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星野光雄

Amphiboles and coexisting ferromagnesian silicates
in granitic rocks in Mahé, Seychelles

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Abstract

A variety of granitic rocks from granodiorite to alkaline granite is developed in Mahé island, Seychelles. Microprobe analyses were made on amphiboles and coexisting minerals.

Amphibole constitutes the most prominent ferromagnesian minerals in the Seychelles granitic rocks. Its chemical composition ranges widely from calcic through sodic-calcic to alkali amphiboles and amphibole composition evolves systematically from Fe-poor to Fe-rich: magnesiohornblende → ferrohornblende → ferroedenite → silicic ferroedenite → ferrichterite and ferrowinchite → riebeckite. Riebeckite occurs abundantly in the alkaline rocks as subsolidus minerals. Throughout the evolution two types of isomorphous substitution, $\text{Mg} \rightleftharpoons \text{Fe}^{2+}$ and $\text{Al}+\text{Ca} \rightleftharpoons \text{Si}+\text{Na}$ principally took place. Compositions of clinopyroxene and biotite also evolve from Fe-poor variety to Fe-rich variety. All these compositional evolutions of the

constituent minerals suggest a comagmatic origin of the Seychelles granitic rocks studied.

In the Seychelles alkaline magma, ferrorichterite crystallized at the late-magmatic stage under conditions of 650 - 700 °C in temperature and of slightly above the QFM-buffer in oxygen fugacity. With falling temperature, oxidizing condition prevailed and riebeckite crystallized.

Generally, in alkaline granite and quartz syenite magmas, ferrorichterite evolves continuously to arfvedsonitic compositions when oxygen fugacity is defined by QFM-buffer even during subsolidus stage. On the other hand, ferrorichterite evolves to riebeckite composition when oxidizing condition prevails. But, in this case, continuous solid-solution between ferrorichterite and riebeckite is not found, presumably owing to an existence of a compositional gap between them.

Introduction

Amphibole is found in various types of granitic rock and its chemical composition is considered to reflect the physico-chemical conditions during crystallization and subsequent cooling of a given granitic magma (Wones, 1981). For example, in many alkaline granitic suites, amphibole compositions are known to evolve strongly with the proceeding of magmatic differentiation (Larsen, 1976; Neumann, 1976; Mitchell & Platt, 1978; Giret et al., 1980; Stephenson & Upton, 1982). Such compositional

evolution of amphibole is ascribed to the gradual changes of magma composition and of temperature-oxygen fugacity conditions. The stability of particularly Fe-rich amphiboles which are characteristically found in the alkaline granitic rocks are largely governed by the oxygen fugacity (Ernst, 1962 & 1966; Charles, 1977).

In this paper, detailed mineralogical properties of amphibole and its coexisting ferromagnesian silicates such as clinopyroxene, biotite and stilpnomelane are described to provide full information about the crystallization and cooling history of the Seychelles granitic magma.

Since the comprehensive survey by Baker (1963), the Seychelles Islands have been known as the oceanic islands having a granitic crust of late Precambrian age. Detailed petrographical studies on the Seychelles granitic rocks, however, were not made until the studies by Agata & Suwa (1983), Hoshino & Suwa (1983) and Suwa et al. (1983). The results of the studies may be outlined as follows for Mahé island.

Seven types of granitic rock such as gneissose tonalite, gneissose granodiorite, leucogranite, porphyritic granite, pink granite, grey granite and gneissose grey granite are distinguished (Fig. 1). Petrochemically and petrographically, the majority of them is similar to the granitic rocks in northeastern Sudan and northern Somalia (Suwa et al., 1983). Agata & Suwa (1983) gave mineralogical data on opaque minerals including magnetite and ilmenite and discussed how the MnO

contents of ilmenite vary with differentiation of the host granitic magma. Hoshino & Suwa (1983) gave mineralogical data on amphiboles including Fe^{2+} -poor and Fe^{2+} -rich hornblendes, ferroedenite, ferrorichterite and riebeckite and discussed how the amphiboles change their properties with differentiation of the host granitic magma.

Some inferences concerning the mutual genetic relations of the Seychelles granitic rocks are allowed by recent isotopic studies. A whole-rock Rb-Sr isochron on various types of granitic rock and their enclaves yields an age of 705 Ma with low initial Sr isotopic ratio of 0.70408 (Michot & Deutsch, 1977; Weis & Deutsch, 1984; Demaiffe et al., 1985). They considered that the Seychelles rocks including the enclaves are comagmatic with each other and their parental magma has been originated from an upper mantle. On the other hand, a detailed Rb-Sr isotopic study (Yanagi et al., 1983) on the Mahé granitic rocks revealed that the gneissose granodiorite (an age of 713 Ma) is older than the porphyritic granite (683 Ma). Rb/Sr ratios also suggest that the gneissose granodiorite is less evolved, the porphyritic granite and the pink granite are mildly evolved and the grey granite is highly evolved. These isotopic data appear to be useful in conjunction with the geological evidence given below.

Geological setting

Suwa et al. (1983) further divided the granitic rocks in Mahé as shown in Fig. 1. The gneissose granodiorite occupies the greater part of the northern Mahé. Its gneissosity with a general NNE trend is considered to be a primary structure. The gneissose granodiorite suffered later mylonitization which movement took place subparallel to the primary gneissosity planes. Mafic enclaves such as amphibolite, metadiorite and metagabbro occur abundantly in the gneissose granodiorite mass. Lesser amount of gneissose tonalite is developed around those mafic enclaves. All rocks described above are intruded by the massive leucogranite. In the central and southern Mahé, massive grey granite extensively occurs accompanied by subordinate amounts of porphyritic granite and massive pink granite. The gneissose grey granite found in the Cerf island, Ste Anne island and their adjacent islets is believed to be a marginal facies of the grey granite (Baker, 1963).

From the field relations, it is apparent that the grey granite is younger than the gneissose granodiorite and even younger than the leucogranite. Although the field relations between grey granite, pink granite and porphyritic granite appear to be gradual with each other, Rb/Sr ratios suggest that the grey granite is of the most evolved rock among them (Yanagi et al., 1983). Therefore the grey granite is thought to be the latest intrusion in Mahé. Thus, the major intrusive events which took place in Mahé are conceived as follows. First event: gneissose

granodiorite at about 713 Ma ago, and followed by leucogranite. Second event: porphyritic granite and pink granite at about 683 Ma ago. Third event: grey granite with a marginal gneissose grey granite.

Petrography

The gneissose granodiorite shows a medium- to coarse-grained granoblastic texture with occasional porphyritic feldspars. This rock consists mainly of oligoclase, quartz, microcline-microperthite, biotite and hornblende in a descending order. Small amounts of ferroaugite and ferroactinolite occur enclosed in hornblende. The ferroactinolite is considered to be a subsolidus mineral. Hornblende occurs as prismatic crystals and rarely shows twinning. This mineral is weakly pleochroic with X=light yellowish green, Y=olive green and Z=green.. Its rim usually exhibits a slight tint of blue. Minute grains of quartz, microcline and fine flakes of biotite are recrystallized in part. Such recrystallization is not due to a regional metamorphism but due to a mylonitization. The metadiorite enclaves consist of andesine and hornblende, with bluish green Z-axial colours. The amphibolite enclaves consist of oligoclase, quartz, hornblende and biotite. The Z-axial colour of hornblende is green. From Rb-Sr isotopic study, Demaiffe et al. (1985) considered these enclaves to be comagmatic with host granites. The gneissose tonalite consists of plagioclase, quartz,

hornblende and biotite. Its texture is similar to that of the gneissose granodiorite.

The leucogranite shows a medium-grained granoblastic texture. This rock consists of oligoclase, microcline-microperthite and biotite. Amphibole is generally absent in this rock.

The porphyritic granite consists of quartz, albite, microcline-microperthite, ferroedenite, biotite, and fluorite. Phenocrystic microperthite attains to 1 cm in grain size and is commonly rimmed with albite. Matrix minerals are generally less than 1 mm. Ferroedenite usually occurs as idiomorphic crystals embedded in the matrix, and has X=light straw yellow, Y=olive green to yellowish brown and Z=bluish yellow to brownish green. Stilpnomelane also occurs as subsolidus minerals.

The pink granite shows a coarse-grained granoblastic texture and this rock consists of microcline-mesoperthite, quartz, albite, ferroedenite, biotite and fluorite. Ferroedenite is moderately pleochroic with X=light greenish yellow, Y=yellowish green and Z=bluish green. The optical angle is $46^{\circ}(-)$. Biotite is commonly intergrown with ferroedenite, and rarely encloses ferroedenite (Fig. 2-D). Subsolidus stilpnomelane flakes commonly occur fringing the primary ferromagnesian minerals.

The grey granite is coarse-grained and exhibits a hypidiomorphic equigranular texture. This rock consists of microcline-mesoperthite, quartz, amphiboles, ferrohedenbergite, annite and fluorite. It belongs to the "hypersolvus granite

type" which is characteristically found in the alkaline to sub-alkaline granitic suites (Tuttle & Bowen, 1958). Albite seams can be seen between the mesoperthite grains. Genetically two kinds of amphibole occur, one belongs to the magmatic amphibole and the other the subsolidus amphibole. The magmatic amphibole is a silicic ferroedenite-ferrorichterite-ferrowinchite variety in composition. This mineral occurs commonly as hypidiomorphic crystals and rarely as interstitial xenomorphic crystals. The ferrorichterite exhibits a strong pleochroism with X=light greenish yellow, Y=deep bluish green and Z=deep yellowish green. Its optical angle is $46^{\circ}(-)$. The ferrowinchite also shows a strong pleochroism with X=yellowish brown, Y=olive green and Z=deep bluish green. These sodic-calcic amphiboles show an abnormal interference colour owing to a strong dispersion of $r < v$. The subsolidus amphibole comprises ferroactinolite and riebeckite. Ferroactinolite occurs as crystals enclosed in the magmatic amphibole (Fig. 2-C) and is considered to be a replacement product of pre-existing clinopyroxene. Riebeckite mantles the magmatic amphibole (Fig. 2-E) and occasionally occurs as flaky aggregates with magnetite grains in the magmatic amphibole (Fig. 2-F). Riebeckite shows a strong pleochroism with X=deep blue, Y=dark blue and Z=light greenish yellow and has an optical angle of nearly 90° . This mineral commonly exhibits an abnormal interference colour. Rounded ferrohedenbergite grains occur as inclusions in the magmatic amphibole (Fig. 2-A) and in mesoperthite (Fig. 2-B). Annite occurs as interstitial small

flakes. Two kinds of stilpnomelane are observed. One is a reddish brown ferristilpnomelane fringing other ferromagnesian minerals (Fig. 2-H), the other is a green ferrostilpnomelane growing along the grain boundaries between feldspars. Undoubtedly these stilpnomelanes crystallized under subsolidus conditions.

