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METAMORPHISM OF THE ROSSLAND VOLCANIC ROCKS, SOUTHERN BRITISH COLUMBIA

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ABSTRACT

Lower Jurassic volcanic rocks forming part of the Rossland Group of southern British Columbia have been variably metamorphosed, both in terms of texture and mineralogy. They can be divided into two distinct zones. In zone 1, igneous phenocrysts (pyroxene, hornblende and spinel) and textures are well preserved. However, the secondary phases calcite, chlorite, albite, epidote and prehnite occur as replacements of plagioclase, olivine and the groundmass as well as infilling vesicles. Zone-2 volcanic rocks, in contrast, are generally totally altered mineralogically, with actinolite, hornblende and biotite extensively developed. In textural development, these rocks vary from porphyritic (igneous) to schistose and hornfelsic. Chemical data on the secondary phases show that chlorite, biotite and amphibole compositions are largely controlled by whole-rock chemistry, but that chlorite and amphibole also show the effect of metamorphic grade or temperature. Epidote composition is probably controlled mainly by oxygen fugacity. The mineral assemblages developed indicate that zone 1 is sub-greenschist facies and experienced temperatures in the range 200–350°C. Zone 2 records temperatures up to about 525-550°C, embracing the greenschist to lower amphibolite facies. Low load-pressures of less than 3 kbar are indicated for zone-2 metamorphic assemblages by the low Na(*M*4) contents of calcic amphibole. The distribution of zones 1 and 2 indicates a south-to-north increase in metamorphic grade. This is in accord with the more regional pattern, which culminates in the gneiss domes north of the Rossland area.

Keywords: metamorphism, Rossland volcanic suite, Lower Jurassic, British Columbia, mineral chemistry, amphibole, biotite, chlorite, epidote, prehnite.

SOMMAIRE

Les roches volcaniques du groupe Rossland, du Sud de la Colombie-Britannique, d'âge Jurassique inférieur, ont été modifiées dans leur texture et leur minéralogie suite à un métamorphisme d'intensité variable. On les trouve dans deux zones distinctes. Dans la zone 1, les phénocristaux (pyroxène, hornblende, spinelle) et les textures sont bien préservées. Cependant, les minéraux secondaires (calcite, chlorite, albite, épidote et prehnite) remplacent le plagioclase, l'olivine et la pâte et remplissent les vacuoles. La minéralogie des roches de la zone 2, par contre, est généralement entièrement modifiée; l'actinote, la hornblende et la biotite sont très répandues. La texture de ces roches varie de porphyritique à schistose à hornfelsique. Les données chimiques montrent que les phases secondaires chlorite, biotite et amphibole reflètent surtout la composition globale de la roche; de plus, la chlorite et l'amphibole montrent les effets du degré de métamorphisme ou de la température. La composition de l'épidote serait surtout fonction de la fugacité d'oxygène. Les assemblages minéralogiques indiquent pour la zone 1 un degré de métamorphisme inférieur au facies schiste vert, et donc un intervalle de température entre 200 et 350°C. Dans la zone 2, la température a atteint entre 525 et 550°C, ce qui équivaut le facies schiste vert ou amphibolite inférieur. La pression indiquée par la teneur en Na du site *M*4 des amphiboles calciques des roches de la zone 2 est inférieure à 3 kbar. La distribution des zones 1 et 2 dans l'espace indique une augmentation de l'intensité du métamorphisme vers le nord, ce qui concorde avec les observations sur une échelle régionale. L'augmentation a atteint un point culminant dans les dômes gneissiques au nord de Rossland.

(Traduit par la Rédaction)

Mots-clés: métamorphisme, suite volcanique de Rossland, Jurassique inférieur, Colombie-Britannique, chimie des minéraux, amphibole, biotite, chlorite, épidote, prehnite.

INTRODUCTION

Within the Lower to Middle Jurassic Rossland Group of southern British Columbia, the Elise Formation is composed predominantly of volcanic rocks. These rocks, referred to here as the Rossland volcanic suite, are Sinemurian to Toarcian in age; they comprise a 3000- to 5000-m succession of agglomerate, ash, and their erosionally reworked derivatives, together

