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ARFVEDSONITE IN GRANITES OF THE INGHAM DISTRICT, NORTH QUEENSLAND

by

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Abstract.

Arfvedsonitic amphiboles have been recognized in granites of the Ingham district, North Queensland.

The minerals occur:

A. in a granite on Hinchinbrook Island;
B. in schlieren and pods of pegmatite in the granite; and
C. in a microgranite dyke on the Burdekin River, on the mainland opposite Hinchinbrook Island.

Although the colour and pleochroism of the minerals in these three occurrences are markedly similar, their optical orientation and some other optical properties (2V, extinction angle) differ considerably. Chemically, the two Hinchinbrook varieties (A and B) appear to be arfvedsonite according to Miyashiro's classification. Of these, the coarse amphibole from the pegmatite is a mixture of two varieties; the optical properties of the more abundant one are closer to those of ferro-hastingsite, though the chemical composition is that of an arfvedsonite. This mineral may be a sodic member of a limited solution-series between arfvedsonite and ferro-hastingsite.

The amphibole variety C in the microgranite dyke has not been chemically analyzed, but it resembles variety A from the Hinchinbrook granite in all respects except optical orientation.

The chemistry and, in part, the optical properties of the North Queensland arfvedsonites, and the petrographic features of their granitic host rocks, are very similar to those reported from Nigeria.

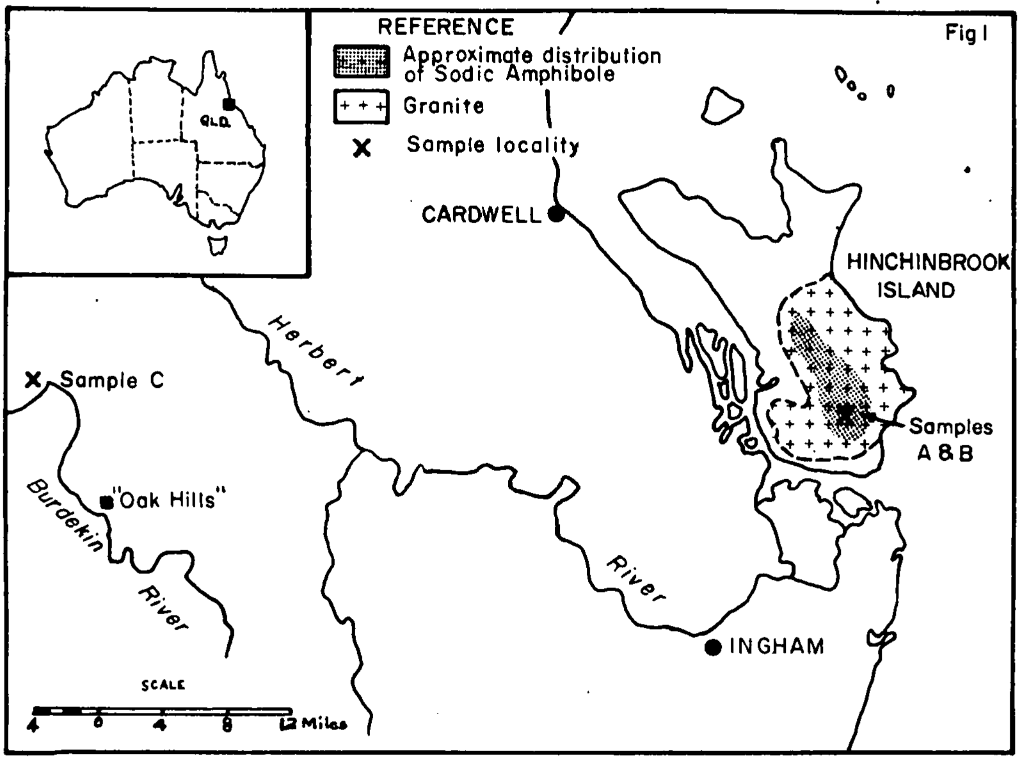

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Fig. 1 - Locality map of the sodic amphibole occurrences, North Queensland.

