BANDED GABBROS OF THE ANAGRAM ISLANDS, GRAHAM LAND

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Abstract. The Anagram Islands are composed of a suite of intrusive rocks which range in composition from olivine-gabbro to tonalite and which are clearly derived from a common parental magma. Vertical banding, consisting of a rhythmic repetition of gabbroic and anorthositic layers, occurs within a narrow zone in the north-western part of the island group. The complex pseudo-sedimentary structures exhibited by this banding are described and illustrated in detail, and their origin is briefly discussed. The injection of volatile-rich residual liquids into the banded gabbros together with late-stage magmatic alteration have caused the widespread development of amphibole at the expense of pyroxene and, to a lesser extent, plagioclase; the former process has also produced rocks which are relatively rich in iron ore.

During the summer of 1960–61, a limited amount of field work was carried out on the Anagram Islands, a group of small islands lying approximately 5 km. north-north-west of the Argentine Islands off the west coast of Graham Land in lat. 65°12′S., long. 64°20′W. (Fig. 1). Only one of the islands (Nob Island) has been officially named and therefore the others which are mentioned in this paper are referred to as islands (*1*), (*2*) and (*3*) (Fig. 2).

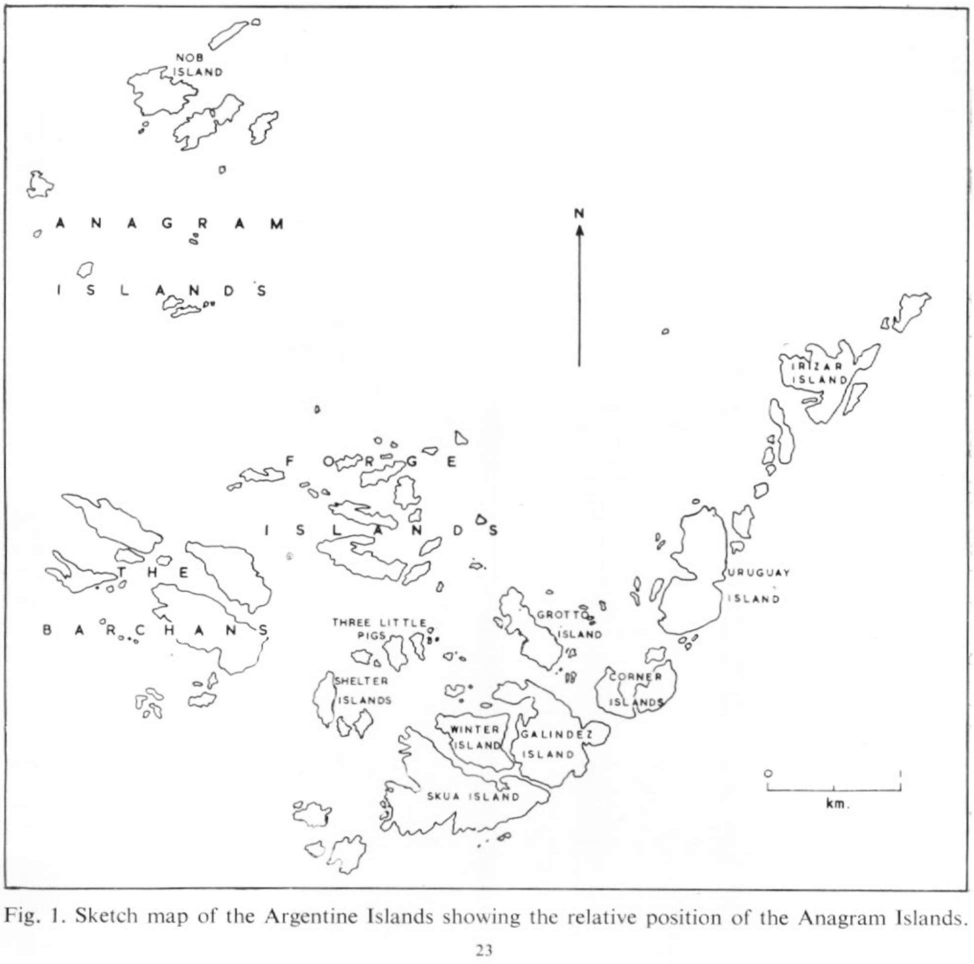

Fig. 1. Sketch map of the Argentine Islands showing the relative position of the Anagram Islands.

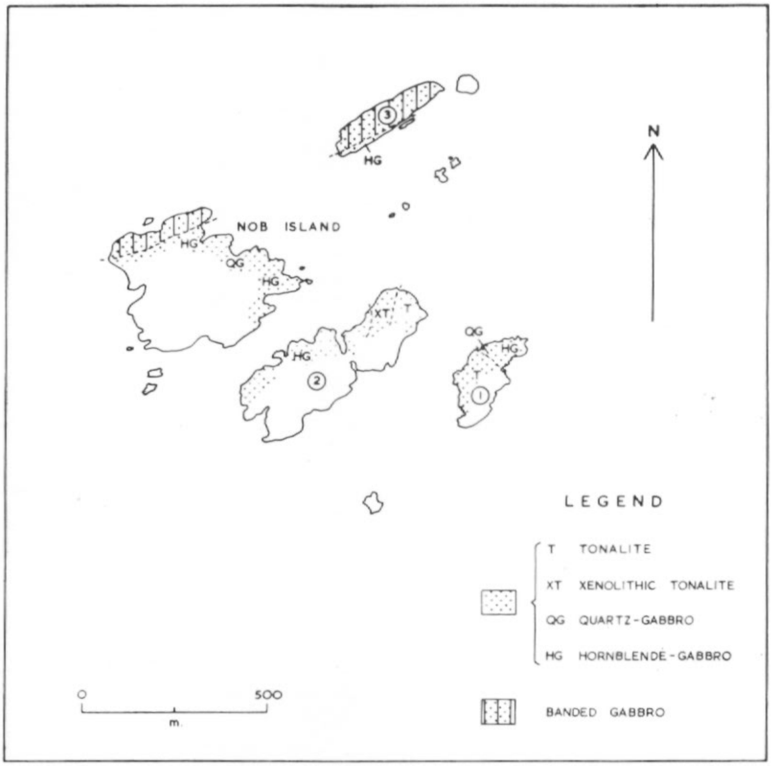

Fig. 2. Geological sketch map of the northern Anagram Islands.

