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IRON-RICH HORNBLENDE PLUS ALBITE IN LOW-PRESSURE METABASITES, CHIBOUGAMAU, QUEBEC

STEPHEN W. KLINE

Department of Geology, University of Georgia, Athens, Georgia 30602, U.S.A.

ABSTRACT

Amphiboles in the Doré Lake Complex, a metamorphosed layered mafic intrusive complex located near Chibougamau, Quebec, have been studied by electron-microprobe techniques. In Fe-rich portions of the complex, ferro-pargasite coexists stably with albite. Regional studies show metamorphism to be in the greenschist facies of the low-pressure (Abukuma) facies series. The occurrence of a hornblende-type amphibole with albite is common in rocks of a medium-pressure facies series; in low-pressure terranes, however, albite changes to oligoclase below the temperature of the actinolite-to-hornblende transition. The association is attributed to the iron-rich bulk composition, which stabilizes hornblende at a subnormal temperature. Other amphiboles in the complex include actinolite and ferro-actinolite, brown Ti-rich ferro-edenitic hornblende, and cummingtonite–grunerite. The brown hornblende is a relict magmatic phase. Actinolite is stable in Mg-rich rocks, but in Fe-rich bulk compositions, ferro-actinolite is converted to ferro-pargasite, given available Na + Al and chemical homogenization. In rocks where homogeneity was not attained, these minerals, "frozen" in incomplete reactions, define a tschermakitic trend on the actinolite side of a miscibility gap and a pargasitic trend on the pargasite side. This fact suggests that the actinolite-to-hornblende transformation was a two-stage process. In some rocks, ferro-pargasite is in stable equilibrium with cummingtonite or grunerite. In these extremely Fe-rich rocks, Fe is concentrated in ferro-pargasite rather than Fe–Mg monoclinic amphibole.

Keywords: amphiboles, metamorphism, low-pressure facies series, ferro-pargasite, cummingtonite–grunerite, hornblende, coexisting amphiboles, Doré Lake Complex, Quebec, greenstone belts.

SOMMAIRE

On a étudié, par microsonde électronique, les amphiboles du complexe du lac Doré, massif stratiforme métamorphisé près de Chibougamau (Québec). Dans la partie du complexe riche en fer, la ferro-pargasite et l'albite coexistent. Ces roches montrent les effets d'un faible métamorphisme régional dans le facies schiste-vert de la série de facies de basse pression du type Abukuma. La coexistence d'une amphibole du type hornblende et d'albite est commune dans une série de roches à facies de pression intermédiaire; dans les cas de métamorphisme à basse pression, toutefois, l'albite se transforme en oligoclase en-dessous de la température de la transformation actinote - hornblende. L'association serait due à la concentration élevée du fer dans ces roches, qui stabiliserait la hornblende à une température en-dessous de la normale. On trouve aussi d'autres amphiboles: actinote, ferro-actinote, hornblende édénitique titanifère brune et cummingtonite - grunerite. La hornblende est une relique magmatique. L'actinote reste stable dans les roches magnésiennes, mais dans les roches ferrifères, la ferro-actinote passe à la ferro-pargasite, étant donné la disponibilité de Na et Al, d'une part, et l'homogénéisation chimique d'autre part. Dans les roches non encore homogénéisées, ces minéraux, figés dans des réactions incomplètes, définissent une lignée tschermakitique du côté de l'actinote et une lignée pargasitique du côté de la pargasite, séparées par une lacune de miscibilité. La transformation d'actinote en hornblende serait donc un processus à deux temps. Dans certaines roches très riches en fer, la ferro-pargasite est en équilibre stable avec cummingtonite ou grunerite, et le fer se concentre de préférence dans la ferro-pargasite.

(Traduit par la Rédaction)

Mots-clés: amphibole, métamorphisme, série de facies de basse pression, ferro-pargasite, cummingtonite - grunerite, hornblende, amphiboles coexistantes, complexe du lac Doré, Québec, ceinture de roches vertes.

INTRODUCTION

The two most important mineralogical changes in metabasites that mark the transition from greenschist to amphibolite facies are well known: the amphibole changes from actinolite to hornblende, and the plagioclase becomes more An-rich, across the peristerite gap from albite to oligoclase. The exact P–T relations of this transition are not well calibrated, but in the low-pressure facies series the change in plagioclase composition is known to occur at a lower temperature than the amphibole transition; in medium-pressure metamorphism, the amphibole transition occurs at a lower temperature (Robinson *et al.* 1982). This phenomenon gave rise to the designation of a greenschist–amphibolite transition facies for rock types of the Barrovian series with the assemblage albite + epidote + hornblende. Although this facies-series relation holds true for the limited compositional range of most metabasites, evidence from the Doré Lake Complex shows that for iron-rich bulk compositions, hornblende can be stable at a lower temperature than plagioclase, even in low-pressure rocks.

GEOLOGY OF THE DORÉ LAKE COMPLEX

The Doré Lake Complex is a metamorphosed Bushveld-like layered mafic body in the Archean Matagami–Chibougamau greenstone belt of the Superior structural province of Quebec (Allard 1970). The greenstone belt was regionally metamorphosed to the greenschist facies during Kenoran metamorphism; owing to the high geothermal gradient prevailing in the Archean, the metamorphic assemblages define a low-pressure facies series (Jolly 1978). Primary igneous cumulus textures are commonly well preserved, and metamorphism is essentially isochemical (Allard 1976).