INTRODUCTION

During regional geological mapping in 1962 and 1963 by combined field parties of the Australian Bureau of Mineral Resources and the Geological Survey of Queensland, samples of granite and pegmatite were collected which contained sodic amphiboles initially identified as 'riebeckite'. As these were believed to be the first recorded occurrences of 'riebeckite' granite in Australia, the rocks and minerals have been more closely investigated.

The samples were obtained from three different rock types: a granite; a pegmatite closely associated with the granite; and a microgranite dyke. The granite and the pegmatite are exposed in the south-eastern part of Hinchinbrook Island, off the coast of North Queensland, and the microgranite crops out as a dyke on the Burdekin River, 9 miles north-north-west of Oak Hills homestead on the mainland opposite Hinchinbrook Island (Fig. 1).

Although the sodic amphiboles in the three rocks are very similar in colour and pleochroism, it was found that they differ in other respects, and that each has a different optical orientation. Chemical analyses were therefore made of the sodic amphiboles from Hinchinbrook Island, but the available sample of the dyke rock was too small for such purpose.

METHODS OF INVESTIGATION

The measured physical and optical characteristics of the three soda-amphiboles are tabulated in Table 1.

The optical properties were obtained by means of normal flat-stage procedures, and were, in part, checked by Dr. A.J.R. White of the Australian National University. Universal-stage work proved very difficult because of strong dispersion and incomplete extinction, and as the results obtained were ambiguous and self-contradictory, the Universal-stage method was discarded.

The refractive indices were measured by the immersion method, using an Abbe refractometer to check the indices of the fluids used. The accuracy of the measurements is probably not better than ± 0.003, as normal blue-filtered lamp light was used (monochromatic sodium light was found to be not practicable) and because there was strong absorption in certain directions.

The specific gravity of only the coarse pegmatitic amphibole was measured, using the immersion and balance method. As this mineral is a mixture of two different varieties of soda-amphibole, the specific gravity differs somewhat from fragment to fragment.

The amphibole was electro-magnetically separated from the crushed granite, and the concentrate was sufficiently pure for chemical analysis, as the rock is relatively free from other mafic minerals. The separation was carried out in the Petrological Laboratory of the Bureau of Mineral Resources in Canberra, and the analyses in the Australian Minerals Development Laboratories, Adelaide, by C.R. Edmond and D.C. Bowditch. The analyses and the cation ratios are tabulated in Table 2.

TABLE 1. PHYSICAL AND OPTICAL PROPERTIES OF THE SODIC AMPHIBOLES, NORTH QUEENSLAND

	AMPHIBOLE A (Species A)	AMPHIBOLE B (Species B, with some intergrown species A)	AMPHIBOLE C (Species C)
Occurrence	In granite, Hinchinbrook Island	In pegmatite, Hinchinbrook Island.	In microgranite dyke, Burdekin River.
Macroscopic appearance	Dark blue to black, longitudinally striated; streak bluish-grey.	Coarse, up to 6 inches long; dark-blue-green to black. Streak grey.	As for A.
Specific gravity	n.d.	3.376 and 3.460 (2 different fragments)	n.d.
Hardness	About 5	About 5	n.d.
Elongation	Length-fast	Length-slow	Length-fast
Extinction	$X \wedge c$: 6° to 7° in sections // (010)	$Z \wedge c$: 16°–23° in sections about normal to acute bisectrix	$X \wedge c$: 6°– 8° in sections // (010)
N_x	1.688 ± 0.003	1.689 ± 0.002	n.d.
N_z	1.699 ± 0.003	1.702 ± 0.003	n.d.
$N_z - N_x$	0.010	0.013	n.d.
Optical sign	Positive(?)	Negative	Positive(?)
2V	Very large	Small to very small, seems to range from almost zero up to about 20°.	Very large
Optical orientation	$X \wedge c$, $Y \wedge a$, $Z=b$; OAP $\perp$ (010)	$X \wedge a$, $Y=b$, $Z \wedge c$; OAP // (010)	$X \wedge c$, $Y=b$, $Z \wedge a$,; OAP // (010)
Pleochroism	X = dark indigo-blue to black	X = light pinkish yellow.	X = dark indigo-blue to black
	Y = light greenish yellow	Y = slaty grey to grey-green	Y = dark slate grey or blue.
	Z = dark slaty grey, grey-blue	Z = dark greenish blue to black	Z = greenish yellow
	Absorption $X \geq Z > Y$	$Z \geq Y > X$	$X \geq Y > Z$
Dispersion	Strong ($v > r$?). Anomalous interference colours as for B, but weaker. Crossed dispersion.	Very strong ($v > r$?); appears simultaneously inclined and horizontal in sections normal to acute bisectrix. No complete extinction in sections // (010). Anomalous blue interference colours in sections // (100), anomalous green and pink-brown or lilac in sections // (010).	n.d.
Twinning // (100)	Rare	Not observed	Common
Zoning	Rare	Not observed	Not observed.