The gneissose grey granite is medium-grained and shows a xenomorphic equigranular texture. The mineral assemblage of this rock is quite similar to the grey granite. There are no textural evidence which indicate the recrystallization episode, hence the weakly foliated structure observed in this rock is regarded as a flow structure. The ferrichterite in this rock shows a strong pleochroism with X=light brownish yellow, Y=deep yellowish green and Z=deep brownish green. It also shows an abnormal interference colour owing to a strong dispersion of $r < v$. Its optical angle is $56^{\circ}(-)$. Riebeckite occurs mostly as radial aggregates (Fig. 2-G). It is strongly pleochroic with X=deep violet blue, Y=dark blue and Z=light greenish yellow and has an optical angle of $76^{\circ}(-)$.

As described above, many interesting ferromagnesian silicates are found in the grey granite and gneissose grey granite. The crystallization sequence of those minerals are recognized, from their textural relations, as follows; ferrohedenbergite \rightarrow silicic ferroedenite-ferrichterite-ferrowinchite \rightarrow annite under magmatic conditions, and riebeckite \rightarrow stilpnomelane under subsolidus conditions. The magmatic

amphibole crystallized simultaneous with or even after alkali feldspar and quartz.

The granitic rocks ubiquitously carry magnetite and Mn containing ilmenite as Fe-Ti oxides (Agata & Suwa, 1983). Sphene, zircon and apatite are also common accessory minerals. Modal percentages of the ferromagnesian minerals are generally low; 6 to 14 % for gneissose granodiorite, less than 6 % for leucogranite, 8 to 9 % for porphyritic granite, 5 to 7 % for pink granite, 5 to 12 % for grey granite and 6 to 9 % for gneissose grey granite.

Suwa et al. (1983) gave chemical compositions of the Seychelles granitic rocks. Such data are plotted in the CaO-(Na₂O+K₂O)-(Al₂O₃+Fe₂O₃) diagram (Fig. 3). CaO contents is exceedingly low in the grey granite and gneissose grey granite. The aluminosity, i.e. the (Na₂O+K₂O)/Al₂O₃ molecular ratio varies; 0.74 for gneissose granodiorite, 0.95 for leucogranite, 0.93 for porphyritic granite, 0.94 for pink granite, 0.93 for grey granite and 1.03 for gneissose grey granite. Iron contents are fairly high in all types of rock. From these chemical properties and mineral parageneses, grey granite and gneissose grey granite are defined as alkaline granite; pink granite, porphyritic granite and leucogranite as sub-alkaline granite; gneissose granodiorite as calc-alkaline granite.

The chemical compositions and modes of the Seychelles alkaline granites are shown in Table 1, and those of an typical alkaline granite from the Kûngnât suite (McDowell & Wyllie, 1971)

are also shown for comparison. The Kûngnât alkaline granite has been offered in a series of melting study of the igneous rocks by them, and its chemical composition is markedly similar to those of the Seychelles alkaline granites.

Mineralogy

Chemical analyses of the ferromagnesian silicates were performed on the Hitachi X-560 Microanalyser at Nagoya University. Analytical conditions are as follows; an accelerating voltage of 15 kV, a specimen current of 12 nA and a beam diameter of 3μ . Standards used here are synthetic quartz (Si), rutile (Ti), corundum (Al), chromic oxide (Cr), wollastonite (Ca), manganosite (Mn) and periclase (Mg), and natural hematite (Fe), albite (Na) and adularia (K). After dead time and background corrections of the raw data, mass absorption and fluorescence were corrected after Bence & Albee (1968), using the correction factors of Albee & Ray (1970).

Amphiboles

Amphibole constitutes the most prominent ferromagnesian minerals in the Seychelles granitic rocks. Its chemical composition ranges widely from calcic through sodic-calcic to alkali amphiboles. Classification and nomenclature of amphiboles follow the I.M.A. recommendation (Leake, 1978). Numbers of cations for calcic and sodic-calcic amphiboles were recalculated on the basis of twenty-three oxygens. The allocating method of

cations to Z, Y, X and A sites in the amphibole standard formula, $A_{0-1}X_2Y_5Z_8O_{22}(OH,F,Cl)_2$, also follows the I.M.A. recommendation. Ferric iron contents in riebeckites were tentatively recalculated on the basis of thirteen cations exclusive of Ca, Na and K and twenty-three oxygens per formula unit, following the procedure originally proposed by Stout (1972). The resulting $Fe^{3+}/(Fe^{2+}+Fe^{3+})$ atomic ratios appear reasonable for riebeckite structure.

The composition often differs from grain to grain even in a single thin section. A single grain shows, more or less, a compositional zoning (Fig. 5). In Table 2, selected chemical compositions are given. It is noteworthy that the Fe contents of the Seychelles amphiboles are generally high, and that the amphibole in the grey granites sometimes exceeds 0.95 in X_{Fe} .

X_{Fe} variations are shown in Fig. 4 in relation to the total alkali contents. The magmatic amphiboles change composition systematically. X_{Fe} increases steadily from gneissose granodiorite through porphyritic granite and pink granite to grey granite. Alkali contents also increase in the same manner. The amphibole compositions in the grey granite and gneissose grey granite are slightly different from each other. The former is higher in X_{Fe} and lower in alkali contents than the latter. Notice that the gneissose grey granite is surely a marginal facies of the grey granite, as pointed out by Baker (1963). The overall evolutionary trend of the magmatic amphiboles in Fig. 4 is comparable with that of clinopyroxene (see below), and

suggests that all the Seychelles granitic rock have been successively differentiated from a common parental magma.

The amphibole evolutionary trend is also shown in the Si-Na_x diagram (Fig. 5). Si content and Na content in X sites together increase with proceeding that evolution, except in the gneissose granodiorite. The most evolved amphibole compositions belong to a ferrorichterite-ferrowinchite variety. On the other hand, the subsolidus amphiboles such as riebeckites and ferroactinolites are plotted in separate compositional field and no continuous solid-solution series is found between subsolidus amphibole groups and magmatic amphibole groups. Hornblendes in mafic enclaves show compositions similar to those in the gneissose granodiorite. The core of the hornblende from the metadiorite, however, is exceedingly rich in tschermakite component.

The evolution of the magmatic amphibole composition is governed mainly by two isomorphous substitutions, $Mg_Y \rightleftharpoons Fe^{2+}_Y$ and $Al_Z + Ca_X \rightleftharpoons Si_Z + Na_X$. The former substitution took place continuously throughout the amphibole evolution (Fig. 4). The latter substitution also appears continuous from the ferroedenite in the porphyritic granite to the ferrorichterite in the alkaline granites (Fig. 5). Compositional zonings shown in Fig. 5 also confirm the latter substitution. This substitutional trend of the Seychelles magmatic amphiboles coincides well with that found in many Si-oversaturated alkaline plutonic suites such as in the Corsica, Kerguelen, Niger and Oslo provinces (Giret et al., 1980).

However, in the Coldwell (Mitchell & Platt, 1978), Kerguelen (Dosso et al., 1979; Giret et al., 1980), Kûngnât (Stephenson & Upton, 1982) and Skye (Thompson, 1976) provinces, unlike in Seychelles, ferrorichterite is known to evolve further towards alkali amphibole compositions at the late-magmatic stage and even under subsolidus conditions and, as a result, continuous solid-solution series can be found between ferrorichterites and alkali amphiboles. In Fig. 6, compositions of Fe and Si enriched sodic-calcic amphiboles and alkali amphiboles in the alkaline granites and quartz syenites from the above provinces and also from the Massachusetts (Lyons, 1976), Nigeria (Borely, 1963) and North Cascades (Stull, 1973) provinces are shown in terms of Na_X and $(\text{Na}+\text{K})_A$. Both parameters should be influenced drastically by the $\text{Fe}^{3+}/\text{Fe}^{2+}$ ratio, then the EPMA data were recalculated after the Stout's procedure which was described previously. This procedure tends to allow slightly larger Na_X and much smaller $(\text{Na}+\text{K})_A$ than ordinary procedure based on 23 oxygens and, as a result, the points shift towards the left side in Fig. 6. Nevertheless, recalculated $(\text{Na}+\text{K})_A$ numbers appear admissible to use, in comparison with those obtained by wet chemical analyses. As shown in Fig. 6, it is suggested that a compositional gap exists between sodic-calcic compositions and riebeckite compositions. This compositional gap may be due to some particular combination of balancing isomorphous substitutions, which is analogous to the compositional gap found between sodic-calcic compositions and glaucophane compositions (Ungaretti et al., 1983). Thus, at

least in the igneous environment, Fe and Si enriched sodic-calcic amphiboles can evolve continuously towards arfvedsonitic compositions as observed in many other provinces, whereas discontinuously towards riebeckite compositions as in Seychelles.