The complex has been studied and mapped in fair detail by G.O. Allard and his students and colleagues. A good summary of their work was published by Allard (1976). The stratigraphy and disposition of the complex are shown in Figure 1. Cryptic chemical layering similar to that in the Bushveld and other layered complexes has been demonstrated. The most notable changes in major elements, from the bottom to the top of the complex, are the decrease in Ca in primary plagioclase and the decrease in Mg/Fe in ferromagnesian minerals. Iron becomes highly concentrated in the upper part of the Layered Zone. Pyroxenites there commonly contain over 25% combined FeO and Fe_2O_3, with most of the iron concentrated in the silicates. The complex is folded into an east-northeast-trending anticline with nearly vertical limbs, and is intruded in the axis by the Chibougamau pluton, a leucotonalite. The complex is truncated on the east by the Grenville Front. Rocks near the Grenville Front were affected slightly by Grenville metamorphism, as indicated by the presence of garnet in some lithologies.

ANALYTICAL METHODS

Over 200 thin sections of samples collected by Allard and coworkers and by the present author were examined with the petrographic microscope. Eighteen samples were selected from the major units of the upper Anorthosite Zone, Layered Zone and Sodagranophyre Zone for electron-probe microanalysis.

The chemical composition of the amphiboles was determined using a MAC 400S electron-probe microanalyzer with 15 kV accelerating potential and a sample current of 0.015 μA. At least five grains

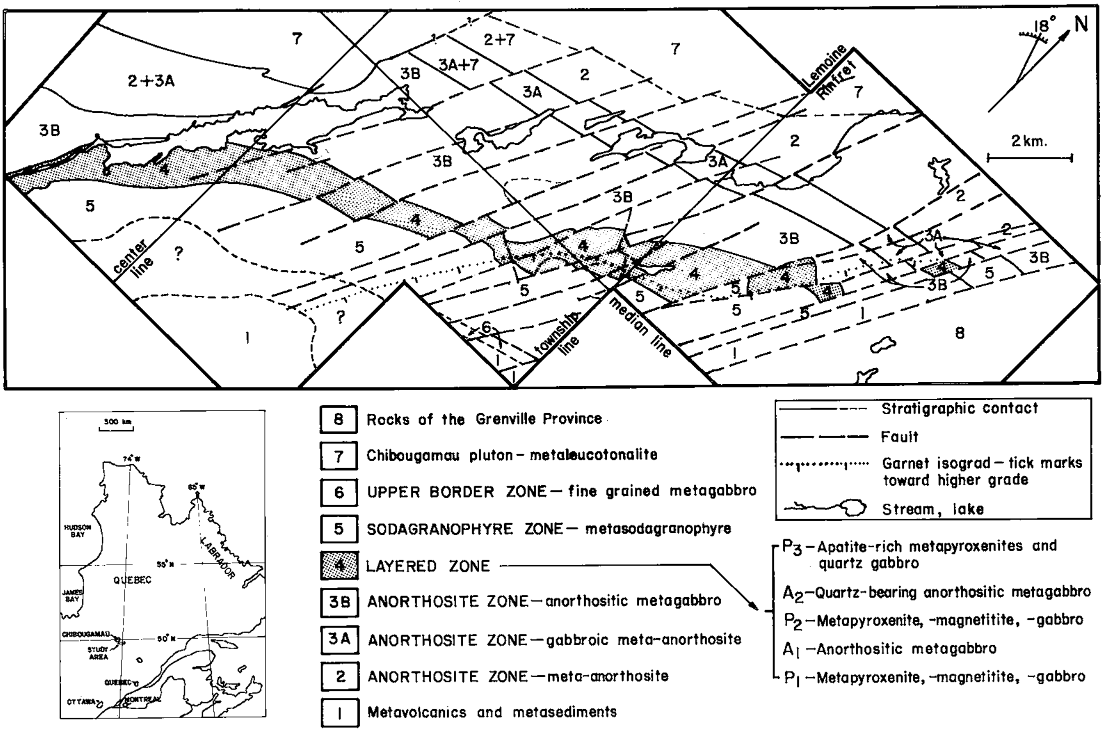

FIG. 1. Map of the southern limb of the Doré Lake Complex, Quebec. This map is a simplified version of that of Caty (1970). The stratigraphy of the complex is also shown.

of each amphibole species were analyzed in each sample with a 50-second counting time divided into two 25-second intervals and a slight change in spot location between the intervals. X-ray spectra were analyzed by an energy-dispersion system, and raw data reduced to weight percent oxide by a computer program developed by J.C. Stormer. The following standards were used: Korath amphibole for Si, Al, Ti, Mg, Ca, Na and K, rhodonite for Mn, and a synthetic fayalite for Fe. Replicate analyses of Kakanui hornblende of known composition were made to estimate standard deviations for the sample analyses (see Table 1).