General Field Relations

The Anagram Islands are composed of intermediate to basic plutonic igneous rocks with tonalite and olivine-gabbro as the extreme members of the series. Although there is no direct evidence of their age, their field and petrographic characteristics are closely similar to the intrusive rocks described by Hooper (1962, p. 27–31) and Goldring (1962, p. 26–39) which are known to belong to the Andean Intrusive Suite. In addition, the quartz-diorites and granodiorites of The Barchans and the Forge Islands, which intrude volcanic rocks of probable Upper Jurassic age, are almost certainly genetically related to the gabbros and tonalites of the Anagram Islands. These rocks are therefore probably late Cretaceous to early Tertiary in age (Adie, 1955, p. 4).

The main geological interest of the Anagram Islands centres on the banded gabbros which form an elongated zone trending south-west to north-east along the north-western margin of Nob Island and on island (*3*). The width of this zone has not been established but, since a small island situated about 0·8 km. to the north-west of island (*3*) is composed of structureless gabbro, it is probable that the banded zone is little more than 0·5 km. wide. An additional feature of interest is the widespread late-stage mineralization of the banded gabbros, producing rocks relatively rich in iron ore.

The distribution of the major rock types is shown in Fig. 2. On island (*2*) the contact between the hornblende-gabbros and the younger tonalites is marked by a broad xenolithic zone which has a maximum width of 75 m. There is a progressive decrease in the size and number of xenoliths with increased distance from the contact. A similar but much narrower intrusion breccia was observed along part of the contact between the gabbros in the banded zone and the adjacent homogeneous gabbros on the eastern edge of island (*3*). The occurrence of these xenolithic zones is regarded as having some significance, since it indicates a relaxation of confining pressure between successive phases of the Andean Intrusive Suite. This is in accordance with the findings of Grimley (1961, p. 3).

A narrow green altered porphyritic dyke intrudes the tonalite on the north coast of island (*2*); this is the only post-Andean dyke recorded in the Anagram Islands.

General Petrology

Although much of the available time in the field was spent in studying the banded gabbros, specimens of all the other rock types were collected and later examined microscopically. A full description and discussion of the banded gabbros is given later, but it should be noted that not all the rocks within the banded zone show a layered structure. The modal analyses of the rocks described in this section are given in Table I. With a few exceptions, all the plagioclase compositions quoted in the succeeding petrographic descriptions were obtained from combined Carlsbad-albite twins which are very common throughout this rock series, but especially so in the basic gabbros.

Table I. Modal Analyses of Major Rock Types of the Anagram Islands

	F.220.2	F.216.2	F.216.13	F.207.2	F.180.1	F.181.1	F.224.4
Quartz	—	—	—	2·7	10·3	16·6	33·3
Potash feldspar	—	—	—	—	2·0	3·7	—
Plagioclase	65·1	27·8	43·6	57·7	51·5	52·4†	54·1
Augite	19·5	39·1	29·6	9·4	13·0	1·3	—
Hypersthene	1·0	11·1	7·7	5·6*	9·6*	—	—
Olivine	5·2	1·7	‡	—	—	—	—
Hornblende	2·0	10·6	9·0	11·9	4·0	12·9	—
Biotite/chlorite	‡	‡	—	4·3	6·2	9·5	11·0§
Iron ore	7·2	9·7	10·1	7·1	3·4	3·3	1·1
Sphene	—	—	—	—	—	‡	—
Epidote	‡	‡	—	—	—	‡	‡
Apatite	—	—	—	1·3	‡	0·3	0·5
Zircon	—	—	—	—	—	‡	‡
Average plagioclase composition	An_{84}	An_{88}	An_{88}	An_{62}	An_{62}	An_{44}	An_{40}

* Includes talc.
† Includes sericite and prehnite.
‡ Present in small quantity.
§ Includes prehnite.

F.220.2 Olivine-gabbro, island (*3*), Anagram Islands.
F.216.2 Hypersthene-gabbro, island (*3*), Anagram Islands.
F.216.13 Gabbroic layer in banded rock, island (*3*), Anagram Islands.
F.207.2 Hornblende-gabbro, Nob Island, Anagram Islands.
F.180.1 Quartz-gabbro, island (*1*), Anagram Islands.
F.181.1 Tonalite, island (*2*), Anagram Islands.
F.224.4 Quartz-diorite, island (*3*), Anagram Islands.

Olivine-gabbro

The only occurrence of uniform olivine-gabbro in the Anagram Islands is in the zone of banded gabbros where it forms dykes and comparatively small, irregularly distributed masses. In the hand specimen, the olivine-gabbro is medium-grained, fresh in appearance and possesses a typical gabbroic texture (F.220.2). In thin section, the olivine ($Fo_{80}Fa_{20}$) is generally fresh and traversed by irregular cracks which are infilled with dusty magnetite or reddish brown haematite. The olivine is locally rimmed with hypersthene and, where olivine and iron ore have a common boundary, some reaction has taken place, producing a complex symplectitic intergrowth of hypersthene and ore. Apart from this mode of occurrence, hypersthene is uncommon. A narrow selvage of pale green amphibole forms round the olivine in places.

Augite, with $2V \simeq 60°$ and $\gamma{:}c = 42°$, tends to form large aggregates of subhedral to anhedral crystals, many displaying repeated twinning and possessing good Schiller structure. In places the clinopyroxene is partially margined by a deep brown hornblende which is probably a primary mineral phase. The hornblende also has orientated inclusions of iron ore.

The plagioclase is very fresh and has an average composition of $Ab_{16}An_{84}$. Combined Carlsbad-albite twins of primary origin are of the synneusis type (Vance, 1961, p. 1107) with highly irregular composition planes. Normal discontinuous zoning only occurs in the poorly twinned crystals, whereas patchy plagioclases are rather more widespread. This patchiness consists of small generally sub-rectangular areas of more sodic composition within the plagioclase and a few patches possess internal twinning which is independent of that in the surrounding host. Furthermore, the development of narrow secondary albite twin lamellae in several crystals clearly originates around these patches. The patches have a composition of approximately $Ab_{40}An_{60}$. Cloudiness, consisting of innumerable tiny specks of iron ore which exist in numerous discrete layers, is universal in the plagioclase. The sodic patches have relatively less clouding but a number have nuclei of larger specks of iron ore.

Two generations of titaniferous magnetite are present in the olivine-gabbro; most of the ore is primary and enclosed in the ferromagnesian minerals but some is definitely of late introduction, since it replaces the earlier silicates, notably plagioclase. Small flakes of pale reddish brown phlogopite cling to the magnetite.

A very narrow late-stage vein, consisting mainly of brown to greenish brown hornblende is present in the thin section. In the immediate vicinity of the vein, augite is extensively altered to hornblende and the plagioclase is partially saussuritized.

