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COEXISTING AMPHIBOLES FROM THE HASTINGS REGION OF SOUTHEASTERN ONTARIO

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ABSTRACT

Basic volcanic rocks in the Hastings area of southeastern Ontario have produced actinolite-hornblende and hornblende-cummingtonite pairs as a result of regional metamorphism in the upper greenschist to mid-amphibolite facies. Textural relations between coexisting hornblende and actinolite suggest a disequilibrium relation, but the chemical analyses are consistent with earlier hypotheses suggesting a miscibility gap between the two phases. Hornblende coexisting with actinolite contains slightly less Na+K and Al^{IV} than that from single-amphibole rocks. "Epidote" plot diagrams for coexisting amphibole and chlorite support the suggestion of a general approach to chemical equilibrium for the amphibole pairs, and for chlorite-cummingtonite, but are less consistent for chlorite-actinolite and chlorite-hornblende. Hornblende shows a general increase in Mg/Mg+Fe(total) with increasing metamorphic grade. Actinolite-hornblende pairs are tentatively interpreted as metastable, and the hornblende-cummingtonite pairs are interpreted as a stable mineral assemblage.

SOMMAIRE

Des roches volcaniques basiques de la région de Hastings dans le sud-ouest de l'Ontario ont produit des paires d'actinolite-hornblende et de hornblende-cummingtonite à la suite de métamorphisme régional sous le faciès métamorphique allant du schiste vert supérieur à l'amphibolite moyen. Les relations texturales entre la hornblende et l'actinolite coexistantes suggèrent qu'il y a un déséquilibre entre les deux; cependant les analyses chimiques sont conformes aux hypothèses précédentes qui postulaient une lacune de miscibilité entre les deux phases. La hornblende, coexistant avec l'actinolite, contient légèrement moins de Na+K et d'Al^{IV} que celle provenant de roches ne renfermant qu'une seule amphibole. Les diagrammes "Epidote" obtenus pour l'amphibole et la chlorite coexistantes viennent supporter les indications d'un tendance générale à l'équilibre pour les paires d'amphiboles et pour la chlorite et la cummingtonite, par contre, ils sont moins probants pour ce qui est des paires chlorite-actinolite et chlorite-hornblende. La hornblende montre une augmentation générale du rapport Mg/Mg+Fe(total) avec intensité métamorphique croissante. On emet l'hypothèse de travail que les paires actinolite-hornblende sont métastables et que les paires hornblende-cummingtonite sont une associatiton minérale stable.

(Traduit par la Rédaction)

INTRODUCTION

The Hastings region of southern Ontario is a unique and somewhat anomalous area of the Grenville Province characterized, in terms of metamorphism, by rocks of unusually low grade in comparison with those from the rest of the province. Lumbers (1967) used the occurrence of albitic plagioclase (identified by optical methods) to define the extent of greenschist facies rocks. The details of the greenschist-amphibolite transition were worked out primarily in Cashel, Limerick, and Tudor townships; the present work was carried out further south in parts of Madoc and Elzevir townships to study the effects of low-grade metamorphism on basic volcanic rocks (Figs. 1 and 2). Other aspects of this study are presented in Sampson (1972).

Following the earlier work of Klein (1966, 1969), Ernst (1968), Robinson & Jaffe (1969), and Cooper & Lovering (1970), numbers of workers have recently discussed aspects of amphibole chemistry, particularly with respect to coexisting varieties (Ernst 1972; Cooper 1972; Stout 1972; Brady 1974; Graham 1974; Hietanen 1974; Keunbaum & Gittins 1974; Grapes 1975; Harte & Graham 1975). This paper presents further data on the controversial actinolite hornblende association and on the hornblende-cummingtonite association. Metavolcanic rocks were divided into three metamorphic zones based largely on the nature of the plagioclase feldspar component. All three zones contained peristerite pairs, but the proportions of calcic plagioclase increase with increasing metamorphic grade. Mineral assemblages are shown in Figure 3 and the modal mineralogy of twenty-six specimens is presented in Appendix 1. The samples from the Tudor metavolcanic suite consist mainly of fine- to medium-grained hornblende-rich mafic rocks that are generally massive and only slightly sheared. Schistose varieties are more common in the northern part of the area where

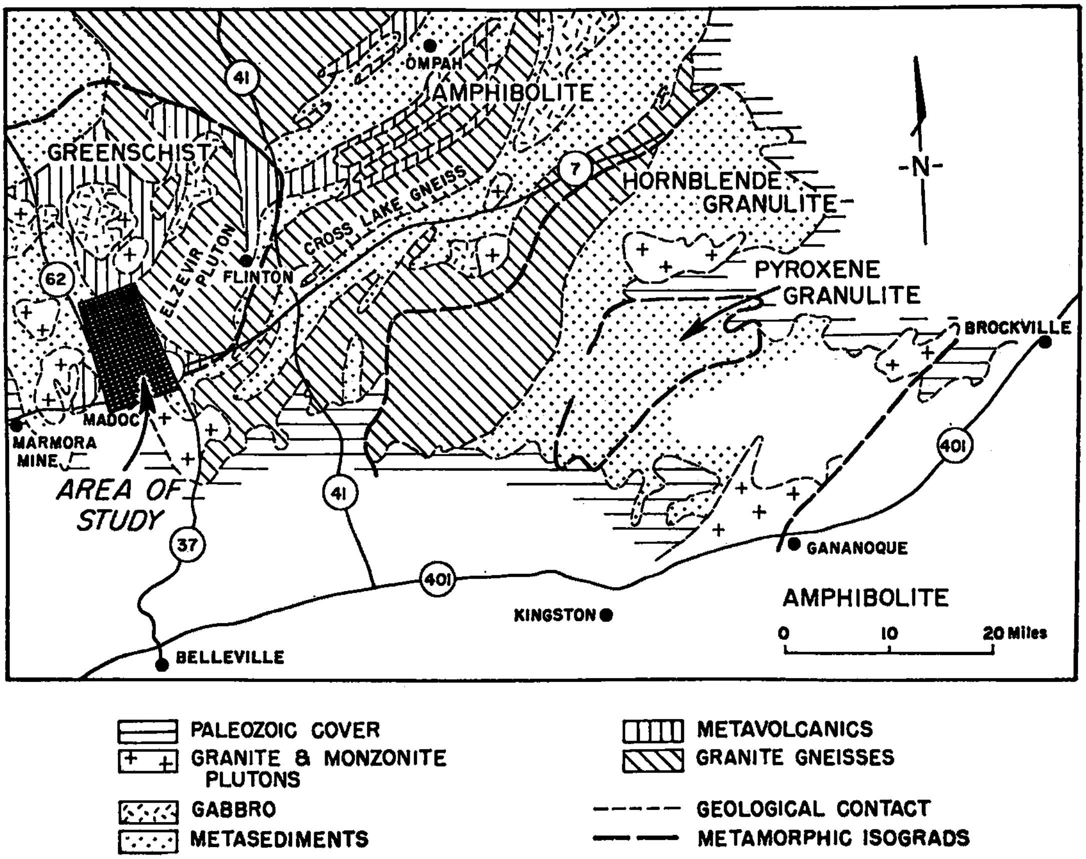

FIG. 1. Generalized geology of southeastern Ontario showing approximate positions of metamorphic isograds. (Modified from Moore 1967).

chlorite is usually the dominant ferromagnesian mineral. Local variations in the chlorite:hornblende ratio give a rather inhomogeneous appearance to the outcrops. Appendix II gives whole-rock analyses of seven rocks used in this study.