TABLE 2 - CHEMICAL ANALYSES AND ATOMIC RATIOS OF SODIC AMPHIBOLES, NORTH QUEENSLAND

	Amphibole A 1)			Amphibole B 2)		
	Analysis	Cation ratios (0-23)	Formula	Analysis	Cation ratios (0-23)	Formula
SiO_2	48.0	Si 7.27	Z= 7.79	47.8	Si 7.60	Z= 7.88
Al_2O_3	2.90	Al 0.52		1.10	Al 0.22	
		Al –			Al –	
TiO_2	1.15	Ti 0.13		0.39	Ti 0.08	
Fe_2O_3	13.6	Fe^{3+} 1.55		9.75	Fe^{3+} 1.16	
FeO	19.3	Fe^{2+} 2.44	Y= 4.49	26.6	Fe^{2+} 3.54	Y= 5.18
ZnO	0.30 3)	Zn 0.04		n.d.		
MnO	1.68	Mn 0.22		2.60	Mn 0.35	
MgO	0.46	Mg 0.11		0.20	Mg 0.05	
CaO	1.41	Ca 0.24		1.35	Ca 0.23	
Na_2O	7.00	Na 2.05	X= 2.49	5.65	Na 1.74	X= 2.09
K_2O	1.02	K 0.20		0.57	K 0.12	
H_2O^+	1.60	OH' 1.61		2.30	OH' 2.44	OH= 2.44
H_2O^-	0.59		OH,F=2.59	0.17		
Li	0.005 3)					
F	2.04 3)	F 0.98		n.d.		
P_2O_5	0.30			0.00		
CO_2	0.04			1.32		
	101.12			99.80		
less O=F	0.86					
	100.26					

1) Amphibole A - sodic amphibole from granite, western slopes of Mount Diamantina, Hinchinbrook Island,
Analyst: D.C. Bowditch

2) Amphibole B - coarse sodic amphibole from pegmatite, same locality.
Analyst: C.R. Edmond.

3) Only Li, F, Cl, and Zn were determined in another sample of Amphibole A, showing the following figures:

Li	0.11
F	1.86
Cl	0.11
Zn	0.05

GEOLOGY AND PETROLOGY.

Hinchinbrook Island.

Hinchinbrook Island, 24 miles long, lies off the North Queensland coast at latitude 18°20'S., longitude 146°15'E. The north-western part of the island in composed of Permo-Carboniferous rhyolites and other volcanic rocks; the south-eastern part is intruded by a Permian granite batholith now eroded to a sculptured mountain complex with peaks rising 3000 feet or more above sea level.

It appears, from the few visits made, that the granite is a pinkish-red leucocratic alaskite or micro-alaskite in the lower levels, and a creamy yellow to grey-white arfvedsonite granite on the upper slopes. Both rocks, but especially the arfvedsonite granite, are vuggy or drusy in varying degree. The approximate distribution of the arfvedsonite granite, as known so far, is sketched in on Fig. 1.