In contrast to the riebeckite, the ferroactinolite is an alkali poor amphibole. Although ferroactinolites are known to occur as late-magmatic minerals in some varieties of alkaline granite (Stephenson & Upton, 1982; Mitchell & Platt, 1978), the Seychelles ferroactinolites do not indicate such an origin, because they always occur within magmatic amphibole crystals (see Fig. 2). Based on the evidence given above, the Seychelles ferroactinolites appear to be the replacement products of pre-existing clinopyroxene under subsolidus conditions.

It is generally accepted that the amphibole composition is partly controlled by the chemical composition of its host rock. Also in Seychelles, rough correlations between compositions of the magmatic amphibole (Figs. 4 and 5) and of their host rocks (Fig. 3) are possible. Namely, X_{Fe} of amphibole tends to increase with X_{Fe} of the host rock. Na_x content of amphibole also increase with decrease in Ca content of the host rock. Recently, Giret et al. (1980) advocated that the high alkaicity (more than 0.9) of the rock favours the crystallization of the Ca-poor and Si-rich amphiboles such as ferrichterite, ferrowinchite and alkali amphiboles. Actually, in Seychelles, such amphiboles occur only in the grey granite and gneissose grey granite with high alkaicity.

Clinopyroxene

Chemical composition of the clinopyroxene analysed ranges from ferroaugite to ferrohedenbergite (Table 3). No compositional zoning is found. The ferric iron content, which was recalculated on the basis of four cations and six oxygens per formula unit, increases with increasing Na content, forming an acmite component in the clinopyroxene structure.

Clinopyroxene compositions are plotted in the Mg - (Fe²⁺+Mn) - Na diagram, which represents approximate diopside (Di) - hedenbergite (Hd) - acmite (Ac) molecular ratios (Fig. 7). The Hd component is relatively minor in clinopyroxenes from the gneissose granodiorite, whereas it is markedly rich in those from the grey granite and gneissose grey granite.

There are two contrasting evolutionary trends of clinopyroxene from alkaline rock suite in the Di - Hd - Ac compositional field. One is the trend from augite through hedenbergite to acmite, as shown in the Ilímaussaq alkaline suite (Larsen, 1976) and the Kûngnât alkaline suite (Stephenson & Upton, 1982). The other is the trend from augite to acmite without marked enrichment in Hd component, as shown in the Morotu alkaline suite (Yagi, 1953). The former trend is ascribed to high Fe_{total}/Mg ratio, relatively low alkali content and fairly low oxygen fugacity of the magma. Compositional variations in the Seychelles clinopyroxenes results in an evolutionary trend

(Fig. 7) which is almost coincident with a portion of the former trend.

Biotite

Chemical compositions of biotite are given in Table 4. The Si content is generally high and exceeds six atoms in the biotite from the gneissose grey granite. X_{Fe} is nearly the same as that of associated amphibole within each type of rock. Biotites from the grey granite and gneissose grey granites are close to the end-member annite in composition.

Stilpnomelane

Most Seychelles stilpnomelanes exhibit dark reddish brown colour, but a greenish variety also occurs in some varieties of grey granite. The brownish variety corresponds to ferristilpnomelane and the greenish variety to ferrostilpnomelane (Hutton, 1938). A ferrostilpnomelane composition from a grey granite is shown in Table 4.

Stilpnomelane is not a rare mineral in igneous rocks. Quin & Johan (1976) reported ferristilpnomelane closely associated with riebeckite in alkaline granite from Corsica. In the Skaergaard intrusion, drusy granophyre carries ferristilpnomelane (Wager & Deer, 1939). Similar mode of occurrence of the stilpnomelane was reported in North Wales (Bloxam & Price, 1961). Sachanbiński & Janeczek (1977) found both ferro- and ferri-stilpnomelanes in pegmatite from Poland. As far as the latter

two provinces are concerned, stilpnomelanes are believed to be the alteration products of iron chlorites. Ferristilpnomelane may occur by the oxidation of pre-existing ferrostilpnomelane even during weathering (Graham, 1976). Eggleton (1972) also recognized that ferrostilpnomelane is easily oxidized to ferristilpnomelane.

Based on the microscopic evidence, the Seychelles stilpnomelanes should be formed by alteration of pre-existing iron rich minerals.

Discussion

Distinct evolutionary trends of ferromagnesian silicates suggest comagmatic origin of the Seychelles granitic rocks, which differentiated successively from a parental magma. The differentiation sequence recognized in this study is from gneissose granodiorite → porphyritic granite → pink granite → grey granite and gneissose grey granite. This sequence agrees well with the field evidence (Suwa et al., 1983) and with the evidence obtained from Rb-Sr isotopic study (Yanagi et al., 1983).

The latest differentiates such as grey granite and gneissose grey granite belong to alkaline granite. As stated previously, the gneissose grey granite is considered to be a marginal facies of the grey granite. It is likely that, within a magma body, alkalis tend to migrate outwards, and there relatively alkali

enriched ferromagnesian silicates are crystallized, as discussed by Hildreth (1981). This is the reason why the clinopyroxene and sodic-calcic amphibole from the gneissose grey granite are always more enriched in alkalis than those from the grey granite.

The ferromagnesian silicates in the above alkaline rocks are considerably rich in iron. Based on textural and chemical properties of those minerals, physico-chemical conditions during crystallization and subsequent cooling of the Seychelles alkaline magma were estimated.

As already stated in the petrographical descriptions, hydrous minerals such as amphiboles and annite in the Seychelles alkaline rocks did not crystallize until late-magmatic stage. This suggests that the host magma was relatively anhydrous, and water saturation was attained in the residual liquid only at the late-magmatic stage (Burnham, 1979; Wones & Gilbert, 1982). Generally, the alkaline magma having a relatively anhydrous nature is typical in the anorogenic regions and such granite is believed to have solidified at a shallow-level in the crust (Loiselle & Wones, 1979; Collins et al., 1982). The evolutionary trend of amphibole found in the Seychelles alkaline rocks also consistent with that in the terrestrial Si-oversaturated anorogenic granites (Giret et al., 1980). Hence, low pressure condition may be probable for the crystallization of the Seychelles alkaline magma. A melting study on the Kûngnât alkaline granite shows that the solidus temperature of this rock is 650-700 °C under 1-2 Kb of P_{H_2O} (McDowell & Wyllie, 1971).

Chemical and modal compositions of the Seychelles alkaline granites are similar to those of the Kûngnât granite (see Table 1), so that temperature and pressure conditions deduced for the crystallization of this may be conceivably extrapolated to the Seychelles alkaline rocks.

Oxygen fugacity of the magma should be an important factor to stabilize the iron enriched minerals. Coexisting Fe-Ti oxides cannot be used in the f_{O_2} estimation, because magnetite is mostly pure and the associated ilmenite is generally Mn enriched (Agata & Suwa, 1983). However, the stable coexistence of quartz and magnetite suggests the f_{O_2} intermediate between HM- and QFM-buffer conditions. Taking the upper stability limit of hedenbergite (Gustafson, 1974) into account, f_{O_2} condition of the Seychelles alkaline magma is allowed to be slightly above the QFM-buffer condition.

The stability relations of the richterite-ferrorichterite system have been studied in detail (Charles, 1975 and 1977). Upper stability limits for two ferrorichterite compositions, $X_{Fe}=1.0$ and 0.8, under 1 Kb of P_{H_2O} are shown in Fig. 8. When the f_{O_2} is defined by NNO-buffer, which condition would be close to that in the Seychelles alkaline magma, ferrorichterite with $X_{Fe}=0.8$ is stable below the equilibrium curve and above which the assemblage clinopyroxene + magnetite + quartz + fluid is stable. Pure ferrorichterite is stable under only very reduced conditions. From these equilibrium curves and from the f_{O_2} condition given above, conceivable crystallization temperature of

the Seychelles ferrorichterites with X_{Fe} ranging from 0.85 to 0.95 (Table 2) is estimated to be 650–700 °C, as shown in Fig. 8. However, alkali feldspar and excess quartz, which are not involved in the Charles' experimental system, may influence the ferrorichterite stabilities. Dissociation of water also may be a factor to control the vapour phase compositions (Burnham, 1979). Nevertheless, the estimated temperature range given above seems concordant with that extrapolated by the melting experiment of McDowell & Wyllie (1971). These temperature and f_{O_2} conditions also appear to be suitable for the crystallization of annite with X_{Fe} more than 0.8 such as in the Seychelles alkaline rocks (Wones & Eugster, 1965).

The Seychelles riebeckites are crystallized in hydrothermal process under subsolidus conditions. As shown in Table 2, the Seychelles riebeckites are very close to the end-member riebeckite in composition. According to Ernst (1962), under 2Kb of $\text{P}_{\text{H}_2\text{O}}$ and under f_{O_2} defined by HM-buffer, such riebeckite is stable below the equilibrium curve in Fig. 8 and above which the assemblage acmite + quartz + magnetite + hematite + fluid is stable. Arfvedsonitic amphiboles prefer around QFM-buffer or more reduced conditions. Hydrothermally formed hematite actually occurs in the Seychelles alkaline rocks (Agata & Suwa, 1983), therefore the temperature and f_{O_2} conditions for the crystallization of riebeckites are allowed as shown in Fig. 8. Thus the ferrorichterite → riebeckite evolution with falling temperature would reflect the oxidizing condition. But the

continuous solid-solution between ferrichterite and riebeckite is not found, presumably owing to an existence of a compositional gap. On the other hand, the continuous ferrichterite → arfvedsonitic amphibole evolution such as in the Coldwell, Kerguelen, Kûngnât and Skye provinces, and also the Oslo provinces (Neumann, 1976) would reflect f_{O_2} defined by QFM-buffer even during the fall in temperature. Actually, the quartz + fayalite + magnetite assemblage is ubiquitous in rocks from the latter groups of province, whereas fayalite is absent in the Seychelles rocks.

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Table 1. Chemical compositions and modes of the Seychelles rocks and a Kûngnât rock.