PETROGRAPHY

Blastoporphyritic and relict amygdaloidal textures are found throughout the sequence. Actinolite occurs mainly as sharply defined cores mantled by hornblende. In Zones I and II, pale green or bluish green nematoblastic hornblende (averaging 0.1 mm in length) is typical and only rarely does the actinolite have contact with other phases. The habit and grain size of hornblende in other rocks are quite variable. They range from fine-grained fibrous varieties to ragged prismatic poikiloblasts 0.5 to 0.7 mm long. No correlation was noted between habit and color or composition. In Zone I, amphiboles show a slight but continuous zoning from pale green cores to bluish green rims. The habit and small grain size of these minerals made it impossible to trace chemical zoning but, in general, this color change corresponds to relative enrichment in Fe and Al toward the rim. Quartz, plagioclase, epidote, ilmenite, and carbonate were commonly found as inclusions in hornblende, but chlorite and biotite were rare as inclusions. Porphyroblastic hornblendes usually have a random orientation, but inclusions either form trails parallel to the crystal lengths or sometimes define an internal foliation continuous with that of the matrix.

In Zone III, hornblende has the distinctive blue-green color (parellel to γ) and commonly shows twinning not noted in specimens of lower grade. This is probably analogous to the blue-green hornblende described by Graham (1974) as a petrographically distinct phase in chlorite-to garnet-zone metabasites from the Scottish Dalradian. Cummingtonite occurs as partial or complete rims mantling blue-green hornblende, or as discrete irregularly terminated prisms (0.05 to 0.2 mm long) with or without hornblende. Lamellar twinning is common in cummingtonite and the hornblende-cummingtonite assemblage is widely found in this zone. There is no compositional difference between cummingtonite that rims hornblende and that occurring as discrete grains.

Textural relations between hornblende and actinolite suggest the possibility of disequilibrium, as noted by several authors, but the common sharp contact between actinolite and mantling hornblende casts some doubt on this apparently obvious interpretation. This topic is discussed below in connection with the chemical data.

A possible three-amphibole assemblage was found at locality 13 in Zone III. The assemblage occurs in a small domain (about 0.4 cm diameter) in which actinolite and very fine-grained patches of cummingtonite are mantled by adjacent hornblende. Chemical data presented below suggest this is a disequilibrium assemblage. Textural evidence suggests that the hornblende-cummingtonite pairs of Zone III represent an equilibrium assemblage.

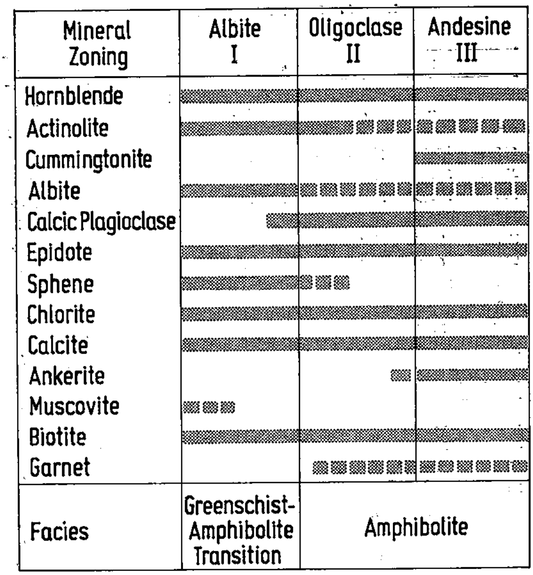

FIG. 3. Mineralogy of the three metamorphic zones in basic metavolcanic rocks at Queensborough area. Dashed lines indicate the mineral is very scarce. Modal data for some typical specimens are presented in Appendix 1.

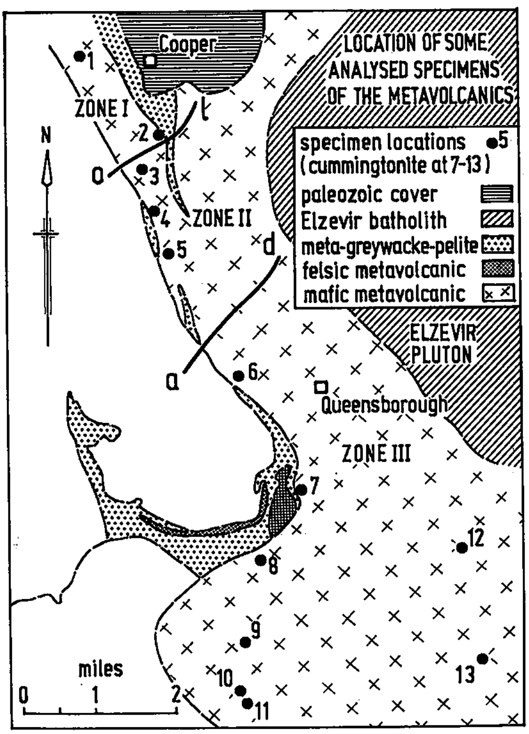

FIG. 2. Sample locations in the metavolcanic unit. Individual hand specimens (1a, 1b, or 2c, 2d etc.) were collected within a few metres of each other at each numbered locality. The lines 0-1 and a-d are drawn, on the basis of plagioclase feldspar compositions, to divide the basic metavolcanic unit into metamorphic zones I, II and III.

MINERAL ANALYSES

Mineral analyses were carried out with an ARL, EMX microprobe using techniques and data processing according to Rucklidge & Gasparrini (1969). Synthetic minerals were used for most standards. Analyses were generally carried out on 4-8 grains of each mineral per section, and 6 or more readings taken for each set of three elements. The specimen was moved after each reading in the case of Na and K analyses.

Thirty-eight amphiboles, including eleven coexisting pairs, have been analyzed and the data, together with structural formulae, are presented in Tables 1 to 4. Lack of data on the Fe^{3+} content of actinolite and cummingtonite is not particularly serious, but for hornblende it places constraints on the interpretation of the analyses. Various suggestions have been made to surmount the problem, but none is entirely satisfactory.