Both the alaskite and the arfvedsonite granite have the characteristics of the hyper-solvus granites of Tuttle & Bowen, and one may therefore infer that the Hinchinbrook granites crystallized at a temperature over 660°C., and in a rather dry environment (Tuttle & Bowen, 1958, pp. 129, 137, et seq.). Although the relationship between the alaskite and the arfvedsonite granite is not precisely known, they are probably closely related genetically in view of their identical structure and texture. The distribution of the two rock types suggests that the arfvedsonite granite may form the roof zone of the alaskite.

In thin sections the alaskite is seen to be a medium-grained or fine-grained allotriomorphic aggregate of quartz and microperthite, containing a little leached brown biotite commonly accompanied by grains of iron oxides. The microperthite is very well developed as regular lamellar film or string perthite grading into vein perthite and rod perthite in places. It is very probably the product of unmixing of an originally homogeneous alkali-feldspar. The albitic and (untwinned) potash-feldspar components are present in roughly equal quantities. Late-stage deuteric albite also occurs, and is distinguished by its polysynthetic twinning, by its clarity and freshness compared with the cloudy appearance of the perthitic feldspar, and by its presence as patch perthite or as irregular rims around some perthite crystals. It also forms microscopically thin dentate, sutured, or lobate contact rims between perthite grains.

All these textural and mineralogical features are strikingly similar to those exhibited by some of the Nigerian granites, illustrated by Jacobson, MacLeod, and Black (1958; photo 11, Plate V, and photo 18, Plate VI, which are almost exact replicas of the Hinchinbrook rocks).

The arfvedsonite granite is a peralkaline rock, texturally and compositionally very similar to the alaskite, but with a greater percentage of deuteric or replacement albite (the rock is similar to that shown on photo 17, Plate VI, by Jacobson et al., 1958). The rock is commonly quartz veined, contains irregular schlieren and patches of feldspathic quartz pegmatite, and is in places rather vuggy, the vugs being lined with quartz crystals and a cellular earthy substance. Biotite apparently has generally been replaced by a scaly to radiating, yellow, greenish, or rust-coloured hydro-micaceous alteration product. The sodic amphibole appears to be a late-stage mineral: it occurs interstitially as fine grained acicular clusters,in places semi-radiating, as well as in larger, individual crystals up to 4 or 5 mm. long, moulded upon and between the feldspars. In one thin section an irregularly intergrown contact rim between amphibole and perthite was observed. Some crystals of sodic amphibole in the pegmatite may be up to 6 inches long. When weathered, the amphibole is thickly encrusted with hydrated iron oxides.

2. The mainland occurrence.

On the mainland, a sodic amphibole forms the mafic constituent of a microgranite dyke on the Burdekin River, 9 miles north-north-west of Oak Hills homestead. The rock consists of quartz and feldspar, with a liberal sprinkling of sodic amphibole. Most of the feldspar is perthitic; other grains show fine-lamellar twinning and irregular rims of potash-feldspar. The plagioclase component is generally an albite-oligoclase; a few crystals with higher refractive indices may be andesine. The potash-feldspar component is normally untwinned, but a faint microcline-grid pattern was observed in one grain. The amphibole resembles that of the Hinchinbrook Island granite in colour and pleochroism, but its optical orientation differs (see Table 1), and twinning parallel to (100) is fairly common.

The texture of the dyke rock is probably not the product of primary crystallization: the rock is thoroughly allotriomorphic; the individual grains show hackly, ragged, irregular outlines, and are interwoven in what may be replacement structures. Perhaps the texture indicates recrystallization and replacement during and after faulting and shearing - a protoclastic effect.

THE AMPHIBOLES.