	Seychelles		Kûngnât
	Grey Gr. (average 3)	Gn.grey Gr. (average 2)	Rieb. Gr.
SiO ₂	74.66	75.50	76.33
TiO ₂	0.23	0.24	0.14
Al ₂ O ₃	12.44	11.96	12.54
Fe ₂ O ₃	0.74	0.83	0.73
FeO	1.62	1.16	0.89
MnO	0.11	0.03	0.02
MgO	0.08	0.30	0.00
CaO	0.46	0.27	0.00
Na ₂ O	4.20	4.33	4.92
K ₂ O	4.32	4.83	4.06
P ₂ O ₅	0.02	0.03	0.30
H ₂ O(+)	0.32	0.21	0.11
H ₂ O(-)	0.15	0.29	0.05
Total	99.35	99.98	100.9
Mode			
Quartz	32.1	28.3	29.3
Alkali feldspar	60.0	64.5	62.4
Hedenbergite	0.2	0.2	-
Amphiboles	4.7	4.8	5.7
Biotite	0.1	0.6	0.3
Stilpnomelane	1.9	0.3	-
Astrophyllite	-	-	1.3
Opaque	0.6	0.9	0.6
Others	0.4	0.4	0.4

Data from Suwa et al.(1983) for the Seychelles rocks and McDowell & Wyllie (1971) for a Kûngnât rock.

Table 2. Representative microprobe analyses of amphiboles in the Seychelles granitic rocks.

Rock* No.	Ferroactinolite		Hornblende		Ferroedenite				Ferrichterite		Ferro- winchite	Riebeckite	
	GD 93008	GG 100101	GD 93003A	GD 93008	PoG 100203	PG 101004	GG 100303A	GG 100101	GnG 101701	GnG 101705A	GG 101601	GnG 101705A	GG 101003
SiO ₂	51.46	49.28	48.41	45.09	45.59	44.60	45.78	46.02	48.13	49.09	50.55	51.38	51.11
TiO ₂	0.00	0.23	1.39	0.27	1.45	1.41	1.33	1.50	1.78	1.80	0.23	0.05	0.01
Al ₂ O ₃	1.87	0.54	5.72	6.39	6.39	6.12	3.18	3.31	2.39	2.43	0.85	0.87	0.29
Cr ₂ O ₃	0.09	0.00	0.00	0.03	0.01	0.01	0.00	0.03	0.00	0.00	0.02	0.00	0.00
FeO**	20.91	34.10	13.73	24.07	23.03	30.03	33.64	33.57	31.20	30.12	33.71	34.77	36.61
MnO	1.99	1.43	1.64	1.82	1.07	1.31	1.22	1.24	0.65	0.62	0.76	0.37	0.69
MgO	8.79	0.72	13.57	6.38	7.43	2.20	1.00	0.34	2.30	2.15	1.48	1.52	0.53
CaO	11.85	9.47	11.42	11.36	10.52	9.67	7.82	7.21	5.99	5.76	6.69	0.21	0.67
Na ₂ O	0.34	1.78	1.06	1.03	1.88	2.19	2.29	3.12	4.09	4.30	2.81	6.49	6.10
K ₂ O	0.26	0.57	0.49	0.82	0.78	0.93	0.96	0.97	1.22	1.22	0.65	0.25	0.05
Total	97.56	98.12	97.43	97.26	98.15	98.47	97.22	97.31	97.75	97.49	97.75	95.91	96.06
Structural formulae on the basis of 23 oxygens.													
Si } Z	7.797	7.932	7.151	7.064	7.014	7.088	7.464	7.497	7.666	7.775	8.056	7.942	7.962
Al ^{IV} }	0.203	0.068	0.849	0.936	0.986	0.912	0.536	0.503	0.334	0.225	0.000	0.058	0.038
Al ^{VI} }	0.130	0.034	0.147	0.244	0.173	0.234	0.076	0.132	0.114	0.229	0.160	0.101	0.015
Cr }	0.001	0.000	0.000	0.003	0.001	0.001	0.000	0.004	0.000	0.000	0.002	0.000	0.000
Ti } Y	0.000	0.028	0.154	0.031	0.168	0.168	0.163	0.184	0.213	0.214	0.027	0.006	0.001
Fe }	2.649	4.590	1.697	3.154	2.954	3.991	4.518	4.573	4.127	3.989	4.460	Fe ^{2+***} 2.613	2.825
Mn }	0.225	0.176	0.015	0.078	0.000	0.085	0.000	0.024	0.000	0.060	0.102	0.048	0.091
Mg }	1.985	0.172	2.987	1.490	1.703	0.521	0.243	0.083	0.546	0.508	0.351	0.350	0.123
Fe }	0.000	0.000	0.000	0.000	0.008	0.000	0.070	0.000	0.030	0.000	0.033	-	-
Mn }	0.030	0.019	0.190	0.164	0.140	0.092	0.168	0.147	0.087	0.023	0.102	-	-
Ca } X	1.924	1.633	1.807	1.908	1.734	1.647	1.367	1.258	1.023	0.978	1.143	0.035	0.112
Na }	0.046	0.348	0.003	0.000	0.118	0.261	0.395	0.595	0.860	0.999	0.722	1.945	1.842
Na } A	0.055	0.207	0.301	0.313	0.442	0.413	0.329	0.391	0.403	0.321	0.146	0.000	0.000
K }	0.051	0.117	0.092	0.165	0.153	0.188	0.200	0.201	0.248	0.246	0.132	0.049	0.010
												Fe ^{3+***} 1.882	1.945
100·X _{Fe} ****	59.4	96.5	38.9	69.3	64.6	88.9	95.1	98.3	88.6	88.9	93.0	92.8	97.5

* GG: Grey granite, GnG: Gneissose grey granite, PG: Pink granite, PoG: Porphyritic granite, GD: Gneissose granodiorite.

** Total iron as FeO.

*** Fe³⁺/Fe²⁺ ratios in riebeckites were estimated on the basis of 13 cations exclusive of Ca, Na and K.**** 100·X_{Fe} = 100·(Fe_{total} + Mn)/(Fe_{total} + Mn + Mg).

Table 3. Representative microprobe analyses of clinopyroxenes in the Seychelles granitic rocks.

Rock* No.	Ferroaugite	Ferrohedenbergite		
	GD 93008	GG 101003	GG 100303A	GnG 101702
SiO ₂	51.77	48.89	48.76	49.72
TiO ₂	0.09	0.17	0.09	0.15
Al ₂ O ₃	0.40	0.19	0.16	0.33
Cr ₂ O ₃	0.02	0.02	0.00	0.03
FeO**	14.87	26.88	28.77	24.99
MnO	1.95	1.47	1.56	1.06
MgO	8.85	1.87	0.79	2.81
CaO	20.63	18.55	17.46	18.67
Na ₂ O	0.71	0.86	1.71	1.81
K ₂ O	0.00	0.01	0.00	0.01
Total	99.28	98.91	99.30	99.58
Structural formulae on the basis of 4 cations and 6 oxygens.				
Si	2.009	2.009	1.998	1.993
Al ^{IV}	0.000	0.000	0.002	0.007
Al ^{VI}	0.018	0.009	0.006	0.009
Ti	0.003	0.005	0.003	0.005
Cr	0.001	0.001	0.000	0.001
Fe ³⁺	0.010	0.030	0.126	0.125
Fe ²⁺	0.473	0.894	0.860	0.712
Mn	0.064	0.051	0.054	0.037
Mg	0.512	0.115	0.048	0.168
Ca	0.857	0.817	0.767	0.802
Na	0.053	0.068	0.136	0.140
K	0.000	0.001	0.000	0.001
100·X _{Fe} ***	51.7	89.4	95.6	83.9
Atomic %				
Fe ²⁺ + Mn	48.7	83.8	83.2	70.9
Mg	46.5	10.2	4.4	15.9
Na	4.8	6.0	12.4	13.2

* GG: Grey granite, GnG: Gneissose grey granite, GD: Gneissose granodiorite.

** Total iron as FeO.

*** $100 \cdot X_{Fe} = 100 \cdot (Fe_{total} + Mn) / (Fe_{total} + Mn + Mg)$.

Table 4. Representative microprobe analyses of biotites and stilpnomelane in the Seychelles granitic rocks.

Rock* No.	Biotite					Ferro- Stilpnomelane
	GD 100102A	PoG 100504A	PG 100601A	GG 100303A	GnG 101701	GG 100505
SiO ₂	39.76	36.89	37.85	35.94	35.83	45.75
TiO ₂	1.54	3.13	2.46	3.59	1.74	0.05
Al ₂ O ₃	13.35	13.30	12.23	10.82	9.95	5.19
Cr ₂ O ₃	0.00	0.00	0.00	0.00	0.00	0.00
FeO**	17.06	27.83	24.73	36.21	37.02	37.10
MnO	0.76	0.29	1.39	0.29	0.40	2.04
MgO	14.20	4.59	8.16	0.48	1.05	1.09
CaO	0.05	0.00	0.08	0.04	0.00	0.12
Na ₂ O	0.02	0.01	0.01	0.02	0.00	0.21
K ₂ O	9.58	9.41	9.47	8.45	8.10	1.93
Total	96.32	95.45	96.38	95.84	94.09	93.47
Structural formulae on the basis of 22 oxygens						8 Si
Si	5.923	5.865	5.898	5.940	6.069	8.000
Al ^{IV}	2.077	2.135	2.102	2.060	1.931	-
Al ^{VI}	0.268	0.357	0.144	0.049	0.055	1.070
Ti	0.173	0.374	0.288	0.446	0.221	0.006
Fe	2.125	3.700	3.222	5.006	5.244	5.426
Mn	0.095	0.039	0.183	0.040	0.057	0.302
Mg	3.151	1.088	1.896	0.118	0.264	0.284
Ca	0.008	0.000	0.013	0.007	0.000	0.022
Na	0.006	0.004	0.002	0.006	0.000	0.072
K	1.820	1.908	1.882	1.781	1.751	0.431
100 X _{Fe}	40.3	77.3	63.0	97.7	95.2	95.0

* GG: Grey granite, GnG: Gneissose grey granite, PG: Pink granite, PoG: Porphyritic granite, GD: Gneissose granodiorite.