TABLE 1. ZONE I AMPHIBOLE ANALYSES

	hornblende-actinolite pairs				single amphibole rocks		
	1a		2a		1b	1c	3
	H	A	H	A			
SiO_2	43.52	54.50	42.91	54.16	41.71	42.26	40.83
Al_2O_3	13.94	2.49	14.42	2.13	13.73	14.34	15.29
FeO	19.79	13.16	19.88	14.45	22.84	20.39	22.05+
MnO	0.23	0.23	0.29	0.28	0.36	0.31	0.26
MgO	7.87	14.93	8.36	15.65	5.84	6.89	6.11+
TiO_2	0.36	0.05	0.39	0.06	0.35	0.30	0.34
CaO	11.54	12.43	11.47	12.17	11.21	11.28	11.53
K_2O	0.54	0.12	0.42	0.02	0.59	0.50	0.50
Na_2O	1.37	bdl	1.10	bdl	1.16	1.08	1.58
H_2O	2.02	2.09	2.02	2.10	1.95	1.97	1.97
TOTAL	101.18	100.00	101.26	101.02	99.74	99.32	100.46
Si	6.47	7.82	6.37	7.74	6.40	6.42	6.21
Al	1.53	0.18	1.63	0.26	1.60	1.58	1.79
Al	0.91	0.24	0.90	0.10	0.89	0.99	0.95
Fe	2.46	1.58	2.47	1.73	2.93	2.59	2.81
Mn	0.029	0.028	0.036	0.034	0.047	0.040	0.034
Mg	1.74	3.19	1.85	3.33	1.34	1.56	1.39
Ti	0.040	0.005	0.044	0.006	0.040	0.034	0.039
Ca	1.84	1.91	1.83	1.86	1.84	1.84	1.88
X + Y	7.02	6.95	7.12	7.07	7.09	7.05	7.10
K	0.102	0.022	0.080	0.004	0.116	0.097	0.097
Na	0.39	-	0.32	-	0.35	0.32	0.47
X_{Mg}	0.411	0.665	0.425	0.654	0.310	0.372	0.28+

Structural formulae calculated on the basis of 23(O)

X_{Mg} = Mg/Mg + Fe + Mn

\+ - average of duplicate analyses

* - oxide weight percent assumed from averaging determinations on other samples. Use of these numbers in calculations is justified by the small range observed in other actual analyses.

bdl - below detectability limit

nd - not determined.

Stout (1972) and Brady (1974) calculated maximum values of Fe^{3+} based on assumed stoichiometry, and Hietanen (1974) artitrarily calculated 20% of total Fe^{2+} as Fe^{3+}. For the present discussion no such corrections have been made and all iron is calculated as FeO. This undoubtedly distorts the tie-line orientations in some of the diagrams, but internal comparisons are still valid and the approach is consistent with a number of recent studies of amphibole chemistry (Robinson & Jaffe 1969; Cooper & Lovering 1970; Graham 1974). Data in the Tables and diagrams are usually separated into the three main metamorphic zones, I, II, and III, and also in terms of the amphibole assemblage — actinolite+hornblende, single amphibole (hornblende), and hornblende+cummingtonite. The last is present only in Zone III. Sample numbers 1 to 13 correspond to a progressive but irregular increase in grade of metamorphism (Fig. 2).

Chemical complexity of the amphiboles precludes the graphical representation of systematic variations on a single diagram. Many different systems have been used to illustrate compositional relations and some of these are shown in Figures 4 to 9. Figure 4 shows the various amphibole compositions in terms of Al^{IV} and Na+K and illustrates the combined edenite (Na, Al^{IV} =Si) and the tschermakite (MgFe)Si=Al^{IV}, Al^{VI} substitutions from tremolite-actinolite. Figure 4A shows the compositions of coexisting hornblende and actinolite from Zones I, II and III. There is a clear separation of the two compositional areas and intermediate varieties have not been found (cf. Graham 1974; Hietanen 1974). Specimens from the lowest metamorphic grade (1a and 2a) show the widest compositional separations, and the single pair from Zone III (13) shows the least separation; the Zone II specimens occupy intermediate positions. This arrangement would be expected if the compositions reflected a simple "solvus control" but it may be fortuitous. Hornblendes from single-amphibole assemblages are shown in Figure 4B and come from all three metamorphic zones. They show no systematic compositional change as a function of grade, but the group as a whole has higher Al^{IV} and total alkali contents than hornblendes coexisting with actinolite. If these hornblende compositions are not solvus controlled, they may be expected to reflect largely the bulk-rock compositions. Coexisting cummingtonite and hornblende

TABLE 2. ZONE II AMPHIBOLE ANALYSES

	Hornblende-Actinolite Pairs						Single Amphibole
	4a		5a		5b		4b
	H	A	H	A	H	A	
SiO_2	44.24	54.31	43.16	53.82	44.19	54.26	42.97
Al_2O_3	13.48	2.59	15.44	2.03	13.46	1.73	14.58
FeO	17.19	12.40	16.53	11.83	16.87	11.17	20.23
MnO	0.29	0.25	0.29	0.26	0.22	0.19	0.30
MgO	9.72	16.01	8.66	16.46	10.05	16.85	7.20
TiO_2	0.35	0.05	0.37*	nd	0.37*	nd	0.30
CaO	11.67	12.39	11.72	12.50	11.45	12.52	11.78
K_2O	0.35	0.03	0.34*	nd	0.34*	nd	0.48
Na_2O	0.98	bdl	1.05*	nd	1.05*	nd	1.50
H_2O	2.03	2.10	2.02	2.07	2.00	2.08	2.01
TOTAL	100.30	100.13	99.58	98.97	100.00	98.80	101.35
Si	6.54	[illegible]	[illegible]	7.77	[illegible]	7.82	[illegible]
Al	1.46	0.24	1.59	0.23	1.39	0.18	1.60
Al	0.89	0.19	1.11	0.12	0.81	0.11	0.96
Fe	2.13	1.48	2.05	1.43	2.11	1.35	2.52
Mn	0.036	0.030	0.036	0.032	0.028	0.023	0.038
Mg	2.14	3.41	1.92	3.54	2.24	3.62	1.60
Ti	0.039	0.005	0.41	-	0.042	-	0.034
Ca	1.85	1.90	1.86	1.93	1.83	1.93	1.88
X + Y	7.07	7.02	7.02	7.05	7.06	7.03	7.02
K	0.066	0.005	0.064	-	0.065	-	0.091
Na	0.28	-	0.300	-	0.31	-	0.43
X_{Mg}	0.497	0.693	0.479	0.701	0.512	0.725	0.385

See footnotes in Table 1.

TABLE 3. ZONE III AMPHIBOLE ANALYSES (HORNBLENDE-ACTINOLITE PAIR AND SINGLE AMPHIBOLE SPECIMENS)

	hornblende-actinolite pair		single amphibole rocks							
	H13	A13	6a	6b	7a	9a	9b	10a	11a	12
SiO_2	45.80	54.05	41.65	44.03	44.74	41.67	42.36	42.59	41.42	42.53
Al_2O_3	12.99	2.87	16.19	14.00	12.65	16.85	15.19	13.55	16.72	16.07
FeO	15.04	12.11	18.32	14.50	17.88+	18.15	17.97	19.13	18.56+	17.49
MnO	0.05	0.04	0.23	0.23	0.23	0.36	0.35	0.32+	0.22	0.20
MgO	11.29	16.64	8.46	10.94	9.27+	7.63	8.50	8.77+	7.37+	8.17
TiO_2	0.38	0.04	0.33*	0.33*	0.37	0.34	0.40	0.48	0.31	0.40
CaO	11.43	11.47	11.20	11.56	11.24	11.34	11.74	11.40	11.24	10.92
K_2O	0.24	0.12	0.31*	0.31*	0.22	0.36	0.50	0.30	0.30	0.27
Na_2O	1.06	0.05	1.46*	1.46*	1.62	1.47	1.40	1.52	1.47	2.01
H_2O	2.06	2.09	2.04	2.05	2.02	2.01	2.01	1.99	2.00	2.02
TOTAL	100.34	99.48	100.19	99.41	100.24	100.18	100.42	100.05	99.61	100.08
Si	6.67	7.74	6.21	6.49	6.63	6.21	6.31	6.40	6.22	6.32
Al	1.33	0.26	1.79	1.51	1.37	1.79	1.69	1.60	1.78	1.68
Al	0.89	0.22	1.06	0.94	0.84	1.17	0.97	0.80	1.18	1.13
Fe	1.83	1.45	2.29	1.79	2.22	2.26	2.24	2.40	2.35	2.17
Mn	0.006	0.005	0.029	0.029	0.029	0.045	0.044	0.041	0.028	0.025
Mg	2.45	3.55	1.88	2.41	2.05	1.69	1.89	1.96	1.63	1.81
Ti	0.042	0.004	0.037	0.036	0.041	0.038	0.045	0.054	0.035	0.045
Ca	1.78	1.76	1.79	1.83	1.79	1.89	1.87	1.83	1.81	1.74
X + Y	7.11	7.00	7.09	7.03	6.97	7.03	7.06	7.10	7.03	7.02
K	0.045	0.022	0.059	0.058	0.042	0.068	0.095	0.057	0.057	0.051
Na	0.300	0.014	0.430	0.420	0.47	0.43	0.40	0.44	0.43	0.58
X_{Mg}	0.572	0.709	0.448	0.570	0.477	0.423	0.453	0.445	0.407	0.452