Colour and pleochroism - the colours of the three varieties of amphibole are very similar, and their pleochroism follows the same crystallographic directions, independent of the optical orientation:

direction of a-axis = pale yellow, green-yellow, or pinkish-yellow.

direction of b-axis = (dark) slate-grey, blue-grey, or green-grey.

direction of c-axis = dark indigo-blue, dark greenish blue, to black.

This pleochroism characterizes members of the riebeckite-arfvedsonite series, and the chemical analyses and optical and physical properties confirm the identification. However, the three amphiboles differ radically in other respects, such as optical orientation, angle of extinction, optical sign, and 2V.

Optical orientation, and other properties. The optical orientation provides one of the most striking points of difference. The orientation shown by the mineral in the Hinchinbrook Island granite (species A) closely conforms to that reported for riebeckite and arfvedsonite by Miyashiro (1957), and is usually the orientation presented in English-language textbooks (Deer, Howie, & Zussman, 1962; Winchell; Moorhouse; etc.). The orientation shown by the amphibole in the dyke rock conforms with that for riebeckite and arfvedsonite as given by Rogers & Kerr (1942) and by many European mineralogists, including Niggli, Tröger, Klockmann (who call riebeckitic amphiboles with orientation A : Osannite). In the pegmatite, the amphibole is seen to be a mixture or "intergrowth" of two varieties (Fig. 2), one of which, (A), is identical with the amphibole in the surrounding granite; the other, (B), however, has an orientation seldom reported for riebeckite-arfvedsonite amphiboles (e.g., Rosenbusch, 1905). The "intergrowths", best recognizable under crossed nicols, are completely irregular, and the boundaries between the two varieties are ill-defined and gradational. Generally, variety A occurs as irregular patches and lamellae in variety B, commonly elongated in the direction of the cleavage, but in places trending across the crystals. Also, variety A appears to replace B along hair-

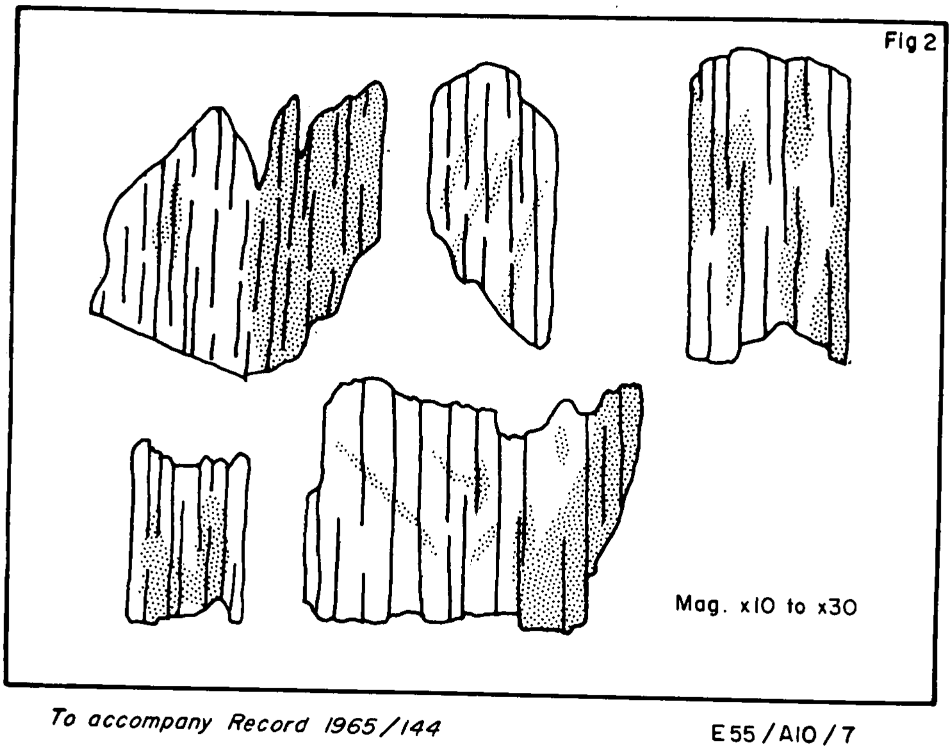

Fig. 2 - 'Intergrowth', or replacement of coarse amphibole variety B by amphibole variety A (shaded).