A structural formula for the amphiboles was calculated from the oxides reported based on 23(O) as discussed in Robinson *et al.* (1982). If the sum of cations, excluding Na and K, is greater than 15, a factor is used to normalize the sum to 15. If the sum of the cations is less than 15, the total is not normalized, and Na is assigned to *M*4 to make up the difference. Ferric iron is estimated by assigning some of the iron to Fe^{3+} so as to achieve a total positive charge of 46.

This particular method was chosen because it allows distribution of Mn, Fe and Mg into the *M*4 site. Since many of these rocks show cummingtonite coexisting with hornblende, the hornblende should be saturated with respect to these components in the *M*4 site. This method also minimizes the calculated amount of Fe^{3+}, whereas normalizing to 13 cations exclusive of Ca, Na and K maximizes Fe^{3+}. Since metamorphic rocks commonly are quite reduced, the real Fe^{3+} content should be closer to the minimum value calculated than to the maximum value.

Names are assigned to the amphiboles according to Leake (1978). Representative compositions are given in Table 1.

PETROLOGY AND MINERAL CHEMISTRY

The rocks studied in detail consist of metagabbros, metaferrogabbros, metaferropyroxenites and metasodagranophyres. In addition to amphiboles, the typical mineral assemblages contain albite + quartz + clinozoisite–epidote ± chlorite ± titanite ± opaque minerals ± primary apatite (± garnet near the Grenville Front). Biotite occurs in some of the granophyres; stilpnomelane and tourmaline are rare accessories in some rocks. Four main kinds of amphibole were found: (1) actinolite – ferro-actinolite, in all the above lithologies, with

TABLE 1. REPRESENTATIVE COMPOSITIONS OF AMPHIBOLE

		A	B	C	D	E	F	G	H	I	J	K	L	M
	SiO_2	54.7	40.3	52.3	42.3	40.4	52.7	39.4	50.0	42.8	38.1	52.9	38.6	0.4
	Al_2O_3	1.9	19.9	0.7	10.1	12.4	1.8	15.7	1.3	9.3	17.7	1.0	14.6	0.3
	TiO_2	0.2	0.1	0.1	2.6	0.2	0.1	0.2	0.3	1.7	0.2	0.0	0.7	0.2
	FeO*	10.4	16.4	29.8	20.4	23.2	16.9	24.3	34.4	25.2	25.5	21.3	28.9	0.3
	MnO	0.4	0.5	0.5	n.d.	0.0	0.4	0.4	1.1	0.2	0.3	n.d.	0.5	0.1
	MgO	17.2	6.9	12.8	7.8	5.8	12.5	3.4	8.7	5.5	2.2	10.2	0.2	0.3
	CaO	11.4	12.1	0.6	11.2	11.2	12.5	11.8	1.8	10.9	10.5	12.3	11.2	0.1
	Na_2O	n.d.	1.7	n.d.	1.3	0.9	n.d.	1.3	n.d.	2.0	2.5	n.d.	1.7	0.6
	K_2O	0.1	0.5	0.1	1.2	0.9	0.1	0.7	0.2	0.5	0.5	0.1	2.1	0.1
	Total	96.3	98.4	96.9	96.9	95.0	97.0	97.2	97.8	98.1	97.5	97.8	98.5	
T	Si	7.86	5.97	7.95	6.52	6.36	7.79	6.13	7.80	6.65	5.97	7.91	6.17	
	Al(IV)	0.14	2.03	0.05	1.48	1.64	0.21	1.87	0.20	1.35	2.03	0.09	1.83	
C	Al(VI)	0.19	1.45	0.09	0.36	0.66	0.11	1.01	0.02	0.35	1.25	0.09	0.92	
	Ti	0.02	0.01	0.01	0.30	0.03	0.01	0.02	0.03	0.20	0.03	-	0.08	
	Fe^{3+}	-	-	-	-	0.45	0.06	0.27	0.08	-	-	-	-	
	Fe^{2+}	1.11	2.01	2.00	2.54	2.50	2.03	2.89	2.85	3.17	3.21	2.64	3.86	
	Mg	3.68	1.53	2.90	1.80	1.36	2.76	0.78	2.02	1.28	0.51	2.27	0.04	
	Mn	-	-	-	-	-	0.03	0.03	-	-	-	-	0.07	
B	Fe^{2+}	0.14	0.02	1.79	0.10	0.10	-	-	1.56	0.10	0.14	0.02	-	
	Mn	0.05	0.06	0.06	-	-	0.02	0.03	0.15	0.02	0.04	-	-	
	Ca	1.76	1.91	0.10	1.85	1.89	1.98	1.97	0.29	1.81	1.76	1.97	1.92	
	Na	-	0.01	-	0.05	0.01	-	-	-	0.07	0.06	-	0.08	
A	Na	-	0.47	-	0.34	0.28	-	0.41	-	0.52	0.70	-	0.44	
	K	0.01	0.09	0.02	0.24	0.18	0.03	0.14	0.04	0.11	0.09	0.03	0.43	
	Ca + Na(B)	1.76	1.96	0.10	1.90	1.90	1.98	1.97	0.29	1.88	1.82	1.97	2.00	
	$Mg/(Mg + Fe^{2+})$	0.75	0.46	0.43	0.41	0.34	0.58	0.21	0.31	0.28	0.13	0.46	0.01	