See footnotes in Table 1.

TABLE 4. ZONE III AMPHIBOLE ANALYSES - HORNBLENDE-CUMMINGTONITE PAIRS

	7b		8		9c		9d		10b		11b		11c		13
	H	C	H	C	H	C	H	C	H	C	H	C	H	C	C
SiO_2	42.69	52.56	41.90	53.56	40.93	52.73	41.98	52.39	42.44	53.53	41.05	52.37	44.13	53.13*	54.17
Al_2O_3	13.23	0.42	14.34	0.59	14.99	0.52	14.85	0.47	14.37	0.37	14.50	0.45	14.11	0.49*	0.51
FeO	20.51	27.22	20.31	27.17	22.54	30.36	21.03	27.83	21.39	28.72	21.89+	29.11+	16.28	22.62	24.99
MnO	0.19	0.56	0.24	0.74	0.25	0.66	0.20	0.60	0.15	0.51	0.34+	1.12+	0.34	0.69*	0.64
MgO	8.12	16.34	7.86	15.86	6.78	14.98	7.87	15.61	6.79	14.61	6.56+	14.20+	10.65	18.83	17.18
TiO_2	0.33	0.01	0.31	0.02	0.33	0.03	0.24	0.01	0.33	0.03	0.33	0.03	0.38	nd	0.01
CaO	10.95+	0.49	10.95+	0.53	10.71+	0.43	10.71+	0.43	11.09+	0.62	10.68+	0.45	11.07+	0.70	0.80
K_2O	0.29+	0.06	0.27+	0.07	0.42+	0.08	0.31+	bdl	0.36+	0.08	0.37+	bdl	0.23+	nd	0.06
Na_2O	1.61+	0.12	1.48+	0.14	1.75+	0.33	1.94+	0.10	1.79+	0.33	1.71+	bdl	1.53	nd	bdl
H_2O	1.98	2.03	1.97	2.03	1.97	2.03	2.00	2.00	1.99	2.02	1.95	1.99	2.05	2.02	2.05
TOTAL	99.90	99.81	99.63	100.71	100.67	102.15	101.13	99.44	100.70	100.82	99.38	99.72	100.77	98.48	100.41
Si	6.45	7.89	6.36	7.90	6.21	7.80	6.29	7.86	6.39	7.93	6.30	7.90	6.46	7.86	7.93
Al	1.55	0.07	1.64	0.10	1.79	0.09	1.71	0.08	1.61	0.07	1.70	0.08	1.54	0.08	0.07
Al	0.81	-	0.92	-	0.90	-	0.91	-	0.94	0.01	0.92	-	0.90	-	0.01
Fe	2.59	3.35	2.58	3.55	2.86	3.75	2.63	3.49	2.69	3.56	2.81	3.67	1.99	2.80	3.06
Mn	0.024	0.070	0.031	0.092	0.032	0.083	0.025	0.076	0.019	0.064	0.044	0.143	0.042	0.086	0.079
Mg	1.83	3.59	1.74	3.45	1.53	3.30	1.76	3.49	1.52	3.23	1.50	3.19	2.33	4.15	3.75
Ti	0.038	0.001	0.035	0.002	0.038	0.003	0.027	0.001	0.037	0.003	0.038	0.003	0.042	-	0.001
Ca	1.77	0.077	1.78	0.084	1.74	0.068	1.72	0.069	1.79	0.098	1.75	0.073	1.174	0.111	0.125
X + Y	7.07	7.09	7.09	7.02	7.10	7.21	7.06	7.03	7.00	6.97	7.06	7.08	7.04	7.15	7.02
K	0.056	0.010	0.052	0.013	0.081	0.015	0.057	-	0.069	0.015	0.072	-	0.043	-	0.011
Na	0.47	0.03	0.43	0.04	0.51	0.09	0.58	0.03	0.50	0.09	0.51	-	0.43	-	-
X_{Mg}	0.412	0.512	0.400	0.486	0.346	0.463	0.399	0.495	0.359	0.471	0.344	0.455	0.534	0.590	0.544

See footnotes in Table 1.

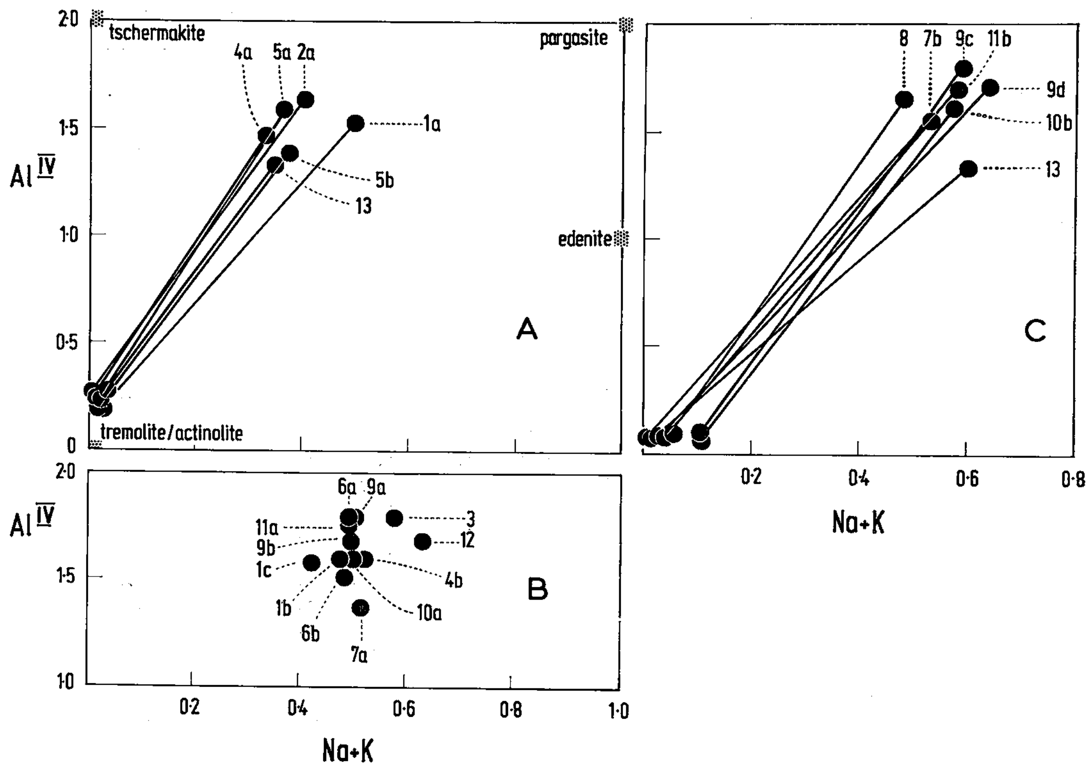

FIG. 4. Amphibole analyses plotted in terms of Na+K and Al^{IV}. (a) hornblende-actinolite pairs; (b) hornblende from single-amphibole rocks; (c) hornblende-cummingtonite pairs. Increasing sample numbers correspond to a progressive but irregular increase in grade of metamorphism.