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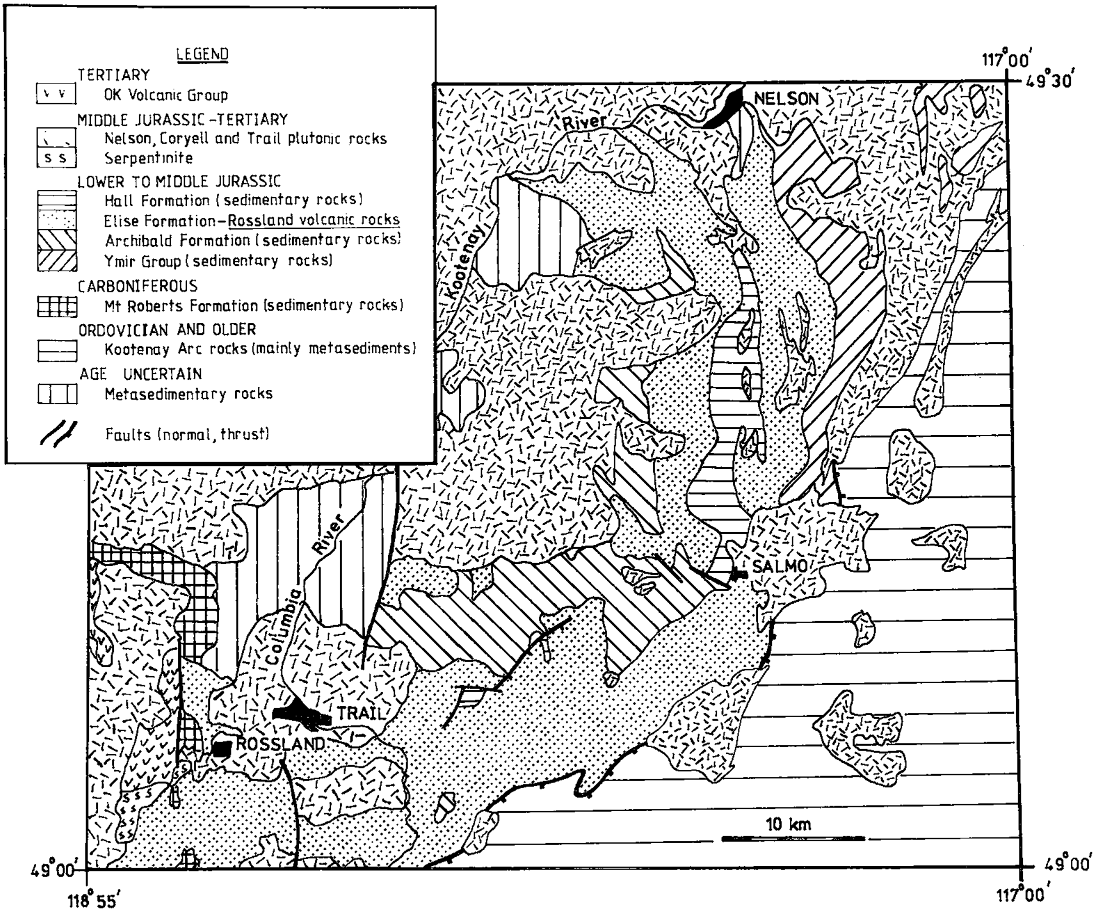

FIG. 1. Geology of the Nelson–Rossland area based on the maps of Little (1960, 1962, 1963, 1964) and Fyles (1970).

with subsidiary brecciated lava flows. Bracketing this volcanic succession are marine shale, siltstone and greywacke of the Hall and Archibald Formations and Ymir Group (Fig. 1).

The samples examined for this study, collected at different times by the author and R. St. J. Lambert (University of Edmonton) from throughout the area underlain by the Elise Formation (Fig. 1), form the basis of a general petrological and geochemical study of the volcanic assemblage. Details of sample localities (shown in Fig. 2) are given in Beddoe-Stephens (1977) and are obtainable from the author on request.

The lavas and agglomeratic fragments are all strongly porphyritic and represent a petrographic range from ankaramite to andesite. However, the predominant variety is basaltic, with about 49–52% SiO_2, 5–7% MgO and 4–6% Na_2O+K_2O and containing phenocrysts of augite, plagioclase and, rarely, hornblende or olivine. The igneous petrology of these rocks is presented in detail by Beddoe-Stephens (in press), with broader tectonic implications discussed by Beddoe-Stephens & Lambert (1981).

Strata within the volcanic sequence are moderately to steeply dipping owing to large-scale, fairly open folding; the strata are cut extensively by members of the Nelson, Trail and Coryell plutons (Fig. 1). This deformational and intrusive episode, termed the Columbian orogeny, was initiated in late Jurassic time and continued into the early Upper Cretaceous (Douglas *et al.* 1970). As a result, the earlier Jurassic rocks have been metamorphosed, both mineralogically and texturally, to a variable extent, and it is this aspect of the volcanic rocks that is the subject of this paper.

VARIABLE METAMORPHISM OF THE VOLCANIC ROCKS

The compositional range of the Rossland volcanic rocks is rather restricted (Beddoe-Stephens, in press) compared with that of many volcanic suites; the common basaltic varieties occur throughout the area. Consequently, the following descriptions apply to this restricted compositional variety, and the textural changes described apply to massive porphyritic extrusive volcanic rocks rather than to tuffaceous or volcaniclastic varieties, although in the most intensely altered rocks this distinction becomes blurred.

In general, the volcanic rocks can be assigned to one of two zones of metamorphism, with zone 2 further subdivided (Table 1). Zones 1 and 2 are separated by a line drawn west from Salmo (Fig. 2). Nowhere in the area have nonamphibolitized zone-1 volcanic rocks been found in contact with amphibolitized zone-2 rocks. Stratigraphic studies (Little 1960, Frebold & Little 1962, Frebold 1959) indicate that the volcanic rocks to the north and south are equivalent in age; Beddoe-Stephens (1977) has shown, by the use of interelement correlation coefficients, that the two zones are compositionally identical and form a single magmatic suite.