Microprobe analyses. FeO* = total Fe as FeO. Oxide percents rounded off to nearest tenth; 0.0 = detected, but less than 0.05; n.d. = not detected. Formulas calculated according to text. A-B: actinolite and ferroan pargasite from one pyroxene pseudomorph in sample 66-267A, a metagabbro from upper part of Anorthorite Zone. B is from rim and A is very close to rim. C-D-E: cummingtonite, brown ferroedenitic hornblende, and ferropargasite from sample 66-262, a P_1 (or P_2?) metaferropyroxenite. The brown hornblende is being replaced by the other two; all three in optical continuity. F-G: actinolite and ferropargasite from sample 66-402, border of a metaferropyroxenite and anorthositic metagabbro. F is from the gabbro and G from the pyroxenite. H-I-J-K: cummingtonite, brown ferroedenitic hornblende, ferropargasite, and ferroactinolite from 67-95, a P_3 metaferropyroxenite. A patch of pargasite (J) surrounds two brown hornblendes. One of them (I) has a core of cummingtonite (H); the other has a core of ferroactinolite (K), thought to be originally pyroxene. L: ferropargasite from sample K-147, a metasodagranophyre. M: Standard deviations of replicate analyses of a Kakanui hornblende standard.

decreasing abundance and increasing iron content toward the top of the complex, (2) blue-green ferro-pargasitic hornblende - ferro-pargasite, also in all the lithologies, with increasing abundance and increasing iron content toward the top, (3) cummingtonite - grunerite, in certain metapyroxenites and metagabbros, as discussed below, and (4) brown ferro-hornblende - ferro-edenitic hornblende in all lithologies, but more prevalent in iron-rich rocks. A number of relatively unmetamorphosed rocks occur in the complex; these preserve primary plagioclase and, less commonly, clinopyroxene and orthopyroxene. The existence of these rocks is probably due to a scarcity of metamorphic fluids or the relative impermeability of some parts of the complex.

Ferro-actinolite and ferro-pargasite are pseudomorphic after clinopyroxene. The proportion of ferro-pargasite relative to ferro-actinolite generally increases toward the more iron-rich upper part of the complex. Where they occur together, the actinolite forms the main part of the pseudomorphs and ferro-pargasite occurs as a rim against plagioclase and commonly as patches within the pseudomorphs. Boundaries are sharp between the two amphiboles. In some cases, the pseudomorph is a single crystal with optical continuity of actinolite and ferro-pargasite; in others it is a polycrystalline