from Zone III are plotted in Figure 4C. Hornblendes overlap the compositional range of Figure 4B and show the same small but clear distinction from those coexisting with actinolite.

Graham (1974) has shown compositional variations for a large number of calciferous amphiboles in terms of Al^{VI}/Si and $Na+K/Al^{VI}$. Similar plots for the Hastings amphiboles are shown in Figures 5 and 6. In Figure 5 the hornblende compositions occupy a much more restricted area than Scottish Dalradian or other areas compiled by Graham, and there is again a sharp contrast in the compositions of coexisting phases with an absence of any intermediate varieties. Relatively high Al^{VI} values were correlated by Graham (1974) with high-pressure metamorphic facies series. This is consistent with occurrences of kyanite in nearby pelitic rocks (Sampson 1972), but further work will be required to determine whether or not this is consistent with an earlier interpretation of facies series in the Haliburton Highlands (Chesworth 1971). Zone III hornblendes coexisting with cummingtonite (Fig. 5B) show a restricted range of Al^{VI} in comparison with other hornblendes (Fig. 5A), but there appears to be no systematic variation with metamorphic grade. The $Al^{VI}/Na+K$ plots of Figure 6 show some of the same features as Figures 4 and 5 but can be compared with the compilations of Graham (1974). Total alkali contents are significantly lower than in most actinolites quoted by Graham, and hornblendes are closer to the tschermakitic trend than to paragasite or edenite. Low-grade samples from the Dalradian were shown by Graham to reflect strongly the edenitic trend with increasing tschermakite content at higher grades. Hornblendes coexisting with actinolite show a tendency to lower Na+K values with increasing grade, but there are only six samples in the group. Hornblendes coexisting with cummingtonite show a higher average Na+K than any other group in Figure 6A. In single-amphibole rocks, hornblende shows lower Na+K in Zone I than the group in Zones II and III, but this same trend is not apparent between Zones II and III.

Figures 4 to 6 demonstrate the operation of tschermakitic and edenitic substitutions, but it is necessary to use a modified form of the AFM plot to illustrate the important variations in Mg-Fe ratios. Figures 7 to 10 show the various amphibole assemblages, together with coexisting chlorite, for some specimens in terms of Harte & Graham's (1974) "epidote" plot (Fig. 7). Chlorite analyses are taken from Sampson (1972). It is in these diagrams that the tie-line orientations become distorted due to calculations of total Fe as FeO. Figure 8 shows the compositions of hornblende and actinolite (pairs) together with coexisting chlorite for three specimens. The general parallelism of tie-lines for the amphibole pairs indicates an approach to equilibrium (except specimen 4a), but crossing tie-lines for chlorite-actinolite and chlorite-hornblende are somewhat more ambiguous. Hornblendes show an increase in the Mg/Mg+Fe ratio with increasing metamorphism, but this trend is less systematic for the actinolite analyses. In the single-amphibole rocks (Fig. 9) there is a general increase in Mg/Mg+Fe as shown by the circled groups of analyses. This grouping does not correspond exactly with Zones I, II and III but is very close to it. The very Mg-rich hornblende in 6b is probably the result of a high Mg/Mg+Fe ratio in the host rock. Comparison of Figures 8 and 9 shows that for any given grade of metamorphism, hornblende from the actinolite-hornblende associations is more magnesium-rich than those from single-amphibole rocks. The parallelism of hornblende-chlorite tie-lines (except specimen 9b) again suggests a general approach to chemical equilibrium. Eight pairs of hornblende and cummingtonite analyses are plotted on Figure 10 with coexisting chlorite for five specimens. These samples are all from Zone III. With the exception of specimen 13, the three-amphibole assemblage, which appears to represent disequilibrium, a close approach to chemical equilibrium is again supported by the tie-line orientations.

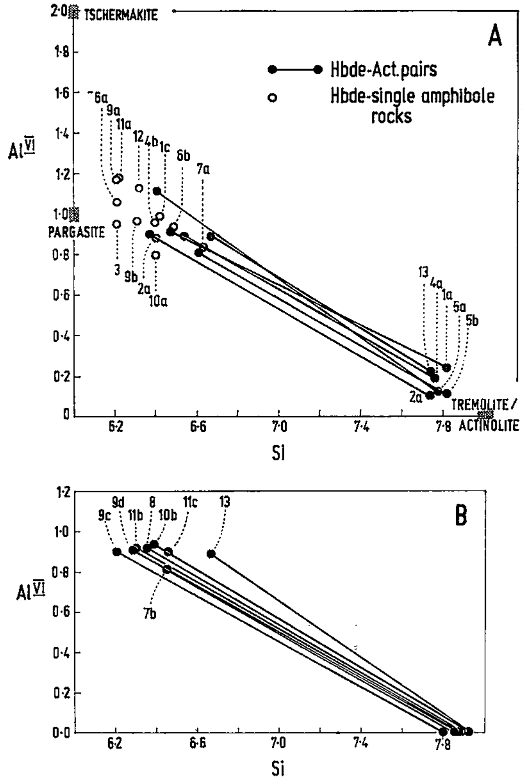

FIG. 5. Amphibole analyses plotted in terms of Al^{VI} and Si from the data of Tables 1-4. (a) hornblende-actinolite pairs (solid circles) and hornblende from single amphibole rocks (open circles); (b) hornblende-cummingtonite pairs. (See also Graham 1974, Fig. 5).

Discussion

Chemical data and textural observations (sharp contacts) on the hornblende-actinolite associations are consistent with an interpretation involving a miscibility gap in this part of the amphibole system (Klein 1969; Cooper & Lovering 1970; Brady 1974). However, it becomes more difficult to explain the presence of single-amphibole rocks of similar bulk composition at the same metamorphic grade as the hornblende-actinolite pairs. Lamellar textures in the amphiboles have previously been considered to represent possible exsolution phenomena, but these were observed only in specimen 13. Compositions of amphibole pairs reported here do not fit the solidus recently proposed by Hietanen (1974). In view of the wide range of amphibole compositions, within the hornblende-actinolite range, compiled by Graham (1974), it seems preferable to regard the actinolite as a relict phase. The surrounding hornblende appears, in many samples, to have an armoring effect and prevents actinolite from taking further part in chemical equilibria. The hornblende in these associations is more magnesian than in actinolite-free assemblages; this is not consistent with a model involving removal of an Mg-rich phase from the effective bulk composition controlling (in part) the mineral equilibria. There is no correlation in these rocks between the occurrence of actinolite and the Mg/Fe ratio of the parent rocks. Consequently, although there seems to be a degree of local equilibrium between hornblende and coexisting actinolite, the two are regarded here as a metastable pair. This is in agreement with the recent interpretations of Graham (1974) and Ernst (1972).