** Total iron as FeO.

*** $100 X_{Fe} = 100 \text{ Fe} / (\text{Fe} + \text{Mg})$.

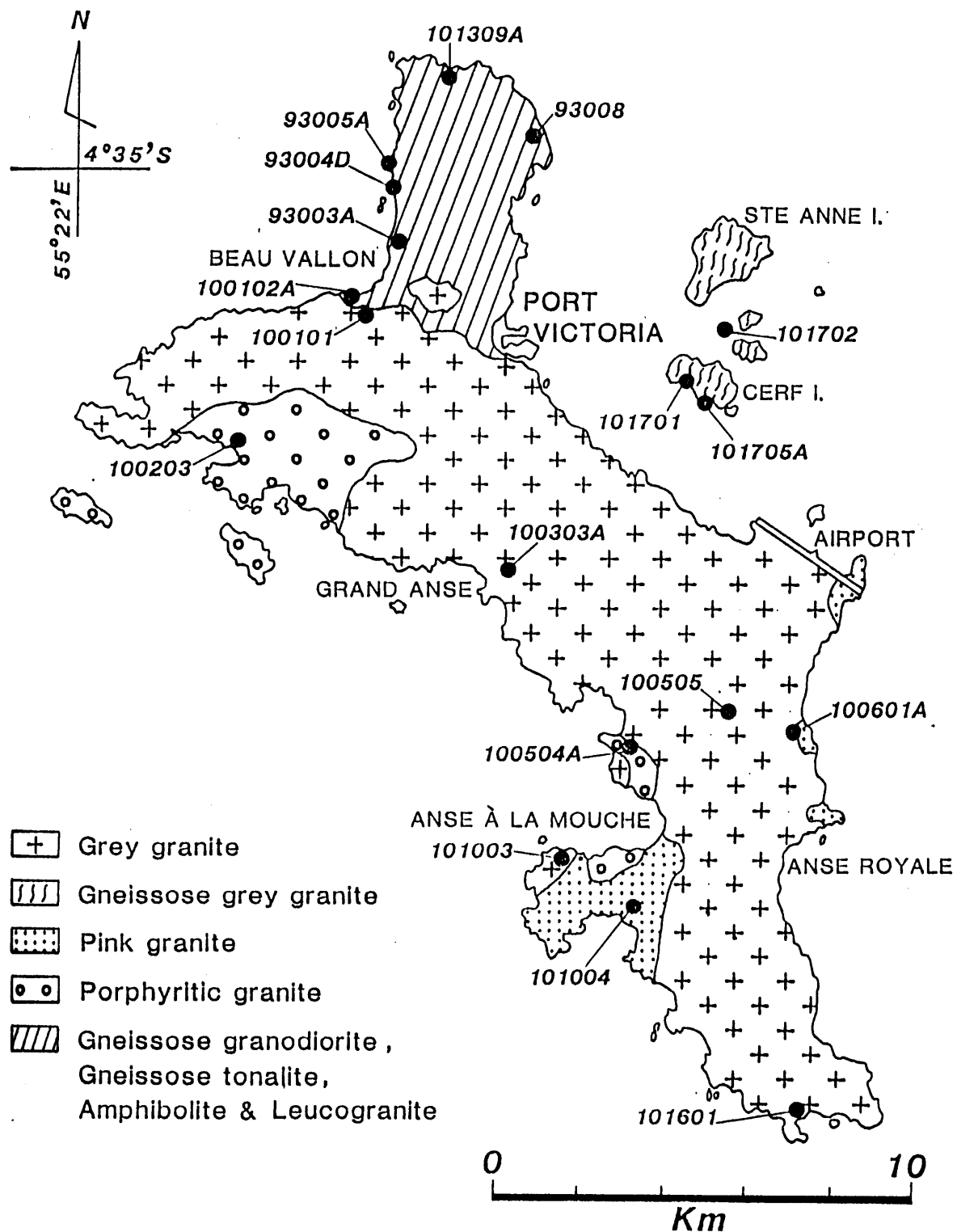
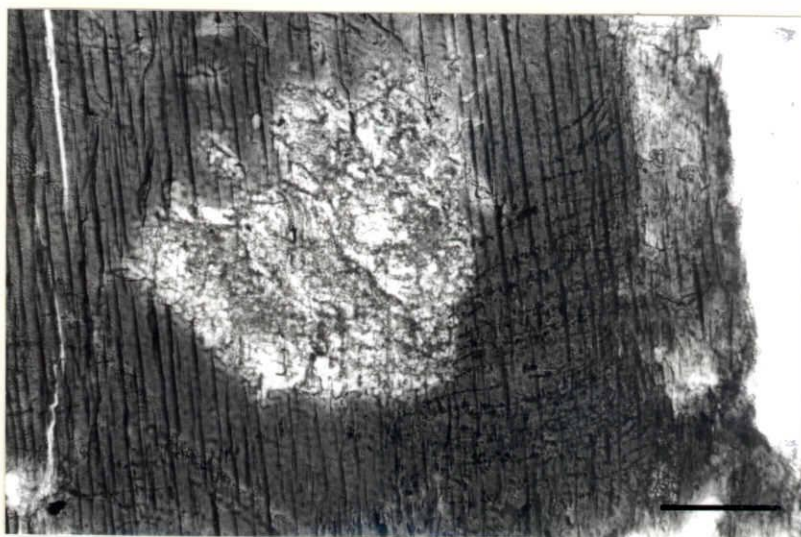


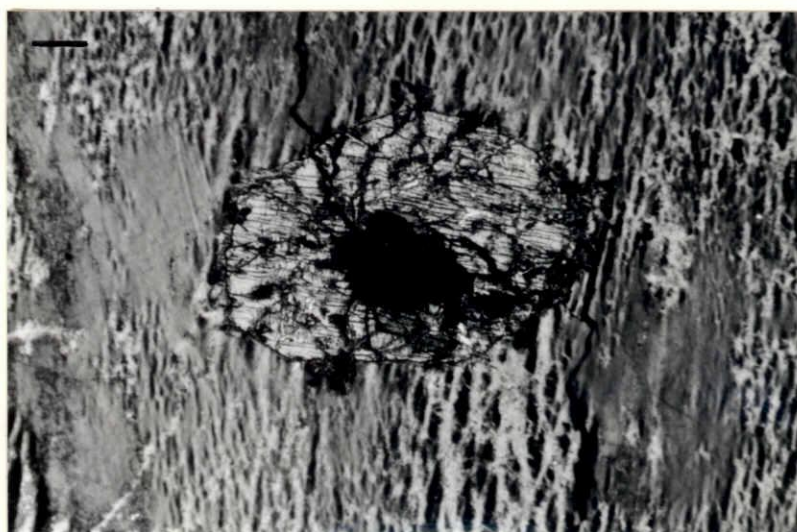
Fig. 1. Geological map of Mahé, Seychelles (after Suwa et al., 1983). Localities of the analysed samples are indicated by solid circles.

Fig. 2. Photomicrographs of the Seychelles granitic rocks. All scale bars are equal to 0.1 mm.

- A. Ferrohedenbergite (centre) enclosed in silicic ferroedenite in grey granite (100303A). One nicol.
- B. Ferrohedenbergite (centre) enclosed in mesoperthite in grey granite (100303A). Crossed nicols.

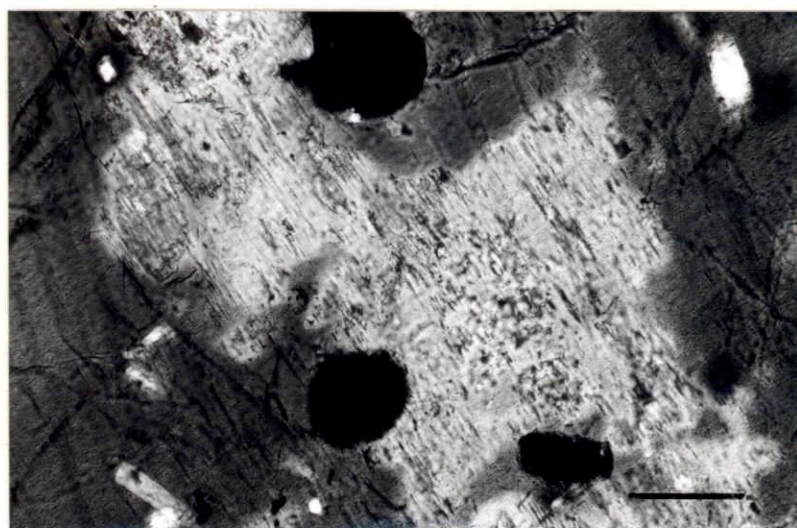


A



B

- C. Ferroactinolite (centre, light grey) enclosed in silicic ferroedenite (dark) in grey granite (100505). Rounded grains of magnetite also are contained in silicic ferroedenite. One nicol.
- D. Ferroedenite (dark) enclosed in biotite in pink granite (KS-81100604). One nicol. This section is kindly offered by K. Suwa.