These grains were selected for their relatively large content of A.

line cracks, and is therefore considered to be the later mineral. Variety B is, in the thin sections examined, present in far greater amounts, so that its chemical analysis (which is not much different from that of A), although representing a heterogeneous mixture of two varieties, still gives a fair idea of the composition of B.

The nature of the "intergrowths" is not clear, but in view of the apparent replacements along cracks they seem to represent replacement structures. The intimate association of the two varieties perhaps offers an explanation for the confusing results from Universal-stage work (in which, more often than not, Y seems to parallel the crystallographic c-axis), and of the strange dispersion, which appears to be inclined as well as horizontal in one and the same crystal. Ernst (1962) also recorded unusual results in his study of arfvedsonites: in natural amphiboles, X paralleled the crystallographic c-axis, whereas in his synthetic minerals this position was taken by Y.

An outer rim or zone is noticeable in some amphibole (A) crystals in the Hinchinbrook granite. It is only faintly expressed by slight differences in colour intensity, and, between crossed nicols, by slightly different extinction angles and interference colours.

Twinning parallel to (100) is rare in the amphibole A of the granite, but is fairly common in amphibole C of the dyke rock.

Chemical analysis. According to the data in Table 2, the 8 tetrahedral positions (Z-group) in the atomic structure cannot be filled to completeness by Si plus Al; this, according to Phillips (1963), would indicate an error in the analysis. If so, many published analyses of the riebeckite-arfvedsonite group of amphiboles are erroneous: 40 percent of the analyses collected by Miyashiro (1957) show this defect.

Li, F, Cl, and Zn have been analyzed in two different samples of amphibole A, and show divergent values. As in one of the thin sections the mineral includes a minute grain of fluorite, the differences might be caused by irregularly distributed small impurities such as fluorite. The content of CO_2 may also be due to some minor impurity, possibly calcite; if this is so the figure for CaO is in need of a small correction, theoretically. The sum of $OH^- + F$ is anomalously high, possibly because of an error in the determination of H_2O^+, or because of the presence of small fluorite impurities.

CLASSIFICATION AND COMPOSITION

A study of the published literature on sodic amphiboles makes it clear that they are not as yet a well-established and properly classified group. Several reasons for this have been mentioned by the various investigators: references on the alkali amphiboles are scarce (Borley, 1963); ion-substitution in the crystal structure is all too easy, leading to complex formulae; published identifications and descriptions have often been erroneous (Miyashiro, 1957), and especially errors in the analytical figure for water content, which are believed to be common, have a pronounced effect on the calculated atomic formula (Phillips, 1963). Usually, chemical analyses are recalculated on the assumption of 24 anions in the formula unit, but Miyashiro worked on the basis of 23 anions because of the unreliability of the analytical figure for water content. In addition, the methods of assigning ions to the different positions in the amphibole structure vary with different authors. For example, in the tetrahedral (or Z) positions, which are ideally occupied by the Si ions, part of the Si can be replaced, according to Borley (1963), by Al, Zr, Ti, and Fe^{3+}; Kaufmann (1963,) however, rejects Ti as a possible substitute, Miyashiro (1957) disallows Fe^{3+}, and Phillips (1963) restricts possible substitution to Al.