The hornblende-cummingtonite assemblages in the Tudor Metavolcanics show some unusual features:

(a) Chlorite is found in virtually all assemblages studied; it occurs as discrete, relatively coarse porphyroblasts, glomeroblastic aggregates, or fine-grained idioblasts in the matrix. In similar occurrences from a variety of regional metamorphic terrains (Shido 1958; Hayama 1965; Seki *et al.* 1967; Robinson & Jaffe 1969) chlorite+quartz disappears before the appearance of cummingtonite in the direction of increasing grade. The hornblende+cummingtonite+chlorite assemblage is more common in plagioclase-free ultramafic rocks of relatively high grade (Kisch & Warnaars 1969; Robinson & Jaffe 1969) where hornblende is more magnesian than coexisting cummingtonite and quartz is absent or very minor. Brady (1974) has reported this three-phase assemblage, together with quartz, near the staurolite isograd in New Hampshire.

(b) Hornblende-cummingtonite assemblages

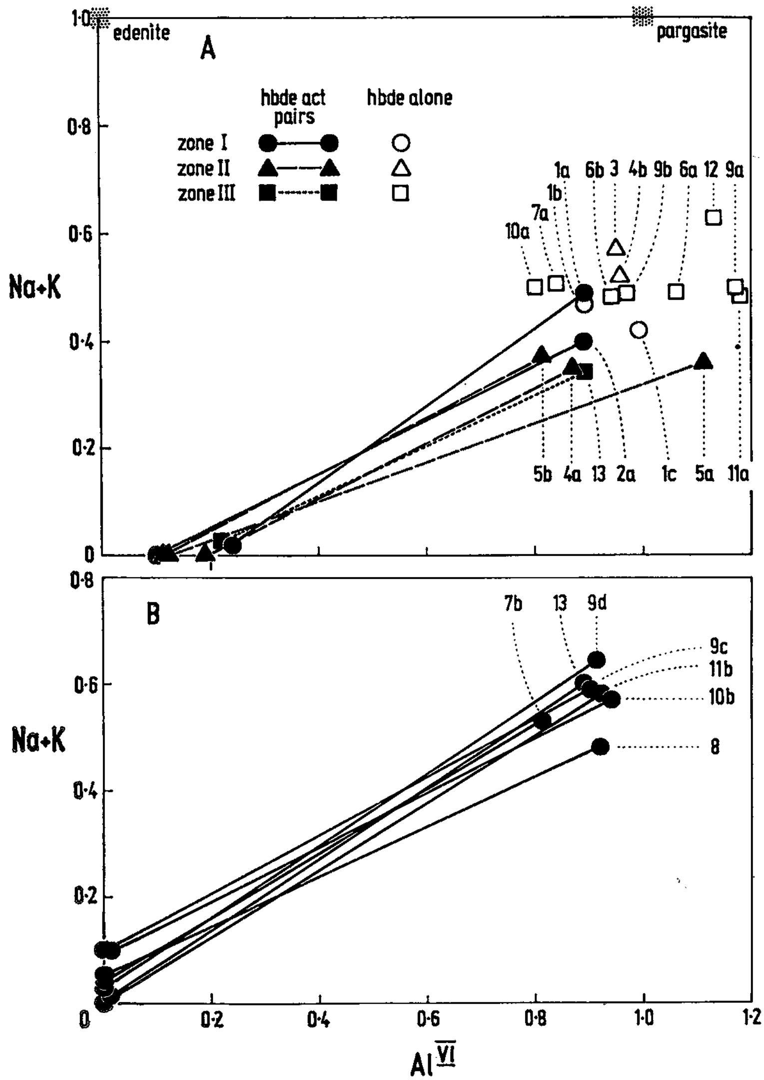

FIG. 6. Amphibole analyses plotted in terms of Al^{VI} and Na+K from the data of Tables 1-4. (a) hornblende-actinolite pairs and hornblende from single-amphibole rocks with different symbols for Zones I, II and III: (b) hornblende-cummingtonite pairs from Zone III.

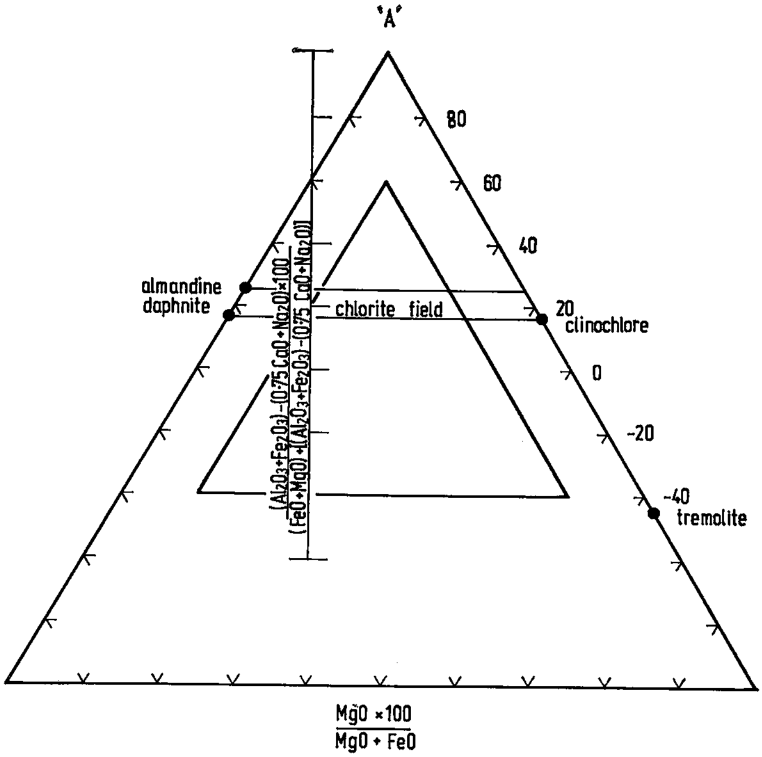

FIG. 7. "Epidote" plot of Harte & Graham (1974). The inner triangle shows the area depicted in Figures 8-10.