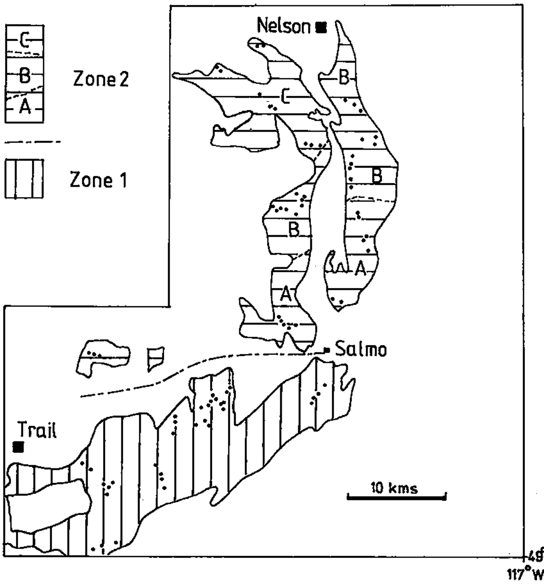

FIG. 2. Distribution of zones 1, 2A, 2B and 2C (see text for discussion). Sampling localities are shown as dots.

Zone 1

The volcanic rocks in this area are characterized by the presence of relict igneous pyroxene, hornblende and spinel, and by the absence of secondary amphibole or biotite. Replacement of olivine by pseudomorphic aggregates of chlorite or calcite (or both) is, however, complete. Similarly, orthopyroxene in some andesitic rocks is represented by tabular, chloritic pseudomorphs. Original plagioclase is only rarely preserved as the rims of phenocrysts, as is evident from primary oscillatory zoning. Otherwise, the core, and more commonly the whole crystal, is clouded with abundant small epidote inclusions (saussurite). In other cases, sericitization has affected the feldspar. Cr-spinel and magnetite microphenocrysts are commonly unaltered, particularly where included in pyroxene or hornblende, but magnetite has been prone to marginal or total replacement by pyrite or pyrrhotite, or by turbid Fe-hydroxides. The fine groundmass that typifies the lavas is invariably highly altered to chloritic and sericitic products

TABLE 1. SUMMARY OF TEXTURES AND MINERALOGY IN ROSSLAND VOLCANIC ROCKS

Zone	sub-Zone	Amphibole (after cpx phenocrysts)	Relict igneous minerals	Secondary minerals	Dominant textural type
1		None	Cpx, Hb, Sp, Pl	Ep, St, Chl, Cc, Pr Ab	Igneous-porphyritic
2	A	Actinolite	rare Cpx	Ep, Chl, Bi, Cc, Ab Mt	Igneous-porphyritic
	B	Actinolite+Hornblende	rare Cpx	Ep, Chl, Bi, Cc, Ab Mt	Igneous-porphyritic but locally sheared
	C	mainly Hornblende	none	Bi, Ep, Pl, Ab, Mt (Chl, Cc)	Schistose

Pl Plagioclase, Ab Albite, Chl Chlorite, St Sericite, Cc Calcite, Ep Epidote, Pr Prehnite, Bi Biotite, Hb Hornblende, Cpx Diopside/Augite, Sp Spinel (Cr-spinel or Ti-magnetite), Mt Magnetite. Phases in brackets are retrograde.

with uncommon patchy and ragged epidote.

Secondary minerals are best developed within vesicles and comprise calcite, epidote, chlorite and prehnite. The last two occur as radial sheaves in zonal arrangement: chlorite rims the cavity and encloses the prehnite. Epidote occurs either as a granular rim in vesicles containing chlorite or as discrete prisms embedded in an aggregate of chlorite or carbonate.

Texturally, zone-1 lavas show little destruction of their porphyritic texture. The only field evidence of their alteration is the milky nature of the plagioclase phenocrysts and a general grey-green coloration.

Zone 2

Rocks in this area are characterized by the extensive development of actinolite, hornblende and biotite and the almost total lack of relict igneous phases. Chlorite and calcite are less abundant than in zone 1, and prehnite is absent.

In subzone A, porphyritic igneous textures have barely been altered, and original pyroxene phenocrysts have been pseudomorphed by actinolitic amphibole. Rarely, relict clinopyroxene forms cores to these pseudomorphs. Plagioclase phenocrysts similarly show little disruption of form, but have been replaced by albite and contain inclusions of epidote. Rare, characteristically shaped pseudomorphs after olivine are composed of epidote aggregates. Biotite is confined to the groundmass as intergrowths with randomly oriented actinolite needles and feldspar. Geographically, subzone A occurs in the southern part of zone 2, closest to zone 1 (Fig. 2).

Farther north, subzone B contains volcanic rocks with basically the same secondary mineral assemblages as A. Hornblende after pyroxene is more extensive, and some crystals consist of actinolite–hornblende intergrowths. However, the textures, although still recognizably igneous, have undergone some modification. Most notable is the local presence of strongly sheared rocks that exhibit an oriented groundmass fabric of biotite, chlorite and actinolite, as well as pressure shadows around pseudomorphed phenocrysts. These pseudomorphs have undergone some shattering and failure along amphibole cleavage planes, indicating amphibolitization prior to shearing. Otherwise, the development of hornblende by recrystallization has led to the loss of some definition in the shape of the original phenocrysts.

In subzone 2C, textural change is far more complete, and metamorphic fabrics occur. In addition, hornblende is the dominant amphibole and forms "strung-out" aggregates on the sites of former phenocrysts. Epidote and feldspar form a granular mosaic between oriented laths of biotite and prisms of hornblende. Rare chlorite interleaved with biotite may indicate retrograde crystallization.