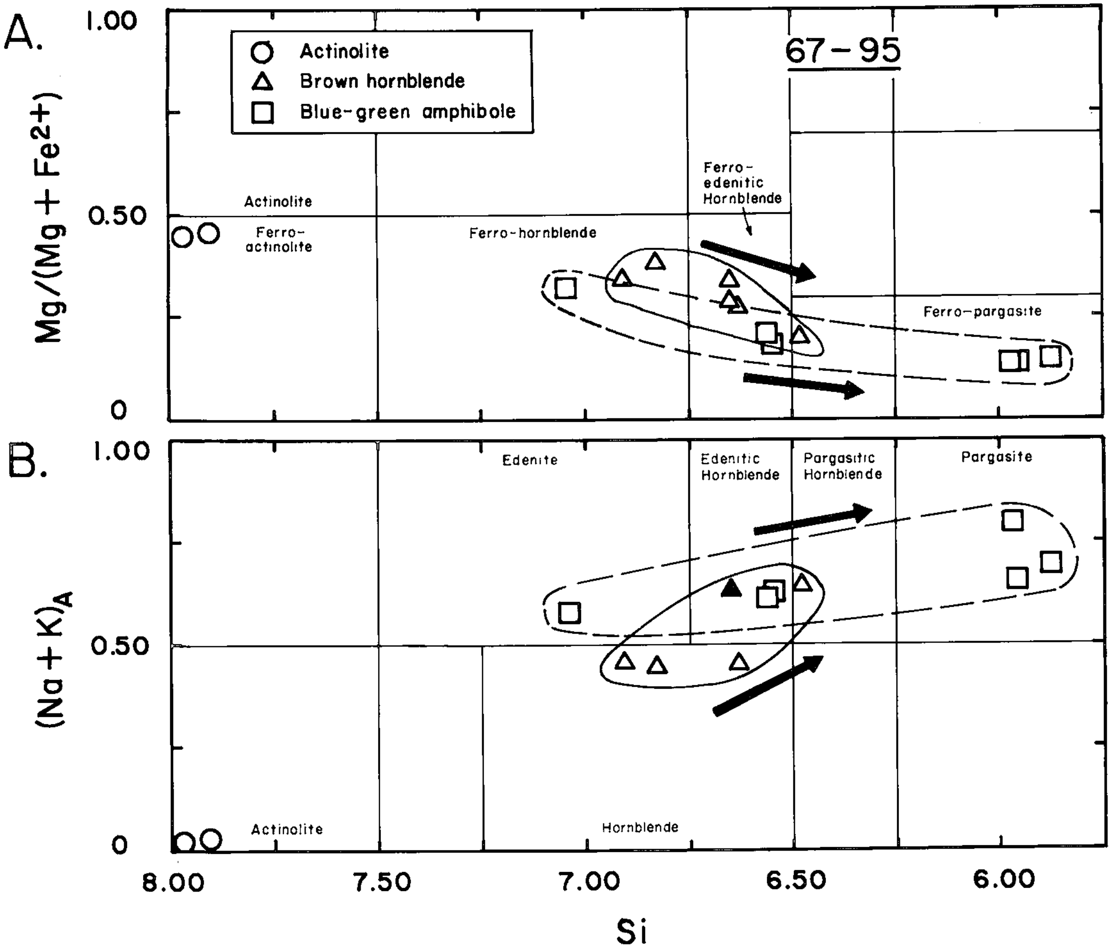

FIG. 2. Calcic amphiboles of sample 67–95, a metaferropyroxenite of the P3 member of the Layered Zone. The cation values are taken from structural formulas calculated from electron-probe data on individual grains. The filled-in triangle represents two identical compositions. Nomenclature according to Leake (1978). In A, the names toward the left pertain to an *A*-site occupancy less than 0.50, and the names toward the right pertain to an *A*-site occupancy greater than 0.50. Note that both the brown and green hornblendes have a pargasitic trend (arrows) and that much overlap occurs between the two.

felted intergrowth, the boundary between actinolite and ferro-pargasite domains still being sharp.

In most occurrences, cummingtonite (or grunerite) is the product of metamorphic replacement of orthopyroxene or fayalite. Sample 67–11 contains relict orthopyroxene partly altered to cummingtonite (and clinopyroxene partly altered to actinolite and ferro-pargasite). In sample 67–81, pseudomorphs after orthopyroxene and fayalite now consist of grunerite with a thick reaction-rim of ferro-pargasite + garnet against plagioclase. In both cases the plagioclase is primary. Because the plagioclase is essentially unaltered, it appears that little to no Ca, Na and Al have been released which might otherwise have reacted with grunerite to form ferro-pargasite in these samples.

The brown hornblende in these rocks is a relict magmatic hornblende. Unmetamorphosed rocks and relict textures in metamorphosed rocks show the brown hornblende as a rim on and inclusions in clinopyroxene and occasionally as a rim on orthopyroxene and as independent crystals. It has an intercumulus texture against euhedral cumulus plagioclase. Its relatively high Ti content, which imparts the brown color, is indicative of the relatively high temperature of formation.

In most cases, the brown hornblende is either not affected by metamorphism and has a sharp boundary against ferro-actinolite and ferro-pargasite, or is partly converted to ferro-pargasite. In some grains in sample 67–81 and in some metaferropyroxenites, the brown hornblende is metamorphosed to ferro-pargasite and to members of the cummingtonite - grunerite series. In sample 66–262, the relationship is clear; a large pseudomorph has a patchy intergrowth of ferro-pargasite and cummingtonite in optical continuity with relict brown ferro-edenitic hornblende (see Table 1 for compositions).

EQUILIBRIUM COEXISTENCE OF AMPHIBOLES

As all four types of amphibole coexist in some of the rocks, it is important to identify which are stable. The stability of the amphiboles is very dependent on bulk composition. The brown hornblende is stable in Mg-rich bulk compositions, but in Fe-rich rocks it is converted to ferro-pargasite. In many cases, the compositions of several grains of brown hornblende in one sample define a trend toward a pargasitic composition, and in many cases brown and green patches grade imperceptibly into each other. Sample 67–95 (Fig. 2) shows not only the pargasitic trend for brown hornblende but even a compositional overlap with the blue-green amphibole. The occurrence in many rocks of fresh-looking brown hornblende with sharp boundaries against ferro-pargasite is probably due to paucity of metamorphic fluids to aid reaction.

Cummingtonite (or grunerite) and ferro-pargasite coexist stably in rocks of ferropyroxenitic bulk composition (low in plagioclase) and in metaferrogabbros that have unaltered plagioclase. That they are both