Hypersthene-gabbro

Like the olivine-gabbro, non-banded hypersthene-gabbros only occur as autoliths and dykes in the banded zone. One specimen (F.216.2) from a dyke is a medium-grained rock with a high colour index and with pyroxene crystals very prominent on weathered surfaces. The modal analysis reveals a low content of plagioclase and a high percentage of pyroxene. A subsidiary amount of olivine is present and both in its composition and paragenesis it is very similar to that in the olivine-gabbro, except that alteration to brown serpentine along cracks and at the margins is evident, while replacement by hypersthene has been considerably more active. In extreme cases, only remnants of olivine occur in the orthopyroxene. The hypersthene is moderately pleochroic with α = pink, β = light pink, γ = very pale green and $2V\alpha \simeq 70°$. It is consistently fresh and rare crystals attain 7 mm. in length. Augite again forms large aggregates in which earlier-formed plagioclases are enclosed, and both orientated inclusions of iron ore parallel to (001) and twinning on {100} are very prominent. Internal patchy alteration to brown amphibole produces a mottled extinction which is characteristic of the clinopyroxene.

The plagioclase has a maximum composition of $Ab_{10}An_{90}$. Although zoning is rare, several crystals have a slightly uneven extinction. In all other respects the plagioclase is identical to that in the olivine-gabbro. All the titaniferous magnetite appears to be primary and is always associated with the ferromagnesian minerals.

A narrow sinuous vein of greenish brown amphibole represents the late-stage introduction of volatile-rich material resulting in extensive replacement of augite and plagioclase by a strongly coloured amphibole, pleochroic from yellow-brown to deep brown. This replacement gives rise to overgrowths of amphibole on pre-existing minerals, creating an intricate network of hornblende which behaves optically as a single unit (Fig. 3a). One such overgrowth is

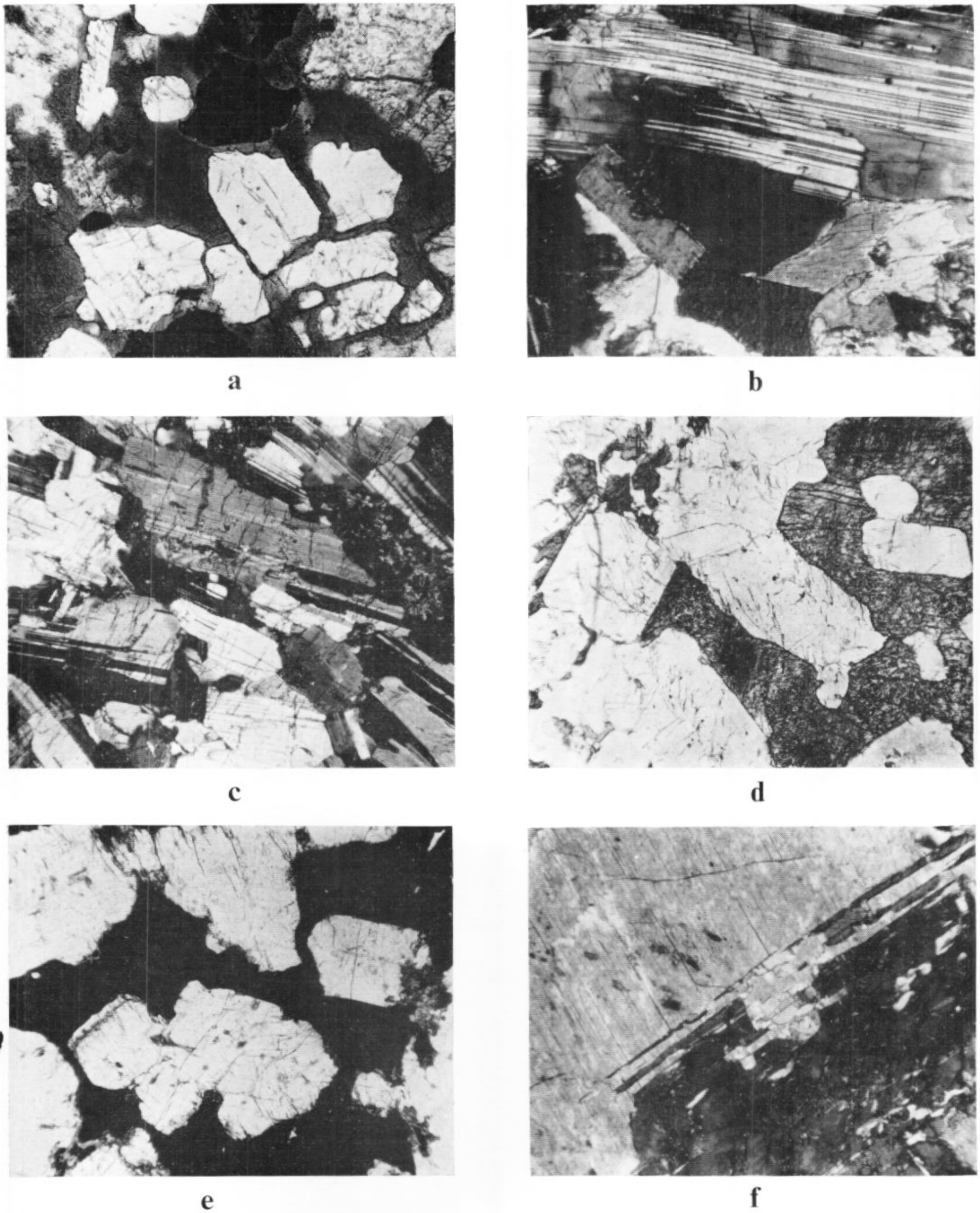

Fig. 3. a. Single large hornblende of secondary origin forming an overgrowth on pyroxene and enclosing several plagioclase crystals; hypersthene-gabbro (F.216.2; ordinary light; × 25).
b. Unstrained quartz, biotite and hornblende adjacent to a large plagioclase with conspicuous bent secondary twin lamellae; hornblende-gabbro (F. 207.2; X-nicols; × 80).
c. Anorthosite layer in banded gabbro, illustrating parallelism of plagioclase crystals (F.206.2; X-nicols; × 25).
d. Poikilitic and ophitic texture in banded gabbro (F.206.2; ordinary light; × 25).
e. Late-stage iron ore enclosing earlier-formed plagioclase; banded gabbro (F.206.2; ordinary light; × 25).
f. Lamellar intergrowth produced by replacement of plagioclase by hornblende; banded gabbro (F.227.6; X-nicols; × 45).