A feature common to zone 2 is the presence of metamorphic magnetite, probably as a replacement of primary magnetite or spinel. Loss of Ti during re-equilibration is made evident by the occurrence of rims of granular sphene on magnetite. Other accessory minerals throughout zone 2 are quartz and K-feldspar.

MINERAL CHEMISTRY

Results of selected analyses of secondary minerals from zones 1 and 2 are given in Table 2. These are representative of the range of compositions found; a complete listing of the analytical results used is given in Beddoe-Stephens (1977). Analytical techniques are briefly described in the Appendix.

Chlorite

Data on chlorite from both zones are plotted in Figure 3, which portrays the major chemical variations in the chlorite group. Relative to zone 1, zone-2 chlorites are richer, on average, in Mg and Al. According to the classification in Deer *et al.* (1962), zone-1 chlorites are brunsvigites and pycnochlorites, whereas zone-2 chlorites fall in the pycnochlorite and ripidolite fields. Figure 4 shows that the Mg/Fe ratio in chlorite is dependent on the whole-rock Mg/Fe ratio, and thus any differences reflect a bias in the samples analyzed. Al, on the other hand, does not seem to be controlled by host-rock composition, since MgO-rich volcanic rocks are generally lower in Al_2O_3 (Beddoe-Stephens, in press). However, Al incorporation (Fig. 3) does not seem to be coupled with Fe–Mg exchange as it is for the biotites and amphiboles (see below), since on the grounds of ionic radius, Al^{vi} and Fe should be positively correlated. More probably, the amount of Al substitution is related to metamorphic grade, that is, the mineralogical environment in which equilibration occurred. The increase of Al in chlorite with higher metamorphic grade in rocks similar to these is reported by Cooper (1972) and Kuniyoshi & Liou (1976), who also found differing behaviors with regard to Fe–Mg, reflecting host-rock control.

TABLE 2. SELECTED ELECTRON-PROBE ANALYSES OF SECONDARY MINERALS IN ROSSLAND VOLCANIC ROCKS

	Chlorite			Prehnite	Epidote				Biotite		
Sample	5036	5088	4029A	5063	5054	5001B	5516B	5530A	4105B	5088	4029B
Analysis*	1(1)	2(2B)	3(2C)	4(1)	5(1)	6(1)	7(2A)	8(2B)	9(2A)	10(2B)	11(2C)
SiO_2	26.80	25.83	26.55	43.31	37.69	38.19	37.22	38.40	36.65	36.47	37.19
TiO_2	0.03	0.09	0.04		0.02	0.03	0.09	0.07	0.71	1.40	1.65
Al_2O_3	15.42	20.23	18.85	23.04	23.00	27.19	21.51	26.57	15.10	16.67	15.89
Fe_2O_3				1.64	12.51	7.35	15.95	8.53			
FeO	30.65	22.36	23.66						13.52	18.79	18.00
MnO	0.39	0.39	0.49			0.13	0.28	00.19	0.22	0.28	0.28
MgO	11.68	17.56	17.20	0.22	0.22	0.01	0.05	0.03	16.61	11.56	12.04
CaO	0.15	0.10	0.03	26.59	22.98	22.92	22.18	23.55	0.13	0.06	0.06
Na_2O	0.02	-	-	0.13	0.07	-	-	-	0.11	0.01	0.04
K_2O	0.03	0.03		0.04		-	-	-	10.16	9.32	9.53
Total	85.13	86.53	86.85	94.82	96.47	95.83	97.09	97.04	96.25	94.55	94.68
Atomic proportions											
Si	6.022	5.442	5.613	6.035	6.015	6.062	6.010	6.059	5.812	5.582	5.666
Al^{iv}	1.978	2.558	2.387	0.000	0.000	0.000	0.000	0.000	2.188	2.418	2.334
Al^{vi}	2.111	2.469	2.332	3.785	4.329	5.086	4.058	4.889	0.422	0.591	0.522
Ti	0.005	0.015	0.006		0.002	0.004	0.011	0.008	0.078	0.161	0.189
Fe^{3+}				0.173	1.660	0.878	1.915	1.013			
Fe^{2+}	5.760	3.939	4.183						1.658	2.403	2.294
Mn	0.075	0.069	0.088			0.017	0.038	0.025	0.027	0.036	0.037
Mg	3.911	5.512	5.419	0.047	0.050	0.003	0.012	0.007	3.629	2.639	2.735
Ca	0.037	0.022	0.008	3.971	3.930	3.896	3.838	3.881	0.020	0.010	0.009
Na	0.010	0.000	0.000	0.036	0.022	0.000	0.000	0.000	0.031	0.002	0.013
K	0.010	0.008	0.000	0.007	0.000	0.000	0.000	0.000	1.901	1.820	1.852
O	28.000	28.000	28.000	22.000	25.000	25.000	25.000	25.000	22.000	22.000	22.000

