexes within earlier Andean rocks. Larger plutonic masses are common and they vary from the Mount Verne porphyry to a coarser pink granite with molybdenite.

A major shear zone intersects the south-eastern corner of the island with as yet uncertain relations to regional structure.

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REFERENCES

ADIE, R. J. 1954. The petrology of Graham Land: I. The Basement Complex; early Palaeozoic plutonic and volcanic rocks. *Falkland Islands Dependencies Survey Scientific Reports*, No. 11, 22 pp.

———. 1964. Geological history. (*In* PRIESTLEY, R. E., ADIE, R. J. *and* G. DE Q. ROBIN, *ed. Antarctic research.* London, Butterworth and Co. (Publishers) Ltd., 118–62.)

DEWAR, G. J. 1970. The geology of Adelaide Island. *British Antarctic Survey Scientific Reports*, No. 57, 66 pp.

FRASER, A. G. 1962. The Upper Jurassic volcanic rocks of Millerand Island, Graham Land. *British Antarctic Survey Preliminary Geological Report*, No. 22, 15 pp. [Unpublished.]

HERRON, E. M. *and* B. E. TUCHOLKE. 1976. Sea floor magnetic patterns and basement structure in the south-eastern Pacific. (*In* HOLLISTER, C. D. *and* C. CRADDOCK, *ed. Initial reports of the Deep Sea Drilling Project*. Washington, D.C., U.S. Government Printing Office, **35**, 263–78.)

SILLITOE, R. H. 1976. Andean mineralisation: a model for the metallogeny of convergent plate margins. (*In* STRONG, D. F., *ed.* Metallogeny and plate tectonics. *Spec. Pap. geol. Ass. Can.*, No. 14, 59–100.)