8 mm. across, and in it plagioclase has been particularly susceptible to replacement. This accounts for the high percentage of hornblende in the mode. The brown amphibole, which is probably rich in iron, is strongly schillerized with rods of iron ore parallel to (010) and (101). Any olivine close to the vein has been completely reduced to a scaly aggregate of talc and finely divided iron ore.

Hornblende-gabbro

Although hornblende-gabbros are widespread on the Anagram Islands, they are not uniform in composition and gradations into quartz-gabbro commonly occur. One hornblende-gabbro (F.207.2) from the eastern tip of island (*2*) is a massive medium-grained rock weathering a pale reddish brown.

In thin section, the ferromagnesian minerals tend to occur in distinct aggregates in which iron ore is generally abundant. Pyroxene is represented by both hypersthene and diopsidic augite; the hypersthene shows varying degrees of alteration to scaly talc, while the augite is invariably replaced by a strongly coloured hornblende having α = light brown, β = brown, γ = brownish green and $\gamma{:}c = 14°$. Replacement by hornblende may be extensive. Biotite is an essential mineral phase and has a characteristic deep foxy red colour, indicating a high iron content. It is closely associated with iron ore, and some grains of magnetite are completely enclosed in a single flake of biotite.

Compared with the olivine- and hypersthene-gabbro, the plagioclase in the hornblende-gabbro is distinctly more patchy and occasional oscillatory zoning constitutes an additional feature. Many crystals have a large calcic core and a sodic rim, but the growth of patches has considerably modified this zoning. There may be a substantial compositional range within a single plagioclase. For example, a few sharply zoned crystals have relict cores of $Ab_{12}An_{88}$ and margins of $Ab_{55}An_{45}$ with an intermediate patchy zone of composition $Ab_{37}An_{63}$. In most plagioclases, however, only compositions $Ab_{37}An_{63}$ and $Ab_{51}An_{49}$ are represented. Another difference in the plagioclase, compared with that in the more basic gabbros, is the more widespread occurrence of fine secondary albite twinning which again appears to have originated around patches. As the secondary glide twinning becomes better developed, it begins to eliminate the complex patchiness and zoning, and in rare crystals it can be demonstrated that the compositional differences are initially removed by individual lamellae. That is, those secondary lamellae which pass through the zoning and patchiness possess a relatively uniform extinction. The final product of this process appears in the form of evenly extinguishing crystals with highly developed twinning having a composition of $Ab_{38}An_{62}$. However, normal, discontinuous zoning commonly occurs at the margins to give an extreme edge of composition $Ab_{52}An_{48}$. Bending of secondary twinning is common, leading to fracturing and truncation of lamellae. Where conspicuous bending of the lamellae occurs, it is noteworthy that the contiguous minerals such as biotite, hornblende and quartz display no evidence of strain whatever, even though, as in one case, the twin lamellae in the plagioclase show an angular variation of 11° (Fig. 3b). This strongly suggests that the bending of the twin lamellae was not occasioned by an externally imposed stress, but was the result of strains set up within the crystal soon after it has formed. Such strains might have been produced by the re-organization of the structure implied in the elimination of patchiness and zoning. The general lack of strain extinction in the interstitial quartz provides further evidence that the rock was not deformed by external forces. Quartz shows incipient replacement of pyroxene and amphibole, especially the former. In places, the plagioclase is partly replaced by iron ore.

Apatite is the most outstanding accessory mineral, forming large crystals up to 2·5 mm. long which habitually occur at the peripheries of ferromagnesian aggregates.

Quartz-gabbro

It was impossible to map quartz-gabbro as a separate rock type in the field and the specimen described here (F.180.1) was obtained from the northern tip of island (*1*). In the hand specimen, it is massive and weathers characteristically to a dark grey.

The modal analysis of the quartz-gabbro (Table I) shows that it is a rock of rather unusual composition in that a relatively high content of quartz and accessory potash feldspar is combined with a high orthopyroxene to total pyroxene ratio. Clinopyroxene, a colourless diopsidic augite, is sparingly altered to a pale green hornblende, whereas alteration to deep reddish brown biotite is much more common. Pink pleochroic hypersthene has crystallized simultaneously with the augite and is replaced in part by talc. Intersertal scaly serpentine possibly represents pseudomorphs after hornblende. In addition to being an alteration product of clinopyroxene, biotite is a primary mineral phase, some of it forming either a partial or complete selvage round iron ore.

All the plagioclase properties which were emphasized in the description of the hornblende-gabbro are even more strongly developed in the quartz-gabbro. Oscillatory zoning is prominent and complex, and patchiness is widespread. The two main compositions present in patchy crystals are $Ab_{18}An_{82}$ and $Ab_{38}An_{62}$, while those plagioclases which have been rendered almost uniform by the advanced development of secondary glide twinning always have the lower composition value. Marginal zoning down to $Ab_{52}An_{48}$ is common. As in the previously described rocks, the plagioclase is clouded. However, except in the patches of $Ab_{18}An_{82}$, the clouding is considerably denser than in the more basic gabbros and the individual particles are correspondingly smaller. Also, the particles are generally accompanied by a great number of delicate needles of iron ore which occur in several orientations apparently unrelated to any cleavage direction. In normal light both secondary albite twinning and oscillatory zoning can be readily discerned by the respective linear and zonal arrangement of the iron ore particles. In the former case the particles are concentrated along the composition planes of the lamellae and in the oscillatory zoned crystals the clouding is much denser in the sodic zones than in the calcic layers. The zoning is further emphasized by the larger dimensions of the particles in the calcic zones. A very few sodic zones are antiperthitic.

Quartz is interstitial and locally corrodes the adjacent plagioclase. Much of the potash feldspar present is micrographically intergrown with quartz.

Tonalite

Tonalite is easily distinguished from the gabbroic rocks by its lower colour index, together with the light grey aspect of the plagioclase. Examination of the thin section reveals that most of the clinopyroxene has been converted to a brownish green hornblende, a little quartz being released as a by-product. The amphibole is completely fresh but it is markedly xenomorphic towards the plagioclase. Biotite is normally associated with, but is not an alteration product of, amphibole and displays only slight marginal alteration to chlorite. The mafic minerals occur in well-defined aggregates which have apparently been moulded around nuclei of titaniferous magnetite.