	Magnetite		Amphibole						
Sample	5049	4105A	5516B	4007	5061	5061	5049	4029B	5077
Analysis*	12(2B)	13(2A)	14(A)	15(2A)	16(2B)	17(2B)	18(2B)	19(2C)	20(2C)
SiO_2	0.18	0.97	54.47	50.67	52.50	43.56	47.82	40.88	56.33
TiO_2	0.12	0.14	0.02	0.08	0.05	0.35	0.74	0.87	0.01
Al_2O_3	0.27	0.43	1.90	4.09	4.46	13.15	7.41	13.14	1.11
Cr_2O_3	0.24	0.78							
Fe_2O_3	67.34	64.61							
FeO	31.01	31.81	8.60	16 40	11.51	16.40	16.87	18.66	6.44
MnO	0.21	0.28	0.24	0.55	0.28	0.35	0.39	0.38	0.19
MgO	0.01	0.12	18.29	12.74	16.17	10.65	11.55	8.23	20.53
CaO			12.69	12.43	12.46	11.65	11.81	12.22	13.50
Na_2O			0.35	0.29	0.28	1.54	0.83	1.27	0.17
K_2O			0.08	0.20	0.10	0.19	0.48	1.78	0.15
Total	99.39	99.13	96.80	97.45	97.50	97.85	97.90	97.41	98.32
Atomic propotions									
Si	0.054	0.298	7.774	7.490	7.504	6.467	7.083	6.270	7.831
Al^{iv}	0.097	0.156	0.226	0.510	0.496	1.553	0.917	1.730	0.169
Al^{vi}			0.093	0.204	0.260	0.770	0.377	0.648	0.013
Ti	0.028	0.032	0.002	0.009	0.005	0.039	0.082	0.100	0.001
Cr	0.060	0.191							
Fe^{3+}	15.679	14.991							
Fe^{2+}	8.022	8.203	1.026	2.027	1.384	2.037	2.090	2.394	0.739
Mn	0.054	0.074	0.029	0.069	0.034	0.044	0.049	0.049	0.022
Mg	0.006	0.053	3.889	2.807	3.463	2.357	2.550	1.881	4.254
Ca			1.940	1.969	1.919	1.854	1.874	2.008	2.011
Na			0.096	0.083	0.077	0.445	0.238	0.377	0.046
K			0.015	0.037	0.018	0.037	0.091	0.344	0.008
O	32.000	32.000	23.000	23.000	23.000	23.000	23.000	23.000	23.000

Notes: Fe expressed as total Fe_2O_3 or FeO except for magnetite where it is determined by stoichiometry. * Analysis no. and subzone in brackets (see text). - not detected.

Prehnite

Prehnite is restricted to zone 1. The mineral is Fe-poor, with its $Fe^{3+}/(Fe^{3+}+Al) = 0.05$ being similar to compositions reported by Kuniyoshi & Liou (1976) from prehnite–pumpellyite-facies metabasalts.

Epidote

Epidote, chlorite and calcite are common to both zones. With an increase in grade, the compositional range of epidote is extended (Cooper 1972, Miyashiro & Seki 1958): within the prehnite–pumpellyite facies, only Fe-rich epidotes occur (Ps_{30-33}), whereas in the greenschist facies, Fe-poor epidotes and clinozoisites appear as other Ca–Al silicates break down. In the Rossland volcanic rocks, both zones contain high- and low-Fe epidotes within the range Ps_{14-32} (Table 2 and Beddoe-Stephens 1977), although a gap is apparent from Ps_{22} to Ps_{27}, possibly reflecting a solvus. Epidote composition is also strongly influenced by oxygen fuga-

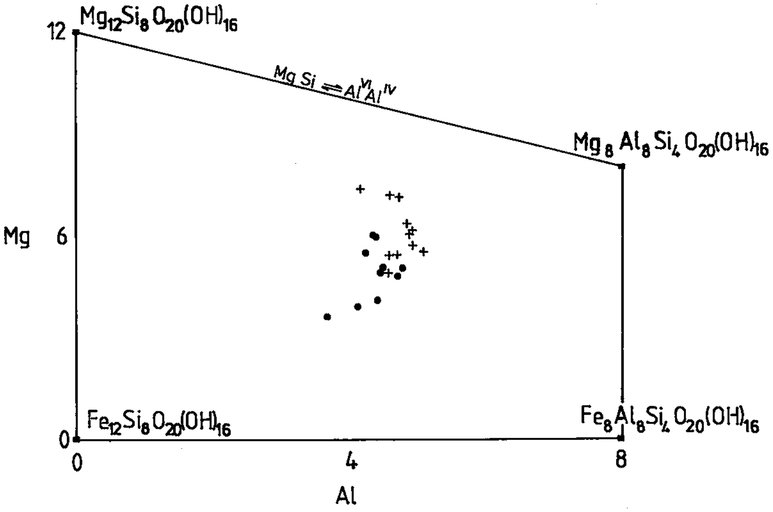

FIG. 3. Mg–Al cation plot of the chlorites. Zone 1 circles, zone 2 crosses.

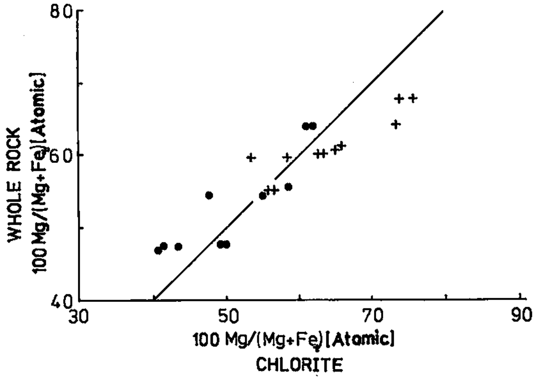

FIG. 4. Atomic Mg/(Mg+Fe_t) relationship between chlorite and the whole rock. Fe_t = total Fe. Symbols as in Figure 3.

city (Liou 1973, Cooper 1972). Four rocks, two from each zone and with epidote compositions Ps_{29}, Ps_{28}, Ps_{18} and Ps_{16}, have measured oxidation ratios $Fe^{3+}/(Fe^{3+}+Fe^{2+})$ of 0.47, 0.41, 0.21 and 0.26, respectively, suggesting that $f(O_2)$ was an important variable during metamorphism of the Rossland volcanic suite.