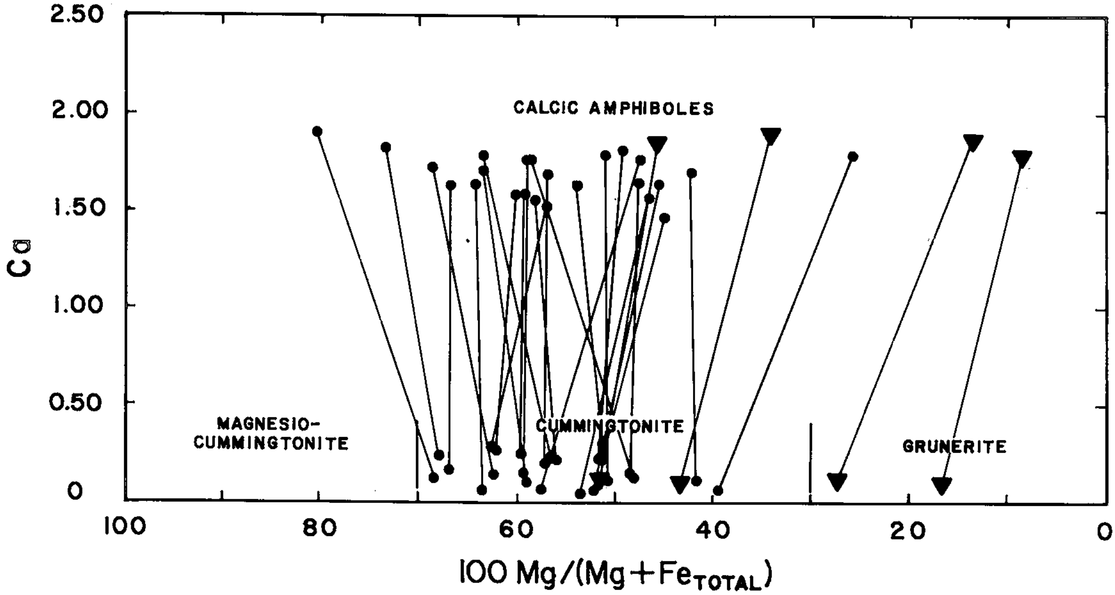

FIG. 3. Magnesium-to-iron ratio in coexisting calcic and monoclinic Fe–Mg amphiboles. Circles represent data taken from Klein (1968, Table 5); triangles represent data from this study.

stable is best illustrated in sample 66–262 (mentioned above), where the brown hornblende is partly replaced by an intergrowth of ferro-pargasite and cummingtonite. In other parts of the thin section, ferro-pargasite and cummingtonite occur together as an intergrowth of distinct prismatic crystals. In rocks where altered plagioclase is present to release sufficient Ca, Na and Al, cummingtonite is not found.

Klein (1968) studied stable cummingtonite and hornblende pairs in rocks of a generally higher Mg/Fe ratio than most found in this study. In most of his rocks, iron was partitioned into cummingtonite relative to hornblende, but for the most iron-rich bulk compositions, a tendency was observed for the hornblende to be the more iron-rich phase. This phenomenon is confirmed in the very iron-rich rocks of the Doré Lake Complex, where the ferro-pargasite is consistently richer in Fe than the coexisting Fe/Mg clinoamphibole (see Fig. 3).

In the more iron-rich rocks of the complex, actinolite is rare and apparently was not stable at peak metamorphic conditions. The instability of ferro-actinolite is inferred from the examples where brown hornblende has altered to ferro-pargasite + cummingtonite (or grunerite). In sample 67–81, for