The plagioclase is even more complicated than in the basic members of this rock series, but the phenomena are of the same kind. Several crystals have exceptionally fine oscillatory zoning in which the individual layers are paper thin and are repeated many times. The zoning never begins at the core and never extends to the margin of any crystal. Generally, the oscillations are superimposed on a three-fold normal discontinuous zoning and the combination of zoning and patchiness produces crystals with a very chaotic appearance. There is not a perfect correspondence between the development of secondary twinning and the elimination of optical inhomogeneities within the plagioclase. It shows great compositional variation. Uniform crystals possessing secondary Carlsbad-albite twinning usually have a composition in the range $Ab_{54}An_{46}$ to $Ab_{48}An_{52}$. One crystal with a three-fold zonary arrangement has a core of $Ab_{20}An_{80}$ and an intermediate zone of $Ab_{56}An_{44}$ within which are patches of the same composition as the marginal zone, i.e. $Ab_{72}An_{28}$. Clouding is absent in the sodic patches and margins. A few crystals have abundant small rounded inclusions of amphibole, biotite and iron ore, a fact which is sometimes adduced as evidence of hybridization (Deer, 1950, p. 183). In all the previously described rocks, the plagioclase is characterized by its freshness, but in the tonalite there is significant alteration to sericite, epidote and, more rarely, prehnite. Sericitization is severe in some cases but it is always confined to the original basic core.

Quartz forms large interstitial masses with uniform extinction. The potash feldspar is remarkably pellucid, has $2V\alpha \simeq 60°$ and its irregular distribution suggests that some potash metasomatism has taken place. It marginally corrodes plagioclase.

Of the accessory minerals apatite is the most abundant, forming small subhedral crystals enclosed in or marginal to amphibole and biotite. A little of the iron ore is encrusted with sphene and scarce zircon is also present.

Quartz-diorite

On island (*3*) a narrow irregular acid vein or dyke cuts the banded gabbros. It is difficult to classify this rock satisfactorily, since it has an anomalous mineralogical composition (Table I), but quartz-diorite is probably the most appropriate designation.

In thin section, several distinctive characteristics of the gabbros and tonalites are seen to be perpetuated. Apart from extremely rare hornblende, the only ferromagnesian mineral is biotite having the pleochroism scheme α = light yellowish brown, $\beta = \gamma$ = strong reddish brown. This strong coloration in the biotite characterizes the whole rock series. Where the biotite is altered to chlorite, it is always accompanied by innumerable sphene granules. Occasionally, the biotite cleavages are disrupted by prehnite lenses.

The sparsely distributed plagioclase phenocrysts in the rock have a general composition of $Ab_{56}An_{44}$ with broad rims of $Ab_{72}An_{28}$ and having internal areas and patches of $Ab_{42}An_{58}$. In general, the smaller crystals have $Ab_{60}An_{40}$ and $Ab_{74}An_{26}$ as the composition extremes and even where secondary twinning is well developed, which is comparatively rare, there is always a distinct sodic rim giving a good Becke line. Oscillatory zoning is common. Clouding is less intense than in the gabbros and tonalites and is completely absent in those parts of a crystal which are more sodic than $Ab_{70}An_{30}$. A little antiperthite is present. Quartz is very abundant and in some of the larger aggregates, corroded remnants of plagioclase occur.

The main accessories are iron ore, apatite, epidote and zircon, the latter producing intensely pleochroic haloes when enclosed in biotite.

Summary

The intrusive sequence of the rocks in the Anagram Islands affords a good illustration of the classical concept of a rock series (Bowen, 1956, p. 60). In the progression from olivine-gabbro to tonalite and quartz-diorite, the discontinuous mineral series from olivine to biotite through orthopyroxene, clinopyroxene and amphibole can be readily traced, while the plagioclase steadily becomes more sodic. However, it is significant that the plagioclase trend does not conform to the principle of a continuous reaction series, but becomes progressively more sodic by a succession of well-defined steps which have been described in full earlier. This behaviour is consistent with the known fact that plagioclases do not form a continuous solid solution series at low temperatures.

Banded Gabbros

Nature of banding

The banding consists of a rhythmic repetition of dark gabbroic and light anorthositic layers whose thickness varies from a fraction of a centimetre to an average maximum of 8 cm. In two major respects the banding differs from the Skaergaard-type layering. First, there is little or no mineralogical gradation from dark to light layers and, secondly, the layering is invariably vertical or steeply dipping whenever it can be observed in section. Concerning the closely analogous banded gabbros on and near Anvers Island, Hooper (1962, p. 27, 37) has emphasized the consistently vertical nature of the banding and stated that there was no evidence for tilting of the gabbros subsequent to their emplacement. Such evidence is also completely lacking in the Anagram Islands.

It has already been stated that not all the gabbros within the banded zone are banded. This arises not only from the presence of large cognate inclusions of uniform olivine- and hypersthene-gabbro, but also from the fact that the banding tends to grade into homogeneous gabbro.

Many of the structures exhibited by the banded gabbros are complex and strongly resemble such sedimentary structures as current and festoon bedding, convolute bedding, back-filled wash-out and drag folding (Figs. 4–9). The bands are rarely rectilinear even over short distances, but form broad sweeping curves in which several individual bands wedge out.

Where one set of bands is truncated by a later series of bands, the angular discordance at the contact is sharp but annealed (Fig. 4). That is, there is no physical discontinuity in the rock nor is there any change in grain-size at the contact. In general, where gabbros of different ages are in juxtaposition, the bands of the younger phase are always parallel or sub-parallel to the contact between them, although irregularities in the contact are rapidly eliminated. An exception to this rule was observed on island (*3*) where bands make high angles with the margins of a large autolith. Small-scale folds in the banding next to the autolith are believed to have been induced by slight rotation of the inclusion. Rather similar flexuring was also observed at other contacts, and at one locality the flexures develop into tight folds which have markedly attenuated limbs (Fig. 5).

Fig. 4. Vertical banding in gabbro illustrating the discordant but annealed contact between phases of different age and the associated slight warping of the older bands. Note the characteristic wedging out of individual layers where the banding changes direction. Island (*3*), Anagram Islands.