Biotite

Composition variations of biotite are governed by the same element substitutions as chlorite and, like Fe/Mg ratios in chlorite, are related to the whole rock, as shown in Figure 5. Unlike chlorite, however, Al substitution is strongly coupled to that of Fe (Fig. 6); the biotites fall close to the line joining phlogopite and siderophyllite. That this trend lies just below the hypothetical line is a reflection of slightly low *Y*-site occupancies [a feature of naturally occurring biotites: Deer *et al.* (1962)] that are partly due to the presence of Ti^{4+}.

Amphibole

Chemical variations in the calcic amphiboles are largely due to the two coupled-substitution reactions:

$Si\ (Mg, Fe^{2+}) \rightleftharpoons Al^{iv}Al^{vi}$ (tschermakite)
$Si\ \square \rightleftharpoons Al^{iv}Na$ (edenite)

Possibly to minimize intercrystalline strains (*cf.*, Helz 1973), these two substitutions tend to run concurrently, thus linking the tremolite and pargasite/hastingsite end-members. This is illustrated for the Rossland amphiboles in Figure 7, where the solid line is Leake's (1965) limit for Al^{vi} incorporation in naturally occurring amphiboles. As in the biotite series, substitution of Fe for Mg in the M_{1-3} sites accompanies that of Al^{vi} and is an effect of ionic size (Choudhuri 1974). This is evident in Figure 8, which shows that hornblende in single specimens is always richer in Al than the coexisting or associated actinolite. Because of this effect, the greenschist–amphibolite (or actinolite–hornblende) transition occurs at a lower grade or temperature in Fe-rich rocks. From Figure 8, however, it is clear that average amphibole composition is related to that of the host rock.

Figure 8 shows, in addition, more detail relating amphibole composition to its host subzone. Group 2A amphiboles are generally actinolitic ($Al^{iv} < 0.5$ cations *per* formula unit) even within Fe-rich whole-rock compositions. Many group-2B rocks contain a range of amphibole compositions, indicating disequilibrium. In some 2B samples, single crystals contain patchy intergrowths of two optically discrete amphiboles, the analyses of which are joined by solid tielines in Figures 7 and 8 (also Table 2, analyses 16 and 17). Such features have been attributed by various authors (Cooper & Lovering 1970, Tagiri 1977) to immiscibility between Al-poor and Al-rich calcic amphiboles. However, in the Rossland rocks, some analyses span the gap defined by the "coexisting pairs" (Fig. 7), suggesting that this is a disequilibrium effect, probably due to sluggish prograde reactions (Grapes & Graham 1978). Group-2C rocks contain the most pargasitic and Fe-rich amphiboles (Table 2, analysis 19), but actinolite does persist in especially Al-poor, Mg-rich rocks such as a massive "clinopyroxenite" associated with 2C metavolcanic rocks (Table 2, analysis 20). In general, then, and bearing in mind the influence of host-rock chemistry, Figure 8 indicates an increasing temperature of metamorphism from A through B to C within zone 2.

Feldspar

The electron-microprobe analysis of altered feldspars from zone 1 is generally impossible owing to their fine grained, cloudy alteration. X-ray-diffraction determinations on separated grains from several samples indicate, however, a low structural state and an albitic composition.

Zone-2 feldspars are more amenable to microprobe analysis. Within subzones 2A and 2B, albite ($An_{0.5-5.0}$) is predominant. In 2C, albite is still encountered in rocks where actinolitic hornblende and epidote are present, but plagioclase with compositions from An_{17} to An_{60} has been recorded in metabasalts with hornblende (Beddoe-Stephens 1977). Between An_5 and An_{17}, the well-known peristerite gap intervenes.

K-feldspar, noted above as occurring in small quantities throughout zone 2, has a measured compositional range of Ab_2Or_{98}–$Ab_{11}Or_{89}$.

Magnetite

This phase is conspicuous in both zones. In zone 1, however, it seems to have retained an igneous composition, as reflected in contents of up to 12% TiO_2 and several percent Al_2O_3, Cr_2O_3 and MgO. In contrast, zone-2 magnetites contain less than about 1% $MgO+TiO_2+Al_2O_3$ (Table 2, analyses 12 and 13). Titanium released as a result of this metamorphic re-equilibration has been involved in the formation of sphene, which forms conspicuous rims on some magnetite grains.