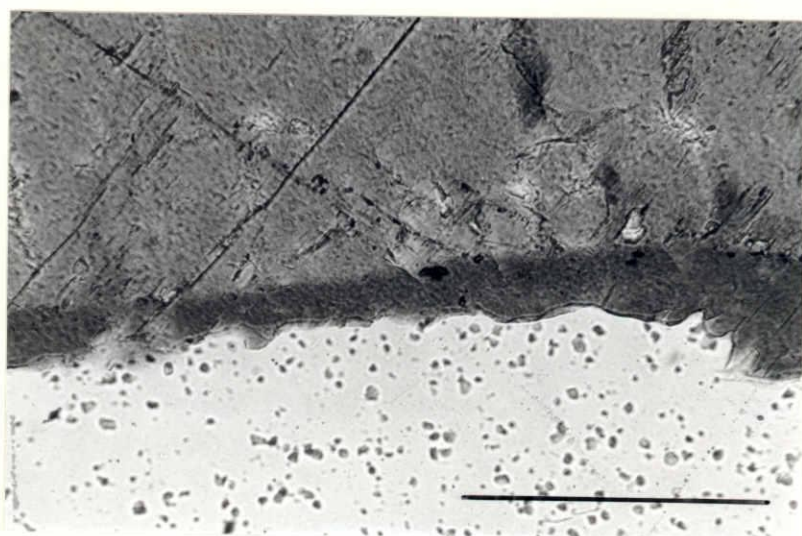


C

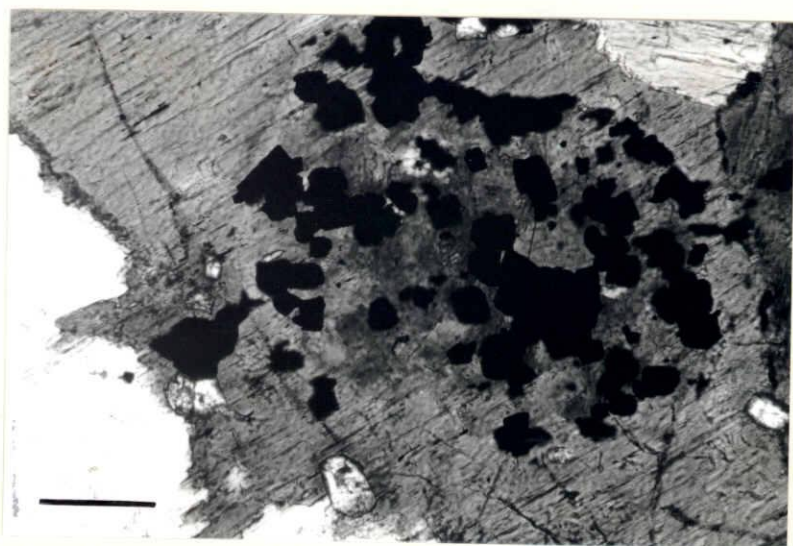


D

- E. Silicic ferroedenite (upper, grey) rimmed with riebeckite (dark grey) in grey granite (100101). One nicol.
- F. Riebeckite flakes (centre, dark part) replacing ferrowinchite in grey granite (101601). Many magnetite grains are associated with the riebeckite flakes. One nicol.

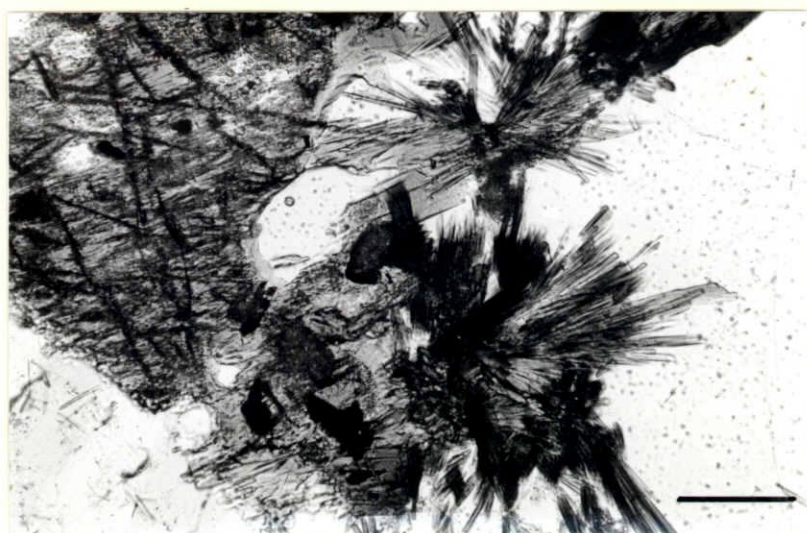


E

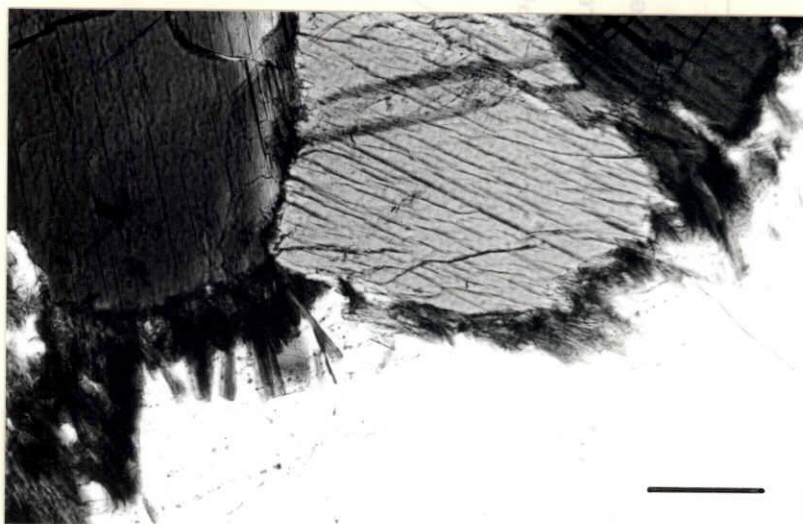


F

- G. Radial aggregates of riebeckite needles (right) and ferrorichterite (left) in gneissose grey granite (101705A). The ferrorichterite is partly replaced by riebeckites. One nicol.
- H. Stilpnomelane flakes (downward) around silicic ferroedenite in grey granite (100303A). One nicol.



G



H

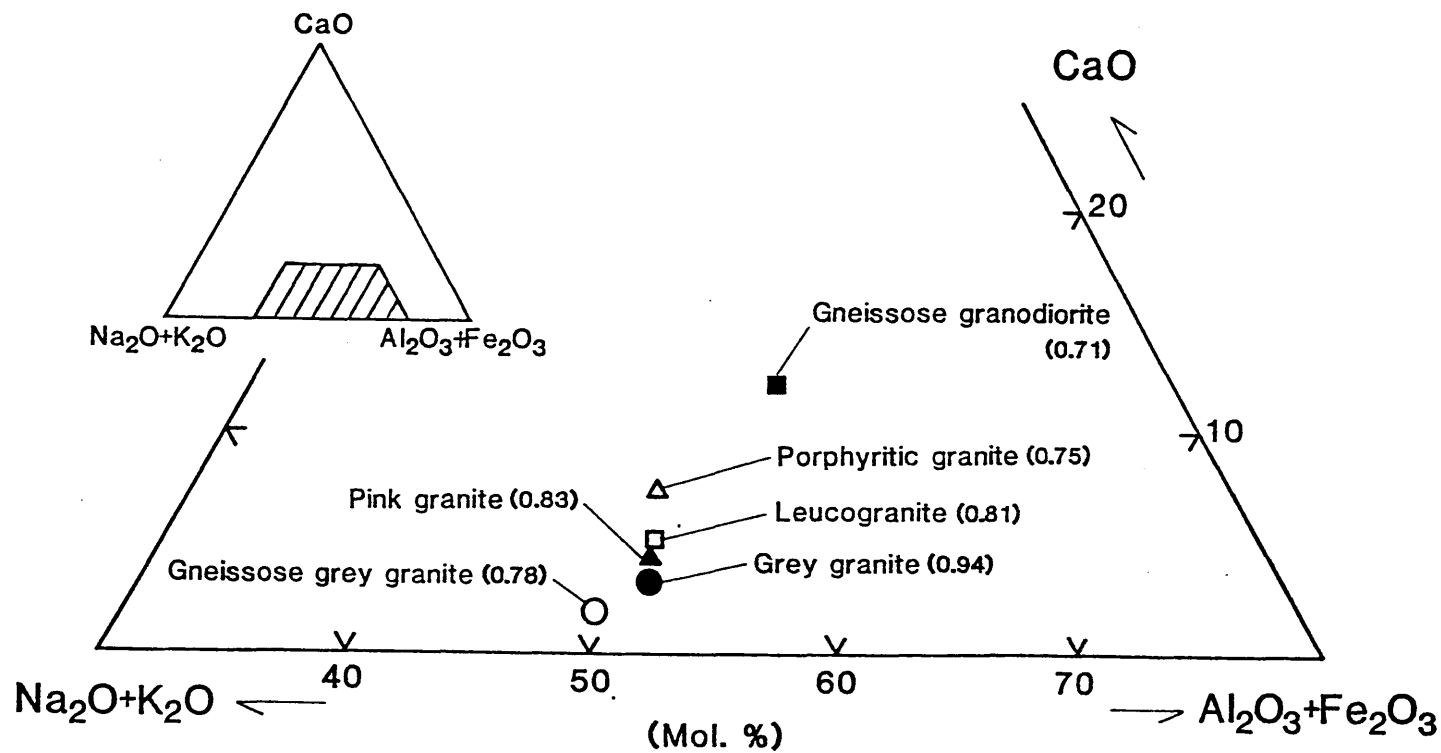


Fig. 3. Average chemical compositions of the Seychelles granitic rocks plotted in the $\text{Ca} - (\text{Na}_2\text{O}+\text{K}_2\text{O}) - (\text{Al}_2\text{O}_3+\text{Fe}_2\text{O}_3)$ diagram. The numbers in parentheses indicate $\text{Fe}_{\text{total}}/(\text{Mg}+\text{Fe}_{\text{total}})$ atomic ratios. Data from Suwa et al. (1983).