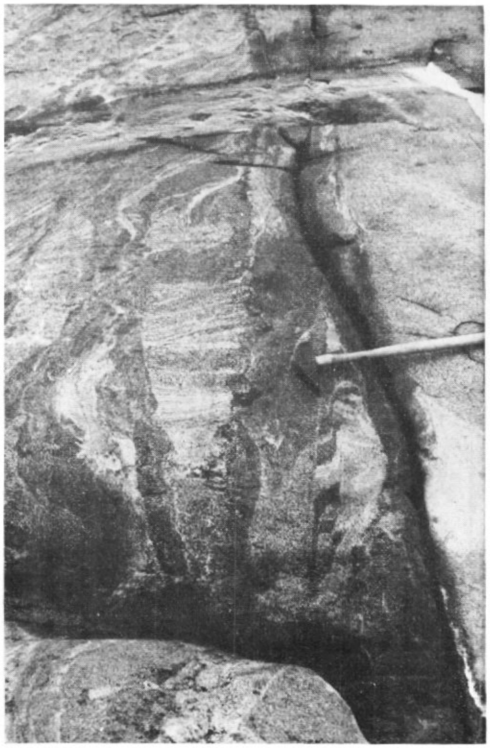

Fig. 5. Irregular dykes and disturbed banding arising from emplacement of gabbroic magma before the previous phases had completely solidified. Small-scale folds with attenuated limbs occur below the hammer head. A dark massive dyke can be seen in the background. Island (*3*), Anagram Islands.

Petrography

Since the melanocratic layers in the banded gabbros have a very similar mineralogy to the cognate inclusions of olivine- and hypersthene-gabbro already described, no detailed petrography need be given here. Instead emphasis will be placed on textural features which furnish evidence regarding the origin of the banding.

The gabbros of the Anagram Islands occur as smooth and relatively unjointed outcrops so that good specimens of banding were very difficult to obtain. The best example of banding is specimen F.216.13, which clearly illustrates the variation in thickness and wedging out of individual bands. Under the microscope the dark band is a hypersthene-gabbro containing a little olivine and with a strongly ophitic texture. A modal analysis of the dark band is given in Table I. Deep brown hornblende, occurring as a marginal alteration product of clinopyroxene, appears to post-date all the plagioclase, because hornblende rims on several adjacent clinopyroxene crystals are linked by narrow ribbons of the same hornblende penetrating along inter-plagioclase boundaries. The complex unit of hornblende thus formed is optically continuous.

The anorthosite layer contains about 2 per cent of interstitial pyroxene and iron ore with a little biotite associated with the latter. The plagioclase has exactly the same composition as that in the dark bands, i.e. $Ab_{12}An_{88}$, although there is slight normal zoning down to $Ab_{22}An_{78}$ in a few cases. It occurs as crystals of predominantly tabular and platy habit whose length ranges from 3·0 to 0·3 mm. Apart from the usual clouding, the plagioclase is extremely fresh in appearance. Texturally, the anorthosite bands are of considerable interest and importance, since the distinctive decussate arrangement defined by the plagioclase precludes a purely static crystallization from a melt. Furthermore, in one section cut normal to the banding and parallel to the present horizontal plane, a faint but definite lineation can be detected in the plagioclase. A similar section from specimen F.206.2 shows a much more pronounced lineation (Fig. 3c) and even the plagioclase and ferromagnesian minerals of the dark band define a crude lineation. When a section cut normal both to the horizontal plane and to the banding was examined, it was found that the plagioclase again has a preferred orientation parallel to the banding, but this is slight. The melanocratic layers in this specimen possess remarkable ophitic and poikilitic textures (Fig. 3d), indicating that both the clinopyroxene and the amphibole crystallized to a large extent from the interstitial liquid. The dark minerals have been severely attacked locally by late magmatic activity resulting in large aggregates of scaly actinolite, biotite and iron ore.

A finely banded rock (F.206.3) in which the layers are from 2 to 5 mm. across was examined microscopically. The banding is not readily apparent in thin section, because separation of dark and light mineral phases is incomplete. Nevertheless, there is a general similarity in texture with the coarsely banded rocks, except that in the anorthosite layers there is no well-defined lineation.

Origin of banding

From the preceding brief petrographic descriptions, it is clear that the banding is a primary igneous structure. There is abundant evidence of secondary activity in many of the banded rocks but, although this has emphasized the banded structures in some instances and has considerably modified them in other places, there is nothing to suggest that it has created the layering. Indeed, all the evidence is to the contrary.

Both the megascopic pseudo-sedimentary structures displayed by the banding and the preferred orientation of plagioclase in the anorthosite layers are indicative of flow. From the microscopic data, the flow was predominantly in a horizontal sense, although a slight vertical component is also apparent in some rocks.

Since the banding is primary and since its vertical or steeply dipping attitude is not the result of subsequent tilting, the physical state of the magma and the environmental conditions at the time of intrusion were clearly such as to effectively counteract gravity. Thus, the gabbroic magma must have been intruded as a crystal mush in which the solid phase was considerably in excess of the liquid phase. Equally certain is the heterogeneous nature of the original magma, as was suggested for the banded gabbros on and near Anvers Island (Hooper, 1962, p. 37). Under a strong horizontally directed pressure laminar flow would be induced in this heterogeneous magma but the precise process whereby the anorthosite layers are formed is difficult to envisage. That the banding was brought about by enforced flow as a result of squeezing is supported by the progressive decrease in definition of the layers away from the original "erosion surfaces", since relative movement would be greatest against rigid material and correspondingly less farther away from the contact. This feature is well illustrated in Figs. 7 and 8.

At least three erosion surfaces are present within the complex banded unit shown in Fig. 8 and five distinct phases of intrusion are shown in Fig. 9. The magma was therefore intruded

Fig. 6. Concentric arrangement of bands showing the sharp contact between different phases illustrated in greater detail in Fig. 4. Island (*3*), Anagram Islands.

Fig. 7. Small convolution in banded gabbro. In the middle distance the banding becomes very poorly defined. Island (*3*), Anagram Islands.

Fig. 8. "Current bedding" and "back-filled wash-out" in banded gabbro. The banding shows a progressive decrease in definition away from the "erosion surfaces". Nob Island, Anagram Islands.

Fig. 9. Complex banding in gabbro simulating festoon bedding in sedimentary rocks. At least five distinct phases of intrusion can be seen. Island (*3*), Anagram Islands.

in a series of small pulses each separated by a short interval of time. The concept of magmatic pulses has been discussed in detail by Harry and Richey (1963).

The large number of autoliths of homogeneous gabbro within the banded zone, together with the sharp angular discordances locally displayed by banding of different ages, strongly suggests that brecciation took place between each intrusive phase. Consequently, there must have been a relaxation of confining pressure between each magmatic pulse. The well-defined intrusive breccias which occur in other parts of the Anagram Islands have already been cited (p. 24) as evidence of diminution of pressure between successive phases of intrusion.

On the whole, the structures in the banded gabbros of the Anagram Islands denote a composite process combining repeated brecciation and enforced flow.