Fig. 3

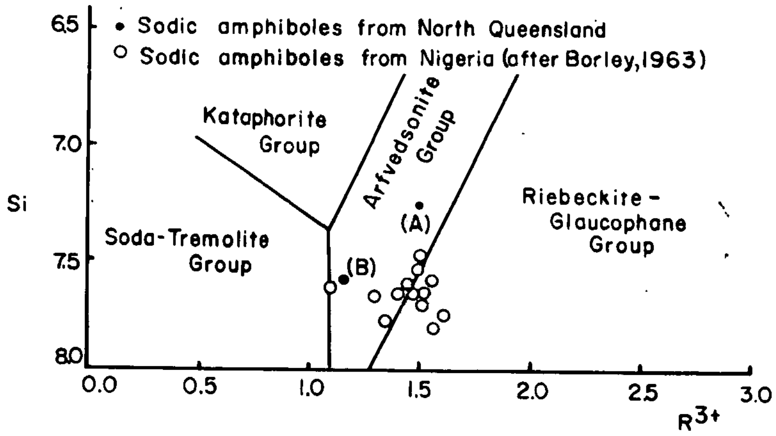

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Fig. 3 - Positions of the North Queensland arfvedsonites in Miyashiro's Si/R^{3+} diagram (Miyashiro, 1957). R^{3+} in this case = Fe^{3+}. Positions of the Nigerian amphiboles as plotted by Borley (1963) are added for comparison.

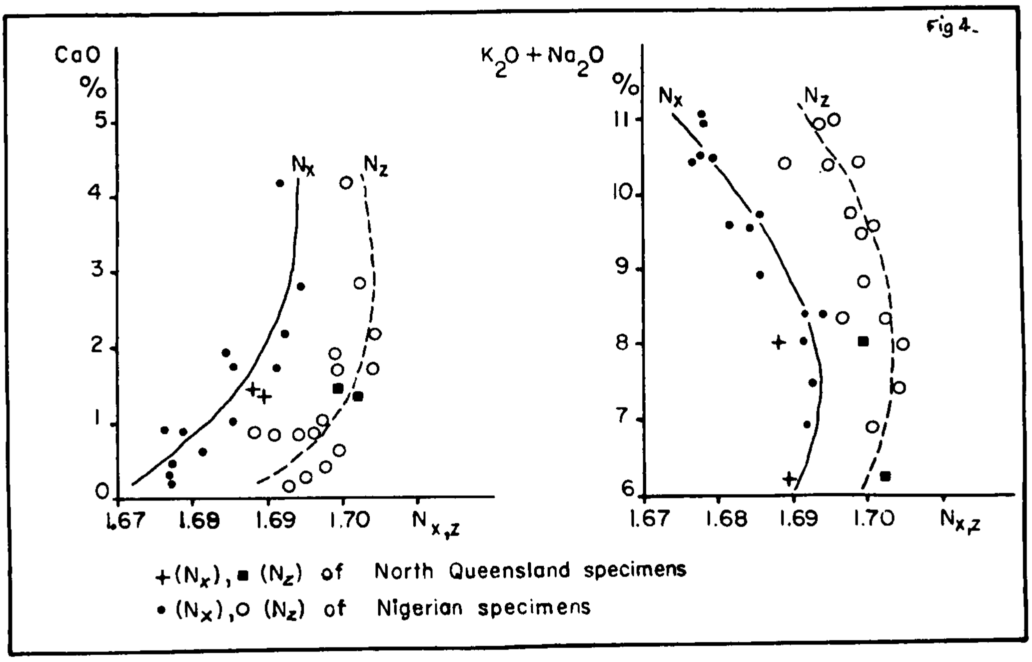

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Fig. 4 - Relations of CaO and K_2O + Na_2O content to the refractive indices of the Queensland arfvedsonites and (for comparison) of the Nigerian amphiboles.

From time to time attempts have been made to establish or improve classification schemes for the sodic amphiboles, most recently by Miyashiro (1957), Kaufmann (1963), and Brock et al. (1964). The classification proposed by Kaufmann for the amphiboles is based on nine parameters, includes at least 55 species names, and seems a little cumbersome and artificial; further, as none of the Queensland sodic amphiboles appear to fit any of his species (closest approximations are his riebeckite, arfvedsonite, and juddite), his classification seems to be incomplete. Miyashiro's scheme can be graphically represented, and is followed in this paper because it facilitates comparison with the Nigerian amphiboles, which strongly resemble the Queensland minerals, and which were also plotted on Miyashiro's diagram by Borley (1963).