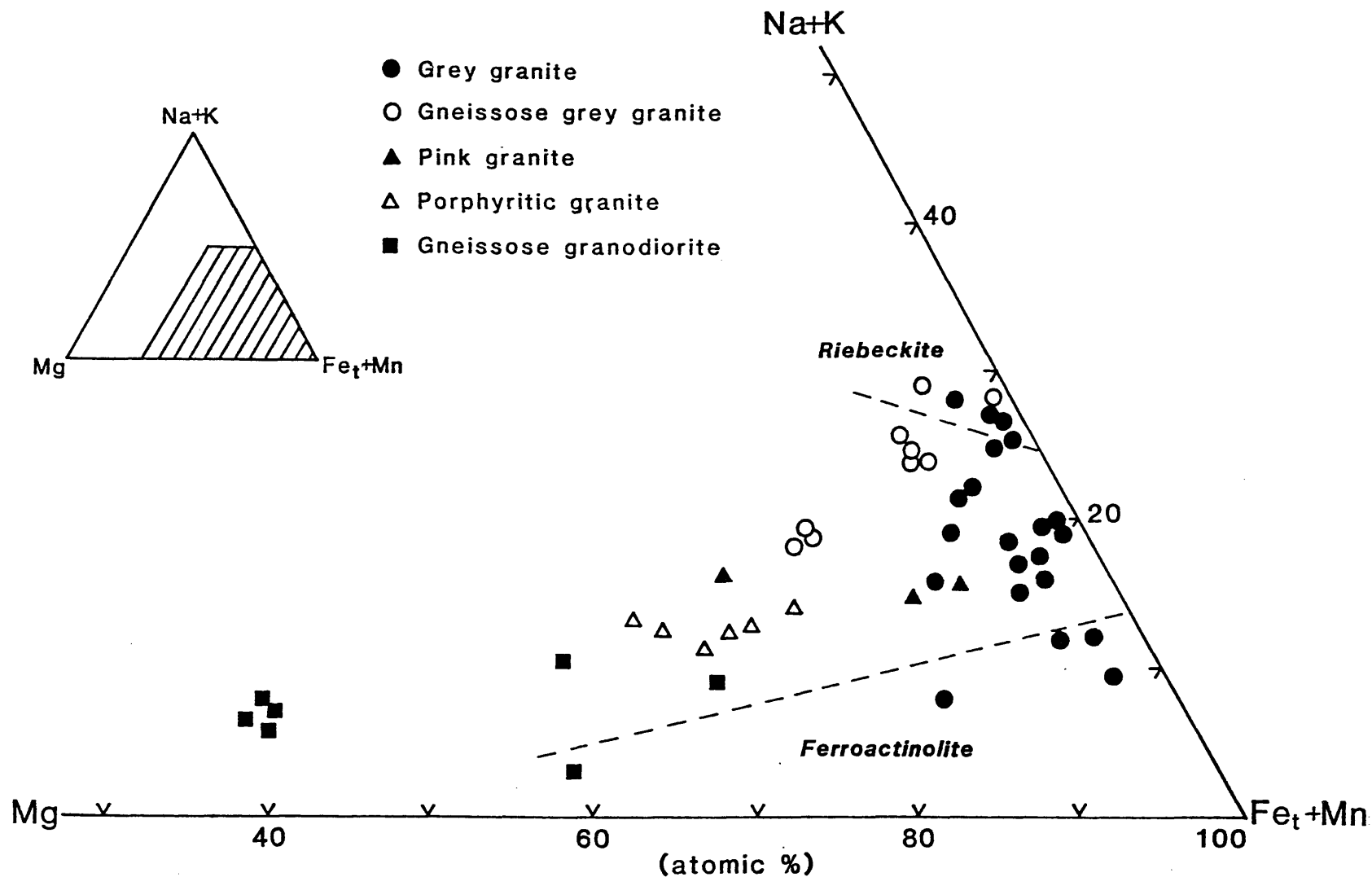
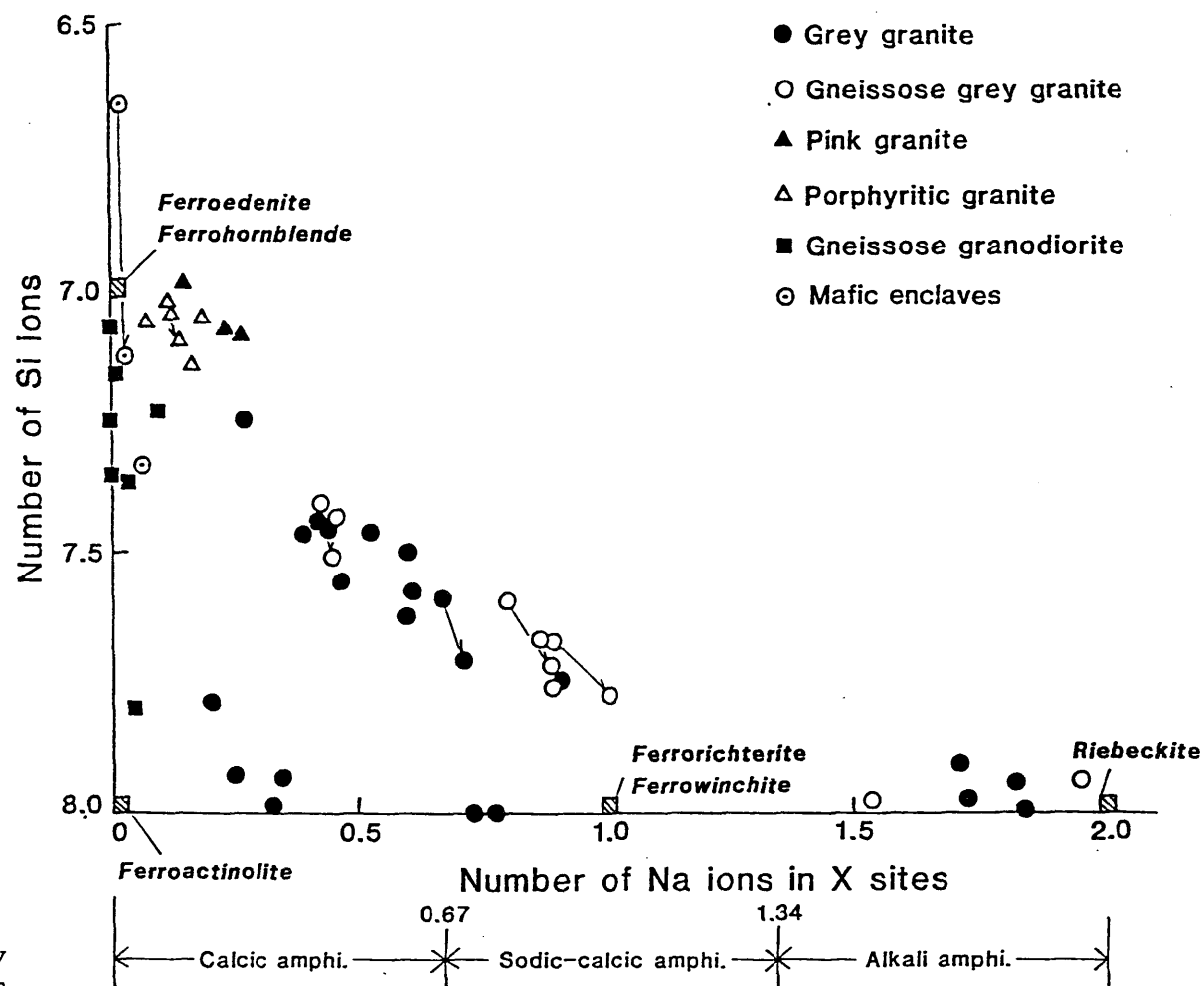


Fig. 4. Amphibole compositions plotted in the Mg - (Fe_{total}+Mn) - (Na+K) diagram. Broken lines: approximate boundaries between ferroactinolite, calcic and sodic-calcic amphiboles and riebeckite.

Fig. 5. Si versus Na in X sites per formula unit of the Seychelles amphiboles. Light arrows: compositional zoning from core to rim in a single grain. Amphibole names are only given for Fe end-members.