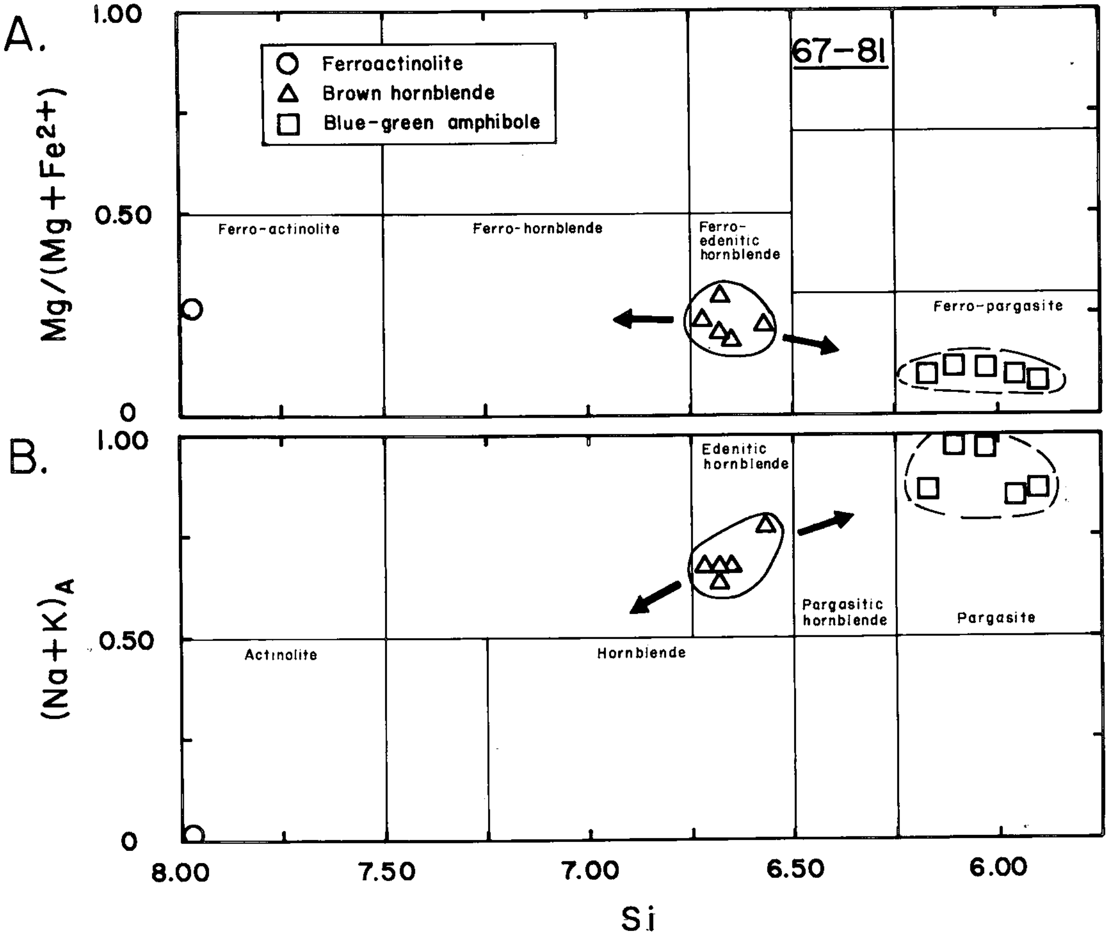

FIG. 4. Calcic amphiboles from sample 67–81, a partly altered metaferrogabbro of the P3 member of the Layered Zone. Atomic proportions are taken from structural formulas calculated from electron-probe data on individual grains. Nomenclature according to Leake (1978). Note that with respect to the elements portrayed, the brown hornblende compositions fall between the pargasitic and the actinolitic amphiboles. The ferro-pargasite has more Al, less Si, greater (Na + K), and lower Mg/Fe than the brown hornblende, whereas ferro-actinolite has less Al, more Si, lower (Na + K) and slightly higher Mg/Fe than brown hornblende. The brown hornblende could almost isochemically provide, as breakdown products, the combination of the other two amphiboles. In place of actinolite, however, grunerite occurs with ferro-pargasite as a breakdown product.

example (Fig. 4), brown hornblende has altered to ferro-pargasite plus grunerite. Visual inspection of Figure 4 and mass-balance calculations show that the brown hornblende could almost isochemically break down into a combination of ferro-actinolite and ferro-pargasite. Instead, the brown hornblende breaks down to grunerite plus ferro-pargasite by releasing Ca and taking up Fe. In addition, the actinolite in such samples occurs only in pyroxene pseudomorphs that have reaction rims of ferro-pargasite and is not found as a product from brown hornblende. The actinolite is therefore thought to have been unstable in these bulk compositions when chemical homogenization has occurred.

Actinolite is stable in more magnesian bulk-compositions. In gabbros of the upper part of the Anorthosite Zone, pyroxenes are altered to actinolite with only a thin rind of ferroan pargasite, and in the even more Mg-rich lower parts of the Anorthosite Zone, actinolite is the sole amphibole with no pargasite, even in contact with plagioclase.

A fairly wide scatter along a pargasitic trend occurs in the compositions of blue-green amphibole. This is thought to be due to incomplete chemical homogenization in these rocks. It is thought that if chemical homogeneity and equilibrium were attained, the stable blue-green amphibole would have a composition similar to those of the more Al-rich ferro-pargasite in these compositional trends.