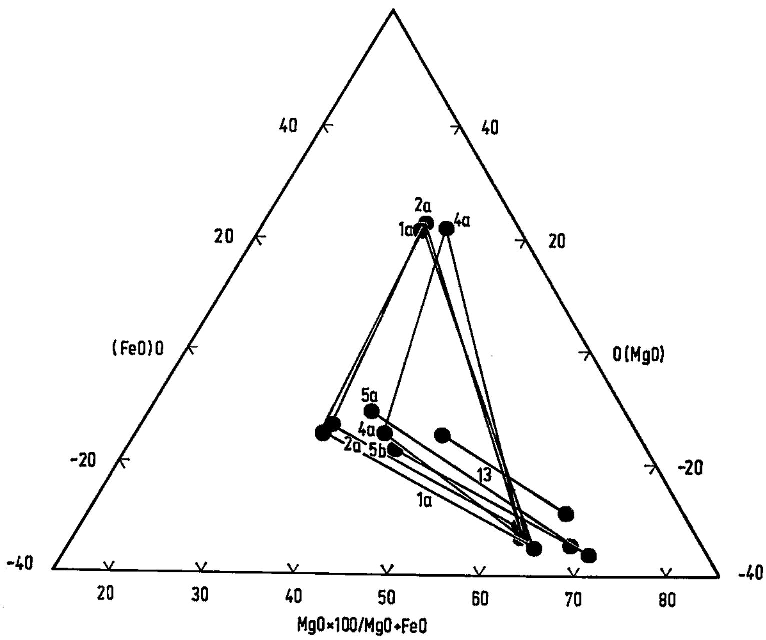

FIG. 8. "Epidote" plot (Harte & Graham 1974) for analyses of hornblende-actinolite pairs and coexisting chlorite for three specimens.

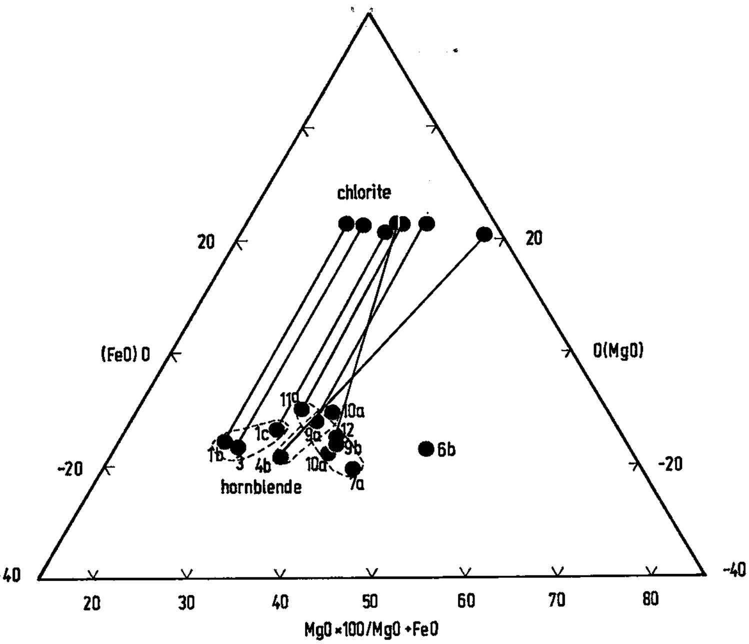

FIG. 9. "Epidote" plot (Harte & Graham 1974) for analyses of hornblende from single-amphibole rocks with coexisting chlorite for some samples. Areas enclosed by the three dashed lines show Mg:Fe ratios for the lowest, middle and highest grade specimens, illustrating the generalized increase in Mg:Fe ratio with increasing metamorphism.

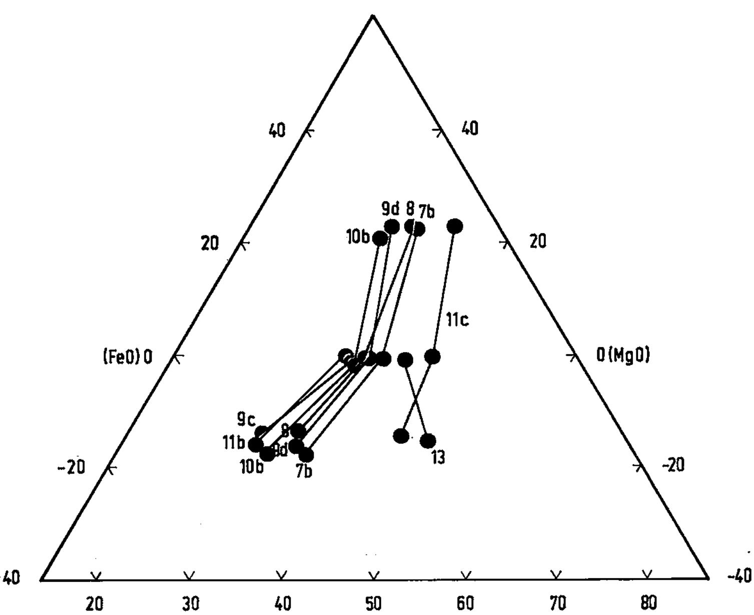

FIG. 10. "Epidote" plot (Harte & Graham 1974) for analyses of hornblende-cummingtonite pairs and coexisting chlorite for some specimens. Specimen 13 is the disequilibrium three-amphibole assemblage.

generally lack carbonate, but the earliest cummingtonite-bearing rocks in this area always contain minor ankerite.

(c) Coexisting plagioclases of peristerite composition are present in one of the samples (11b), whereas albite has not been recorded in hornblende-cummingtonite rocks.

These features suggest that the hornblende-cummingtonite assemblages of this study formed at a relatively low grade of metamorphism, possibly by reactions involving ankerite and chlorite. The petrographic data and compositions of coexisting minerals suggest the following type of reaction for the origin of cummingtonite (at least in the carbonate-bearing assemblages):

$$\text{Hbd} + \text{Chl} + \text{Ank} + \text{Qtz} \rightarrow \text{Cum} + \text{Plag} + H_2O + CO_2$$

The reactant assemblage is absent from Zone I, occurs occasionally in Zone II, and may occur within a few feet of the cummingtonite-bearing assemblages in Zone III. The Zone III assemblages may indicate sharp local gradients in the relative fugacities of water and carbon dioxide. Ankerite occurs with decreasing frequency with increasing distance to the south of a-d (Fig. 2).

Conclusions

Chemical compositions of hornblendes from basic metavolcanic rocks in the greenschist to amphibolite facies of regional metamorphism are dependent on the total mineral assemblage as well as bulk-rock compositions and relative metamorphic grade. Although chemical data from coexisting hornblende+actinolite are consistent with the concept of a miscibility gap, the occurrence of single-amphibole (hornblende) rocks of similar bulk composition and metamorphic grade suggests that these actinolites are most likely metastable relicts. This is supported by textural relations between the two phases. Detailed X-ray examination of specimens from the intermediate compositional range may help to finally resolve the debate on the existence of a miscibility gap in this system.

Cummingtonite seems to coexist stably with hornblende in the transitional upper greenschist/lower amphibolite facies rocks. This represents an extension of the previously assumed stability field for cummingtonite toward lower temperatures.

Relatively high Al^{VI} contents in the hornblende are consistent with a Barrovian type of facies series rather than the low-pressure Abukuma type.

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APPENDIX

1a: Fine-grained basic schist (?amydaloidal) with blastoporphyritic twinned albite; nematoblastic pale green hornblende and chlorite aligned parallel to the foliation; colorless actinolite occurs (sparsely) in the cores of the coarser hornblendes; epidote and calcite are also porphyroblastic.

2a: Fine-grained blastoporphyritic schist similar to 1a; specimen 2b has the same assemblage as 2a except for the presence of rare biotite in the former; total amphibole (none analyzed) is less than 5%, whereas 30-35% chlorite is present in 2b. Only albitic feldspar is present in 2b.