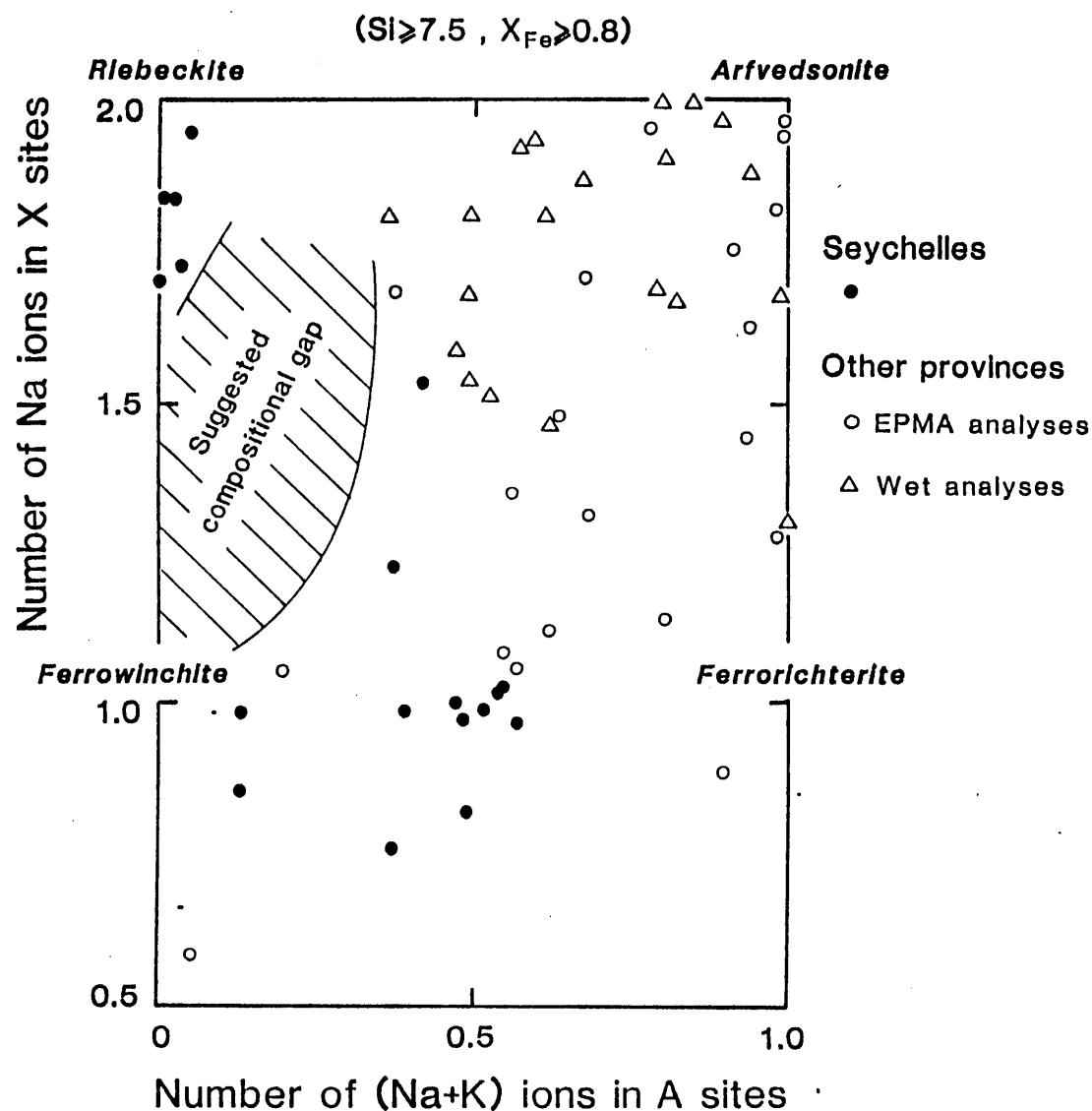


Fig. 6. Na in X sites versus (Na+K) in A sites per formula unit of Si- and Fe-rich amphiboles from various alkaline plutonic suites. Data sources are as follows: wet chemical analyses are from Massachusetts (Lyons, 1976), Nigeria (Borely, 1963) and North Cascades (Stull, 1973); EPMA analyses are from Coldwell (Mitchell & Platt, 1978), Kerguelen (Giret et al., 1980), Kûngnât (Stephenson & Upton, 1982), Skye (Thompson, 1976) and Seychelles (this study). EPMA data were recalculated to obtain the structural formulae, following the Stout's procedure (see text).

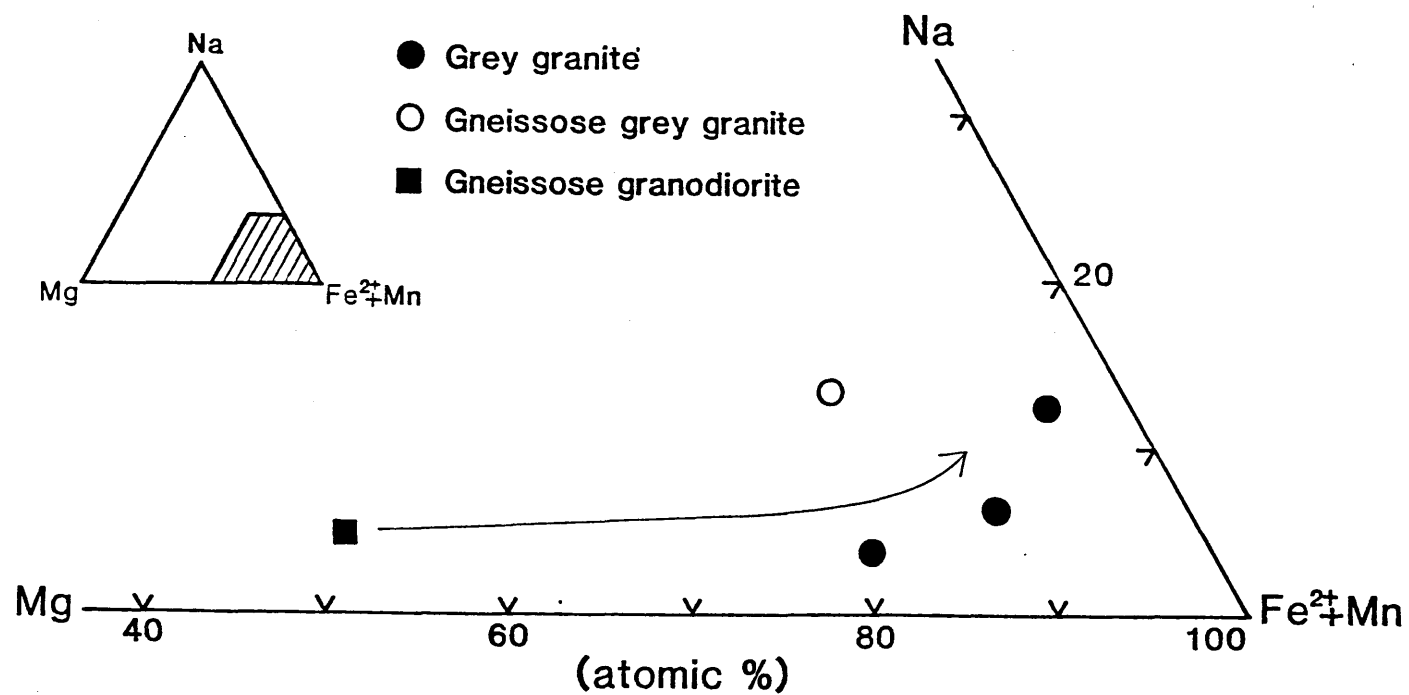


Fig. 7. Clinopyroxene compositions plotted in the Mg - (Fe²⁺+Mn) - Na diagram.
Evolutionary trend of the Seychelles clinopyroxene is indicated by an arrow.

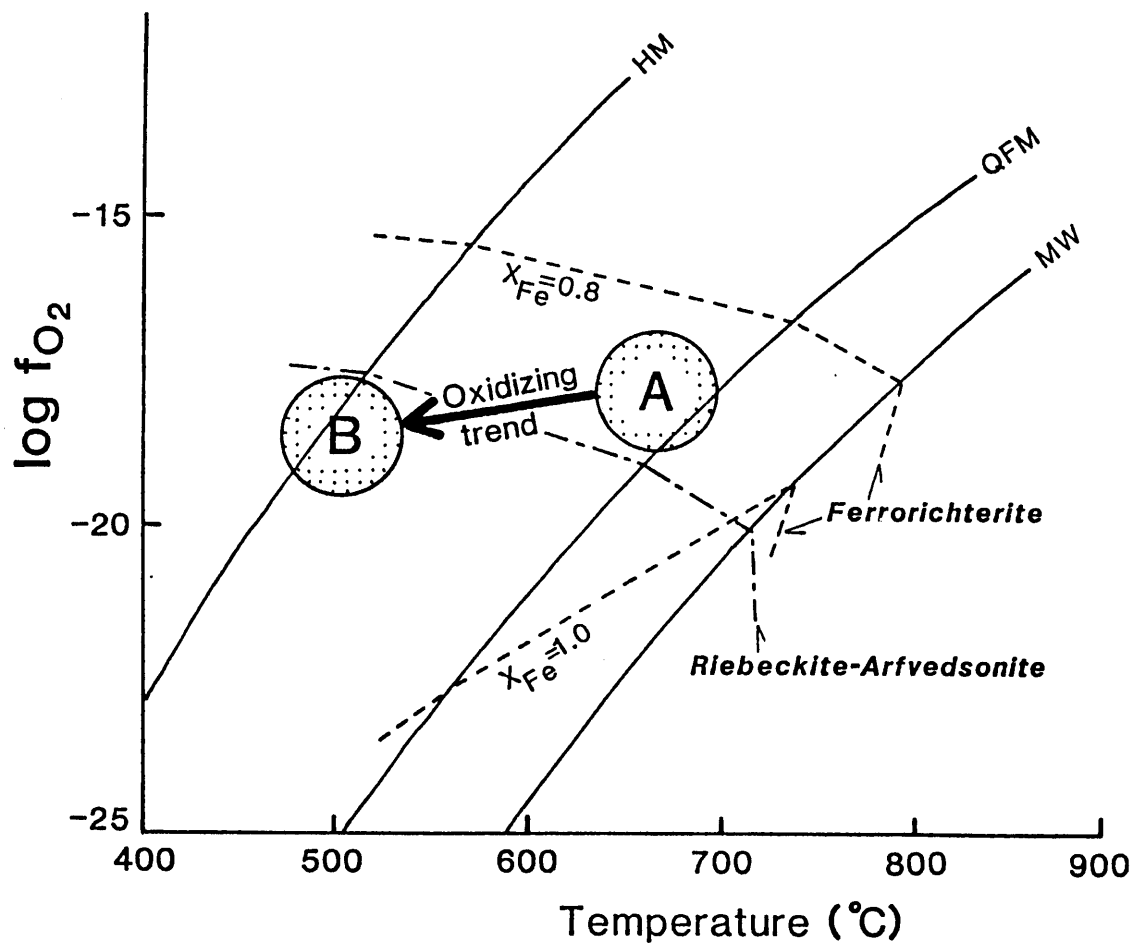


Fig. 8. Change in temperature-oxygen fugacity conditions during crystallization and subsequent cooling of the Seychelles granitic magma. Circles A and B represent the crystallization condition of ferrorichterite and riebeckite, respectively. Ferrorichterite stability curves are from Charles (1975 and 1977), riebeckite-arfvedsonite stability curve is from Ernst (1962). HM: hematite-magnetite buffer curve, FMQ: fayalite-magnetite-quartz buffer curve and MW: magnetite-wustite buffer curve (Eugster & Wones, 1962).