One objection to the theory of fluxion-brecciation outlined above is the consistently steep or vertical dip of the banding. If fracturing had taken place, the banding would be expected to have a variable dip. In addition, there is a singular lack of cataclastic textures, and contacts are invariably annealed. However, any fragmentary material resulting from brecciation could easily be removed by the succeeding phase and the contact subsequently healed.

Later phases were locally emplaced before the preceding intrusion had completed its crystallization. As shown in Fig. 5, this results in very irregular dyke-like bodies characterized by diffuse margins, lack of matching of margins, pinching and swelling, and inter-mixing of dyke material with the host. Such features are identical to those in the early dykes intruding the Donegal granites described by Pitcher and Read (1960, p. 58–59). In contrast, several late intrusions in the banded zone form regular finer-grained dykes with clearly defined but unchilled margins (Fig. 5). Dykes of this type are generally more basic than the wall rock and were clearly intruded when the latter was comparatively rigid.

Late Magmatic Alteration and Mineralization

Secondary alteration is widespread in the zone of banded gabbros. Even the olivine- and hypersthene-gabbros of fresh appearance which form large cognate inclusions within the banded zone bear evidence of slight late-stage activity. As a result of this, olivine is altered to talc, plagioclase is partially converted to epidote, and clinopyroxene is overgrown and replaced by hornblende. However, attention will be confined to the more severe forms of secondary alteration which occur in many parts of the banded zone.

Field characteristics

Although the secondary activity in the banded gabbros is linked with the late introduction of amphibole, iron ore and lime-rich minerals such as epidote, sphene and calcite, the actual form of alteration varies considerably. A rough four-fold classification which attempts to distinguish the different modes of alteration was made on the basis of field observations, but transitions from one mode to another are common.

In the banded rocks late magmatic action is seen initially in the preferential alteration of the melanocratic layers with the conspicuous development of hornblende derived in part from the original pyroxene (F.206.2). As alteration increases, the banding becomes progressively less distinct. This is attributable partly to the incipient replacement of plagioclase by amphibole and iron ore in the leucocratic layer, and partly to the overall modification in texture which has taken place (F.227.10). Further alteration results in a continuation of these trends, and ultimately the banding is completely obliterated, the product being a medium- to coarse-grained amphibole-rich rock.

Miarolitic structure constitutes a second form of late-stage alteration in the zone of banded gabbros. The cavities or vugs are extremely abundant locally. They are generally small and consist essentially of a coarse intergrowth of plagioclase and hornblende accompanied by varying amounts of epidote, magnetite, iron pyrites and chalcopyrite. Associated with these vugs are small nodules which display a crude concentric structure comprising a core of amphibole or epidote surrounded by a layer of altered milky white plagioclase. The reverse arrangement also occurs in rare instances.

Introduction of late magmatic products commonly takes the form of narrow veins rich in hornblende with varying proportions of plagioclase, epidote and iron ore. These veins are characterized by their coarse grain, their irregularity both in thickness and direction, and the transverse nature of the prismatic hornblendes. Most of the veins are less than 5 cm. wide and they may be either concordant with the structure of the wall rock or independent of it. In many places they either peter out or else degenerate into a series of disconnected vugs or narrow lensoid streaks. The veins increase in number and complexity where the wall rock has been rendered coarse-grained by earlier phases of pneumatolytic action.

By far the most important effects of secondary alteration are to be seen in the numerous lensoid masses of coarse-grained highly altered gabbro which occur throughout the banded zone. On the north-west corner of Nob Island, these irregularly shaped lenses attain a maximum size of about 30 m. long and 10 m. wide but, in general, they are much smaller than this and grade downwards into the veins already described. Mineralogically, the zones comprise hornblende and plagioclase with subsidiary pyroxene and epidote, and they are impregnated with appreciable quantities of iron ore. An indistinct banding parallel to the long axis of the lensoid zones is normally present, but the masses themselves may be either concordant or discordant with respect to the primary banding in the host rock.

The pegmatitic lenses yield the highest concentrations of iron ore in the banded zone and several specimens contain nearly 30 per cent. Much of the ore is magnetite; iron pyrites and chalcopyrite only occur in minor amounts. The magnetite is massive in form with a tendency towards local platy development. On freshly broken surfaces it has a splendent lustre, whereas on weathered surfaces it is dull steel-grey in colour with a sub-metallic lustre. Several specimens show a deep blue or purple tarnish. Iron pyrites readily oxidizes to reddish brown limonite, so that those lensoid ore bodies which contain this mineral in significant amounts are easily identified by their characteristic staining. Chalcopyrite is locally oxidized to malachite.

Petrography

A banded gabbro bearing a clear imprint of late magmatic activity is illustrated by specimen F.206.2. Parts of the rock have completely escaped alteration, apart from the typical marginal alteration of clinopyroxene to brown and green hornblende, but immediately adjacent areas have been extensively attacked. Of the pyroxenes, hypersthene alters by far the more readily and survives only in small granular aggregates, which are liberally peppered with and intergrown with iron ore and are enclosed in large areas of pale actinolitic amphibole, biotite and iron ore, accompanied in places by talc and chlorite. The actinolite has rather variable optics with an apparent gradation from distinctly pleochroic to very weakly pleochroic types; nevertheless, it is always easily distinguishable from the normal green hornblende not only by its paler colour but also by its rather scaly habit. The hornblende has an extinction angle, $\gamma:c = 25°$, while the actinolite has a maximum extinction angle of 17°. Much of the actinolite has the pleochroism scheme α = very pale greenish brown, β = pale green-brown, and γ = pale green, although some is virtually colourless.

Where it has been drastically altered, clinopyroxene yields an intergrowth of greenish brown hornblende and pale green actinolite rather similar to the aggregates derived from hypersthene. The occurrence of biotite in these aggregates is directly linked with the presence of iron ore around which it forms broad fine-grained zones. Degradation of biotite to chlorite and granular sphene is generally slight; in one place it is heavily prehnitized.

Plagioclase, with a maximum composition of $Ab_{12}An_{88}$, has escaped severe alteration, although it is commonly traversed by a network of tiny cracks containing a dark brown indeterminate material. There are two generations of titaniferous magnetite and the complex replacement textures (Fig. 3e) indicate that much of the iron ore was introduced just before the final consolidation of the rock. A pale green amphibole of uncertain species replaces the plagioclase to a certain extent.

Lime-bearing accessory minerals such as prehnite, epidote and calcite show that the residual magmatic material contained lime as well as iron. Leucoxene occurs as pseudomorphs after iron ore and also as fine dust in plagioclase.