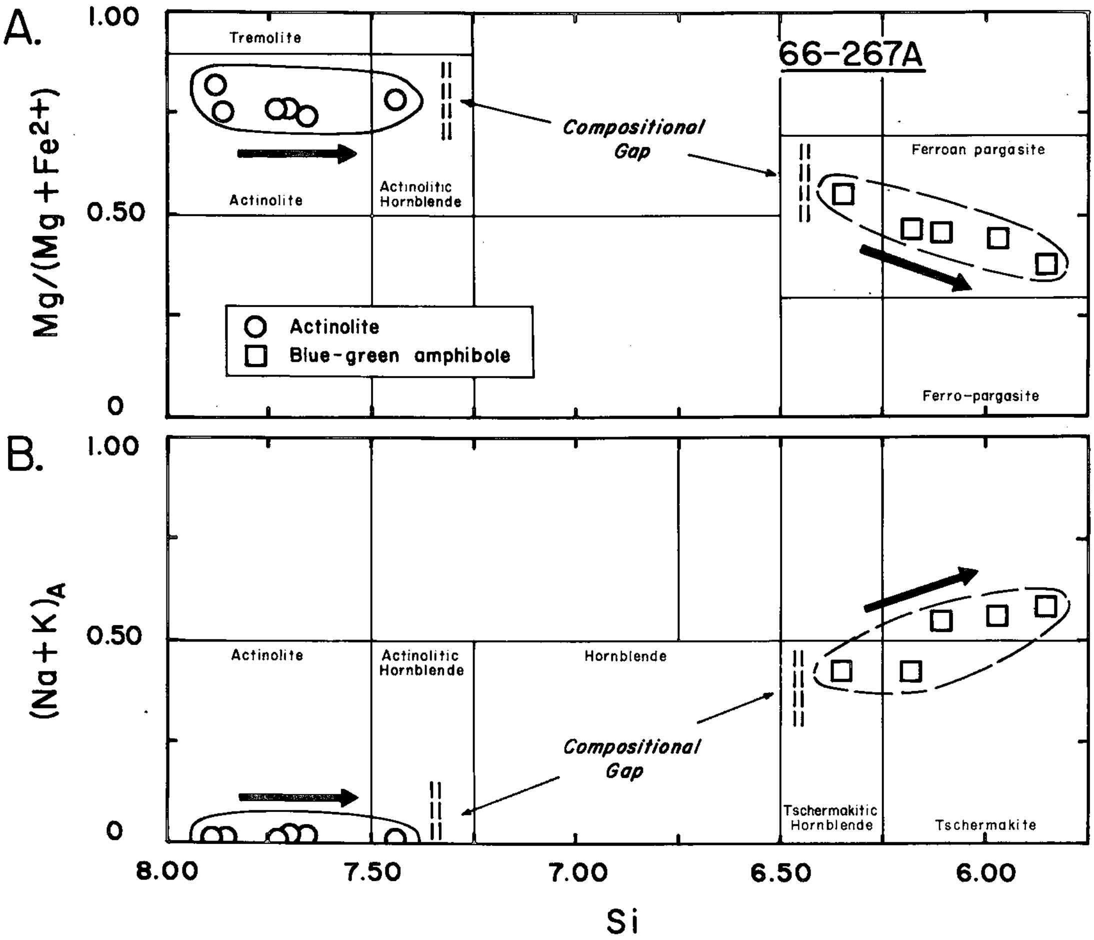

FIG. 5. Calcic amphiboles from sample 66–267A, a partly altered metagabbro from the upper part of the Anorthosite Zone. Atomic proportions are taken from structural formulas calculated from electron-probe data on individual grains. Nomenclature according to Leake (1978). Actinolite compositions fall along a tschermakitic trend, and hornblende compositions fall on a pargasitic trend (arrows emphasize these trends). The compositional gap between them is thought to be due to immiscibility.

DISCUSSION AND CONCLUSIONS

In a low-grade stage of metamorphism, perhaps during burial metamorphism (Jolly 1978), most of the rocks of the complex had their pyroxenes converted to actinolites and Fe–Mg monoclinic amphibole, and plagioclase altered to albite + epidote. During a later, higher-grade stage, reactions of some still fresh plagioclase, or albite + epidote, with ferro-actinolite and with Fe–Mg amphibole produced ferro-pargasite in iron-rich rocks. These reactions apparently occurred under a low activity of water, leaving some rocks partly unaltered. Paucity of water and incomplete chemical homogenization also explain the occurrence of relict ferro-actinolite and brown hornblende and the wide compositional scatter along a pargasitic trend for the blue-green amphibole.

At the peak of metamorphism, ferro-actinolite was unstable in the presence of available Na + Al and reacted to form ferro-pargasite. In many of the rocks chemical homogeneity was not attained, leaving ferro-actinolite in the core of pyroxene pseudomorphs coexisting with ferro-pargasite on the rim. Effects of the solvus between the two can be seen in the partly reacted grains that are "frozen" in various compositions along the chemical pathway between them. Where ferro-actinolite is rimmed by ferro-pargasite, a sharp boundary occurs, and a wide gap between actinolite compositions and pargasite compositions is present. In a few (for example, Fig. 5), ferro-actinolite compositions occur along a trend to ferro-actinolitic hornblende, with no compositional change other than aluminum enrichment; then there is a compositional jump to ferro-tschermakitic or ferro-pargasitic hornblende with greater *A*-site occupancy and a trend toward ferro-pargasite. There seems to be a two-stage effect in the coupled substitutions that transform actinolite into hornblende (Grapes 1975, Robinson *et al.* 1982). As ferro-actinolite converts to ferro-pargasite, first there is a simple tschermakitic substitution, and subsequently the composition crosses the solvus with combined edenitic and tschermakitic substitutions giving a pargasitic trend.

In the iron-rich portions of the Doré Lake Complex, "hornblende" (*i.e.*, ferro-pargasite) is in stable equilibrium with albite at a greenschist grade in a low-pressure facies-series environment. In contrast, metabasalts in the surrounding metavolcanic rocks have typical greenschist-facies assemblages (Allard 1976). A medium-pressure overprint could be called upon to produce the hornblende–albite coexistence for parts of the complex very close to the Grenville Front, but some of the rocks in this study containing ferro-pargasite are up to 9 km from the Front. Furthermore, blue-green amphibole is reported from the northern limb of the complex, over 28 km from the Grenville Front. Partially analyzed compositions (Baskin 1975) are similar to those of ferro-pargasite in this study. Even within a few hundred metres of the Grenville Front, it is only in the iron-rich parts of the complex that the blue-green hornblende occurs.

It is the iron-rich nature of these amphiboles that is thought to stabilize "hornblende" at lower temperatures than normal. The lower-temperature stability of iron-rich hornblende was also noticed by Harte & Graham (1975). A lower-temperature transition from actinolite to hornblende for iron-rich bulk compositions can be predicted from experimental studies, which show that ferro-actinolite is stable only under reducing conditions and at lower temperature than more Mg-rich actinolite (Ernst 1968).

Because the Mg/Fe ratio is a strong factor in fixing the limits of amphibole stability in metabasites, bulk-rock composition should be considered when determining isograds for the greenschist- to amphibolite-facies transition. The relatively minor compositional differences among most typical metabasalts probably would not greatly affect the temperature of the actinolite-to-hornblende transition, but in iron-rich terranes or lithologic units, the compositional effect on this transition is significant. In low-pressure terranes, the plagioclase transition occurs at a lower temperature than the amphibole transition for average metabasite compositions, but in iron-rich rocks this relationship can be reversed. The occurrence of a transitional facies from greenschist to amphibolite facies, with the assemblage albite + epidote + hornblende, is not dependent on pressure alone, but also on the Mg/Fe ratio of the bulk composition.

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