4a: Massive fine-grained amphibolite with composite amphibole porphyroblasts (0.15×0.10 mm) consisting of subordinate blue-green hornblende as thin rims around pale green actinolite. Matrix contains fibrous hornblende, rounded epidote granules, twinned subidioblastic oligoclase (An 27), chlorite, and calcite.

5a: Slightly sheared mafic metavolcanic with ragged prismatic amphibole porphyroblast (0.2 to 0.5 mm) consisting of patchy intergrowths with sharp rectilinear contacts. Lamelar-twinned chlorite and, occasionally, epidote are also porphyroblastic. Untwinned plagioclase (An 28-34) is predominant in sutured matrix.

5b: Texturally similar to 5a; contains nematoblastic hornblende-actinolite and rare orange-brown biotite porphyroblasts in sutured foliated matrix. Biotite occasionally occurs as inclusions in the pale green hornblende. The feldspar is an homogeneous untwinned oligoclase (An 24).

13: Massive amphibolite consisting mainly of

APPENDIX 1a. APPROXIMATE MODES AND PETROGRAPHIC NOTES ON SAMPLES IN WHICH HORNBLENDE-ACTINOLITE PAIRS WERE ANALYSED

	ZONE I		ZONE II		ZONE III	
	1a	2a	4a	5a	5b	13
Qtz	15	10	-	-	5	5
Feldspar	15-20	20-25	40	30-35	25-30	20
Hbd+Act	10	40	50-55	55-60	50-55	70
Cum	-	-	-	-	-	tr
Chl	25	2-5	2-5	tr	5	2
Ep	15	10	tr	2	10-15	-
Bio	tr	-	-	-	tr	-
Ct	5	15	tr	2	tr	tr
Sph	-	tr	tr	tr	-	-
Ilm	+	+	+	-	+	+
Ru	-	-	+	-	-	-

TR TRACE
\+ TRACE-MINOR
\- NOT DETECTED

APPENDIX 1b. HORNBLENDE-CUMMINGTONITE PAIRS. ALL SAMPLES ARE LOCATED IN ZONE III

	7b	8	9c	9d	10b	11b	11c
Qtz	{	{	{	35	{	{	{
Feldspar	35	30	45	{ 15	45	25	35
Ep	-	-	-	-	-	-	-
Hbd	35	40	25	10	35	40	50
Cum	15	5	25	20	15	20	2
Chl	5	10	tr	5	1	-	10
Bio	-	-	-	10	5	tr	5
Ank	10	5-10	-	-	-	-	-
Ilm	+	+	+	+	+	+	+
Mt	-	+	+	+	-	+	-
Py	-	-	+	+	-	+	-

plagioclase (An 27-30) and green hornblende; both minerals are occasionally twinned. Lath-shaped twinned chlorite microporphyroblasts are locallv glomeroblastic. Actinolite is present in two isolated domains in the polished thin section, in each case mantled by hornblende. Within 0.2 mm of one actinolite-hornblende association, very fine, patchy (?) cummingtonite occurs in an adjacent hornblende. Under high magnification, fine oriented lamellae of an unidentified phase can be seen in several of the hornblendes in this section.

7b: Mesocratic granofels containing subidioblastic blue-green hornblende (2-3 mm) partly rimmed by cummingtonite, and anhedral ankerite porphyroblasts in fine quartzo-feldspathic matrix. Cummingtonite also occurs as randomly oriented acicular inclusions in ankerite and blebs of the latter mineral are sometimes present as inclusions in hornblende. Chlorite occurs both in matrix and as glomeroblastic aggregates of twinned crystals.

8: Mineralogically and texturally similar to 7b

APPENDIX 1c. MINERAL ASSEMBLAGES OF SINGLE AMPHIBOLE (HORNBLENDE) SPECIMENS; ASSEMBLAGES 1e AND 6b ARE IDENTICAL TO 1d AND 6a RESPECTIVELY; ALL ASSEMBLAGES CONTAIN QUARTZ AND EPIDOTE EXCEPT 12 WHICH IS QUARTZ-FREE

	Zone I			Zone II			Zone III						
	1b	1c	1d	3	4b	4c	6a	7a	9a	9b	10a	11a	12
Hbd	X	X		X	X		X	X	X	X	X	X	X
Ab	X	X	X										
Plag				X	X	X	X	X	X	X	X	X	X
Chl	X	X	X	X	X	X	X		X			X	X
Bio	X	X		X	X					X	X	X	X
Ct		X	X	X		X	X					X	X
Ank								X				X	X
Ilm	X		X	X	X		X	X	X	X	X	X	X
Py				X	X		X	X	X	X	X		X
Ru					X								
Mt	X												

APPENDIX 2. ELECTRON MICROPROBE ANALYSES OF WHOLE-ROCK GLASSES (Rucklidge et al. 1970)

	1a	4a	4b	5a	9a	10a	11c	WI[1]	WI[2]
SiO_2	49.80	51.72	54.72	51.61	54.17	53.85	52.82	53.14	52.90
TiO_2	1.27	1.14	1.37	1.46	1.50	2.37	1.02	1.08	1.09
Al_2O_3	18.92	17.83	17.69	15.27	17.53	15.17	16.14	15.14	15.03
FeO^x	10.33	8.42	10.67	9.28	8.84	10.62	11.24	9.12	9.95
MnO	0.14	0.16	0.12	0.20	0.20	0.23	0.23	0.18	0.17
MgO	5.71	8.41	6.07	8.24	4.33	6.47	8.12	6.60	6.52
CaO	8.74	8.72	4.78	11.81	9.22	8.57	7.55	10.77	10.92
Na_2O	3.28	4.46	3.24	2.87	3.01	3.12	3.20	2.35	2.15
K_2O	0.10	0.16	0.96	0.32	0.17	0.61	1.32	0.71	0.63
	98.29	101.02	99.62	101.06	98.97	101.01	101.64	99.09	99.36

x Total iron as FeO

1 This study

2 Preferred chemical analysis

except that cummingtonite is sparse and idioblastic magnetite is in this specimen.

9c: Dark grey granofels with acicular blue-green hornblende and cummingtonite occurring primarily as discrete sharply terminated porphyroblasts 0.2-0.4 mm in length. Carbonate is found in sutured quartzo-feldspathic matrix.

9d: Massive amphibole-poor metabreccia consisting of mafic patches in brownish grey felsitic matrix; the mafic domains contain coarse (up to 1 mm) blue-green hornblende rimmed by ragged cummingtonite. Prismatic cummingtonite (0.2-0.7 mm long) with rare blebs of blue-green hornblende is characteristic of the felsitic domain. The bulk composition of this rock is probably richer in alkalis and silica than other hornblende-cummingtonite hosts described here.

10b: Nematoblastic blue-green hornblende and twinned cummingtonite (0.5-1.0 mm) define a crude foliation in an equigranular mosaic of untwinned oligoclase and quartz. Patchy cummingtonite overgrowths on hornblende are also found. Greenish brown biotite present as in 9d.

11b: Texturally similar to 10b; contains relatively abundant opaque minerals and sparse apatite.

11c: Massive amphibolite with poikiloblastic hornblende and smaller cummingtonite porphyroblasts; lath-shaped chlorite (0.80×0.05 mm), commonly showing lamellar twinning, and orange-brown biotite are also porphyroblastic. Granoblastic matrix consists of untwinned oligoclase and quartz.