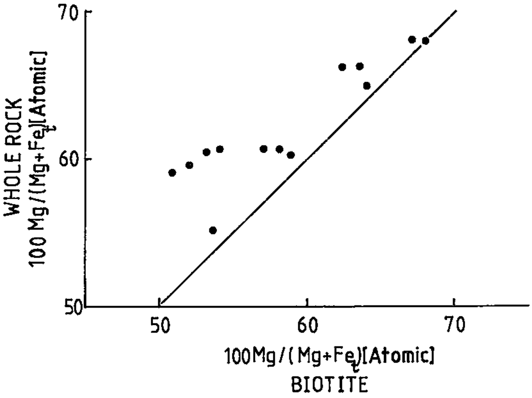

FIG. 5. Atomic Mg/Mg+Fe_t) relationship between biotite and the whole rock.

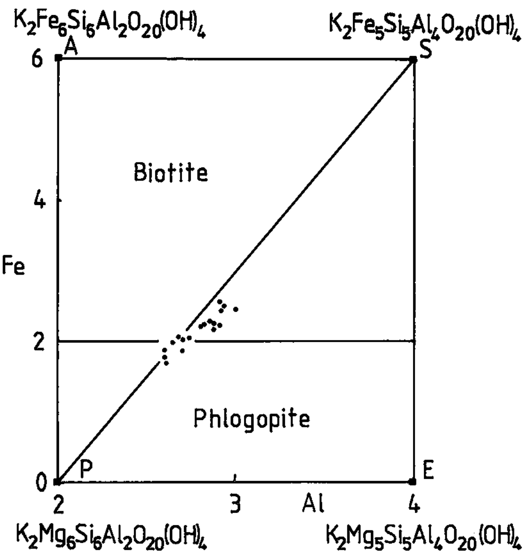

FIG. 6. Fe_t–Al cation plot of the biotites. The arbitary division between the biotite and phlogopite fields is taken from Deer *et al.* (1962). P phlogopite, A annite, S siderophyllite, E eastonite.

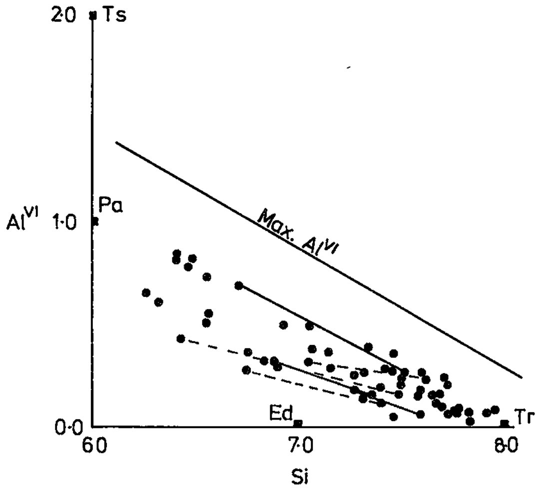

FIG. 7. Si–Al^{vi} cation plot of the amphiboles. Solid tielines link coexisting actinolites and hornblendes within one crystal; dashed tielines link those within one thin section. Ts tschermakite, Pa pargasite, Tr tremolite, Ed edenite.

P–T CONDITIONS OF METAMORPHISM

The variable alteration of the Rossland volcanic suite described above indicates an increase in metamorphic grade from south to north. Zone-1 rocks, lacking amphibole but containing prehnite, are subgreenschist; the absence of zeolites in these rocks constrains them to the prehnite–pumpellyite facies of Turner (1968) or the very low grade of Winkler (1974). Zone-2 rocks, containing extensive amphibole, are typical greenstones and belong to the greenschist facies (Turner 1968) or low grade (Winkler 1974).

Over a considerable pressure range ($<$1–8 kbar), zeolites, such as analcime or heulandite, are stable only to about 200°C (Nitsch 1968, Liou 1971); thus, zone-1 volcanic rocks have probably been subjected to temperatures as least as high as this. The maximum temperatures permissible in zone 1 are governed by the appearance of actinolite and the disappearance of prehnite. At low pressures ($<$1–3 kbar), the reaction prehnite + chlorite + quartz = clinozoisite + actinolite + H_2O occurs at about 350°C (Nitsch 1971). At higher pressures, actinolite is formed and prehnite destroyed at lower temperatures, but the resulting actinolite–pumpellyite facies is transitional to the glaucophane–blueschist facies. Pressure estimates from zone 2 (see below) and petrographic evidence rule out the presence of this facies. Within zone 1, low pressures of metamorphism may be indicated by the lack of pumpellyite. However, the thermal stabilities of Ca–Al silicates such as prehnite and pumpellyite are lowered sharply in the presence of minor amounts of CO_2 (Glassley 1974). For example, the left-to-right progression of Hashimoto's (1972) reaction pumpellyite + CO_2 = epidote + chlorite + calcite + quartz shows that CO_2 levels could account for the lack of pumpellyite and the presence of Fe-poor epidote in zone 1.

Petrographic observations indicate that the actinolite-forming reaction quoted above cannot account for all the amphibole in zone 2. Most amphibole, particularly that which replaced pyroxene, probably formed by reactions such as diopside + chlorite + H_2O = actinolite + clinozoisite or diopside + H_2O + CO_2 = actinolite + calcite + quartz.

The formation of biotite is complex and involves the K-rich components in the groundmass of zone-1 volcanic rocks. A possible generalized reaction (Winkler 1974) is phengite (sericite) + chlorite(1) = biotite + chlorite (2) + quartz. A feature of such a reaction is that chlorite(2) is richer in Al than chlorite (1) (*cf.*, Fig. 3).