In another banded rock (F.227.10), secondary alteration has produced similar features to those just described. A few small ellipsoidal masses of a pale yellowish brown fibrous serpentine, accompanied by dense clusters of iron ore, may in part represent original olivine but the larger areas of bastite, fringed by a pale green scaly actinolite and a little talc, are probably derived from orthopyroxene. As before, the accessories which include calcite, apatite and epidote indicate considerable ingress of lime, although much of the epidote is secondary after plagioclase.

Both deep brown iron-rich hornblende with excellent Schiller structure and the typical greenish brown hornblende are present as rims on clinopyroxene, but it is uncertain whether there is any compositional break between the two types. In addition, there are small amounts of a strongly pleochroic amphibole with α = light yellowish green, β = dark green and γ = deep greenish blue. These optics suggest a soda-rich amphibole, but it was impossible to make a precise identification. It is always fibrous and occurs either as an internal alteration product of clinopyroxene or as a marginal variation of normal green hornblende.

A typical specimen of heavily uralitized gabbro (F.227.9) in which any original banding has been destroyed exhibits a more widespread transformation of pre-existing minerals than was apparent in the altered gabbros which still retain their layered structure. Augite is dusted with iron ore and is considerably altered to brown or brownish green hornblende, while the hornblende itself has a bleached appearance in places. This is caused by the growth of a very pale actinolite at the expense of the hornblende. The local conversion of actinolite to biotite and pale reddish brown phlogopite is closely connected with the abundant iron ore accompanying the scaly aggregates in which the actinolite characteristically occurs. No orthopyroxene remains, but a little bastite is present. Small patches of fibrous soda-rich amphibole, pleochroic from deep slaty blue to strong green, exist in one or two green hornblende crystals.

Plagioclase has a fairly uniform composition of $Ab_{10}An_{90}$, and in addition to the irregular network of cracks which is so distinctive in the altered rocks, it is internally replaced in a few places by a pale brown spherulitic (?) leucoxene and also by greenish brown hornblende.

Epidote, sphene and calcite are sporadically distributed and altogether they constitute about 3 per cent of the total rock.

In a late-stage vein which permeates the altered gabbro, the pyroxene→amphibole reaction is further advanced, so much so that augite survives mainly at or near the margins of the vein. Deeply pigmented sodic amphibole occurs in the same setting as in the remainder of the rock and actinolite and iron ore display excellent symplectitic intergrowths. Leucoxene, possessing a deep brown colour in transmitted light and showing a superb milk-white colour in reflected light forms relatively large interstitial areas between big hornblende crystals, and occurs as orientated rods in hornblende. Several plagioclases have a faint oscillatory zoning in or adjacent to the vein, while others have a very turbid appearance on account of secondary products such as brown leucoxene and turbid scaly (?) prehnite. Titaniferous magnetite builds intricate skeletal networks around previously formed plagioclase and irregularly shaped masses within pyroxene and amphibole. As shown in the approximate modal analysis in Table II, the vein is rich in iron ore. It also contains significant amounts of calcite, epidote and sphene, which to some extent replace plagioclase and amphibole.

TABLE II. MODAL ANALYSES OF ALTERED BANDED GABBROS

	F.227.6	F.227.9*	F.216.7*
Plagioclase	32·7	17	43
Augite	8·8	9	12
Hornblende/actinolite	35·4	47	13
Biotite/chlorite	†	—	3
Iron ore	17·4	23	29
Leucoxene	†	†	—
Sphene } Epidote } Calcite }	5·7	4	—
Prehnite	—	†	—

* Approximate analysis only.
† Present but not estimated.

F.227.6 Uralitized gabbro, Nob Island, Anagram Islands.
F.227.9 Late-stage vein in uralitized gabbro, Nob Island, Anagram Islands.
F.216.7 Iron-rich gabbro from lensoid mass, island (*3*), Anagram Islands.

The coarse altered gabbros which constitute the main rock type in the numerous lensoid masses may be usefully regarded as the large-scale equivalent of the small veins. One such gabbro (F.226.13) has a pronounced pegmatitic texture with several marginally uralitized clinopyroxene crystals greater than 1 cm. long. The pyroxene is a heavily schillerized augite with $\gamma{:}c = 46°$. Brown to greenish brown hornblende is not only an alteration product of pyroxene, but also occurs as separate crystals of considerable size. Aggregates of actinolite are common and again there are small patches of strongly coloured soda-rich amphibole in hornblende. The iron ore diplays the usual replacement textures and includes pyrite and chalcopyrite as well as ilmenitic magnetite. Epidote occurs in several large concentrations, some of which have formed at the expense of plagioclase.

A similar, though slightly less coarse, gabbro (F.227.6) from another lensoid mass has a very altered assemblage. Some augite still remains; it has a muddy appearance in places and its alteration has yielded a variable intergrowth of green and brown hornblende of which the brown variety appears to have preceded the green one. An outstanding feature of this rock is the magnificent textures produced by the replacement of plagioclase by hornblende. Initially this process appears to have taken place preferentially along albite twin lamellae and calcic layers in oscillatory zoned crystals, which results in a lamellar intergrowth (Fig. 3f). In extreme cases the plagioclase is almost engulfed by the amphibole so that it remains only as small remnants. The plagioclase is also extensively replaced by epidote, calcite, sphene and leucoxene.

Genesis of iron ore

To some extent the alteration in the banded gabbros of the Anagram Islands is the normal process of uralitization which is widely developed in many basic igneous masses, and which is very common in the basic rocks of the Andean Intrusive Suite of Graham Land (Adie, 1955, p. 13). Adie (1955, p. 15) has distinguished hornblendes of primary and secondary origin and it was generally possible to make a similar distinction in the rocks of the Anagram Islands. Certainly, there is little doubt that the pale green to colourless actinolite is the result of secondary activity. It is believed that the development of actinolite arose from processes which, though definitely secondary, are nevertheless strictly magmatic. The actinolite probably formed in response to the pneumatolytic action of volatile-rich fluids on the original pyroxene and possibly also on primary hornblende.

Pneumatolytic action, however, was not the sole agent of alteration in the banded gabbros, since significant amounts of iron ore and lime were clearly introduced into the rocks. Both the mode of occurrence of the iron-rich rocks and the textural criteria show that the active fluids were injected into the rocks prior to their final consolidation. The iron ore characteristically occurs in a skeletal network enclosing and corroding earlier-formed silicates (notably plagioclase), although it also cuts across some of the ferromagnesian minerals.

It is concluded, therefore, that the iron ore deposits in the banded gabbros of the Anagram Islands originated from residual liquid injection. The fluids were derived from the same gabbroic magma and were not formed during any subsequent geological event.

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