The positions of the Hinchinbrook amphiboles have been plotted in Figure 3 onto one of Miyashiro's diagrams. They fall in his arfvedsonite field, which is in general agreement with the other data, although colour and pleochroism of variety A would have fitted riebeckite slightly better. The Queensland sodic amphiboles can in many respects be compared to the Nigerian amphiboles, which, originally named riebeckite (Jacobson et al., 1958), were later more correctly described as arfvedsonite or riebeckitic arfvedsonite (Borley, 1963). Figure 4 presents the positions of the Hinchinbrook amphiboles as well as those of the Nigerian minerals in a diagram which demonstrates the relations of refractive indices to CaO and $Na_2O + K_2O$ content. It is also possible to compare the two sets of minerals in other types of diagram, such as those used by Borley (1963), and in all instances they bring out the resemblance of the Queensland minerals to the Nigerian amphiboles. The geological settings are also much alike, and ring-complexes abound in Nigeria as well as in North Queensland.

It should be noted that the optical properties of the coarse species B are rather different from those normally given for arfvedsonite or riebeckite. Its colour is less intensely blue than that of variety A and tends towards green, and the yellow colour in the direction of the crystallographic a-axis has a pinkish or brownish hue instead of the more usual greenish yellow. These colour shades could be indicative of arfvedsonite, but the other optical properties (orientation, extinction angle, optical sign, and small 2V) are much more characteristic for ferro-hastingsite. The chemical analysis, the optics, and the close association of the mineral with arfvedsonite A together therefore appear to support the conclusion of Borley & Frost (1963) that there is evidence of a limited solid-solution series between ferro-hastingsite and sodic amphiboles. Billings (1928) had already remarked on an "alkali-hastingsite" which occurs in alkaline rocks and cannot be separated by optical methods from members of the hastingsite group.

Although, unfortunately, no analysis could be made of the amphibole in the dyke rock, there seems little doubt that the mineral belongs to the arfvedsonite-riebeckite group.

Concluding remarks.

According to Ernst (1962), pure riebeckite cannot crystallize directly from a silicate melt, whereas amphiboles of arfvedsonitic composition mainly occur as primary constituents of silicic or alkalic syenites and granites that have a high alkali and low calcium content, and which are enriched in iron relative to magnesium.

Rocks containing ferro-hastingsite normally crystallize earlier in the magmatic sequence than those containing arfvedsonite (Billings, 1928).

Tuttle & Bowen (1958) suggested that low water content in a magma may be essential for the formation of riebeckite-arfvedsonite amphibole; this condition is fulfilled in the hypersolvus granites, which are truly magmatic rocks, composed of quartz and perthite, and crystallized at high temperatures.

The conditions on Hinchinbrook Island appear to conform to these observations: the granite seems to be of the hypersolvus type, is composed of quartz and perthite feldspar, is apparently low in CaO, and probably contains more Fe than Mg. The coarse arfvedsonite B, with its ferro-hastingsite affinities is partly replaced by normal arfvedsonite A, and hence is the older mineral. This would suggest that the pegmatite had crystallized earlier than the final consolidation or reconstitution of the arfvedsonite granite in which it is contained. Perhaps the arfvedsonite granite was formed during a late stage in the intrusion of the batholith, when the roof area of the magma chamber became enriched in sodium and possibly iron. Previously crystallized biotite was largely destroyed in the process, and the crystals of coarse arfvedsonite B in the schlieren of pegmatite that had crystallized out a little earlier, in the roof zone where the few volatiles were concentrated, were partly replaced by the later, more sodic, arfvedsonite A. The remaining melt, poor in volatiles, in the central and lower regions of the batholith, crystallized out as the 'dry' fine-grained to medium-grained alaskite.

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