Reactions forming hornblende from actinolite proceed over a range of temperatures. Experiments by Liou *et al.* (1974) on metabasaltic rocks similar in composition to Rossland basalts suggest temperatures in the range 450–550°C. Hornblende-forming reactions have been described as the simultaneous consumption of epidote, albite and chlorite and as the production of a more calcic plagioclase (Grapes & Graham 1978, Liou *et al.* 1974). This is noticeably the case in subzone 2C where chlorite, epidote and calcite are much reduced in abundance relative to 2A and 2B. Thus, in the north of the Rossland–Nelson area, conditions relevant to the upper greenschist and amphibolite facies were attained during metamorphism.

Evidence for low pressures of equilibration of zone-2 rocks can be inferred from amphibole compositions. The content of the crossite or glaucophane end-member, represented by Na in the *M*4 site, is regarded as pressure-dependent by Brown (1977). For amphiboles coexisting with epidote, albite, chlorite and an Fe-oxide, Brown has tentatively calibrated an Al^{iv}–Na (*M*4) diagram for total pressure. With selected amphiboles that meet these criteria, Na(*M*4) was calculated assuming that Fe^{3+} was at a maximum consistent with stoichiometry (see Appendix). The maximum Na(*M*4) calculated

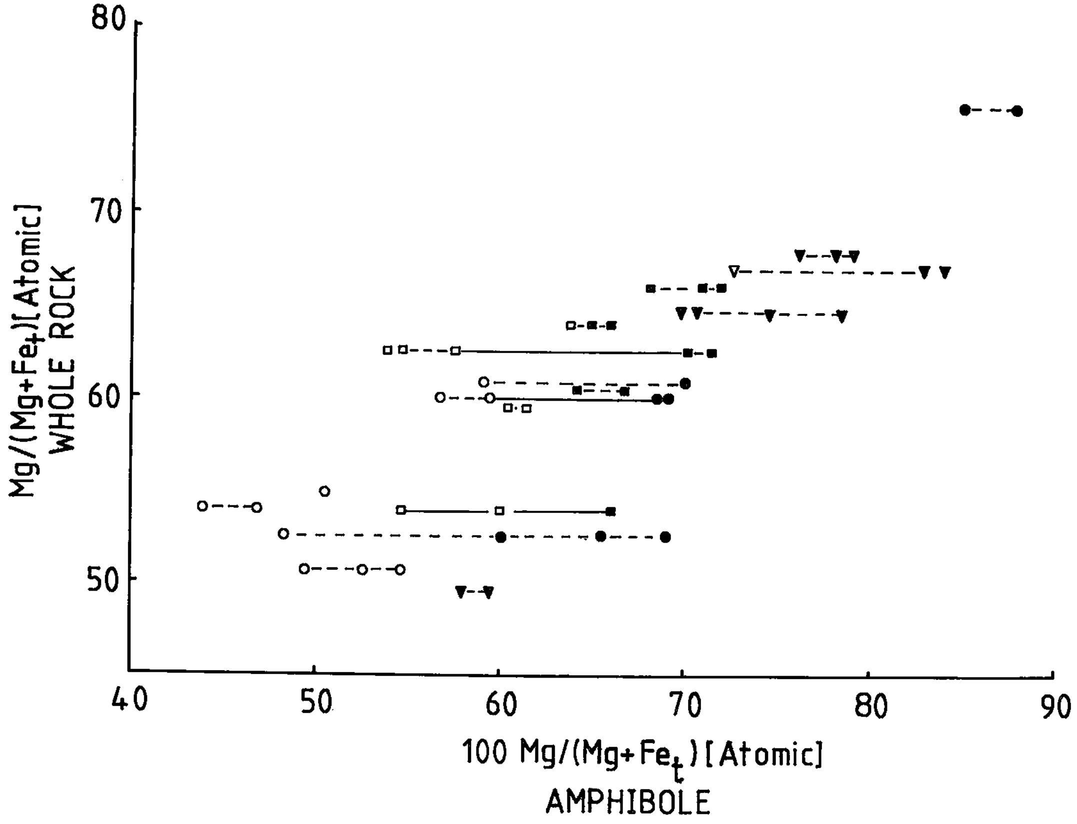

FIG. 8. Atomic Mg/(Mg+Fe$_t$) relationship between amphibole and the whole rock. Filled symbols are actinolite (Al^{iv} $<$ 0.5 cations *per* formula unit), and hollow symbols are hornblende (Al^{iv} $<$ 0.5 cations). Zone 2A triangles, zone 2B squares, zone 2C circles. Tielines as in Figure 7.

in either actinolite or hornblende is 0.2 cations *per* formula unit, which from Brown's (1977) graph gives a pressure estimate of less than 3 kbar.

DISCUSSION

The degree of metamorphism, both thermal and kinetic, increases from south to north, with a lateral temperature-gradient on the order of 10°C/km. The volume of plutonic rocks that intruded the volcanic pile also increases northward (Figs. 1, 2), so that the metamorphism could be interpreted to be of contact type. Indeed, Kuniyoshi & Liou (1976) have shown that greenschist-facies metabasic rocks (*i.e.*, actinolite-bearing) can be produced up to 3–4 km from the contact of a massive plutonic body. However, in the Rossland volcanic suite, petrographic study has shown that the transformation of pyroxene to amphibole in subzone 2B occurred prior to shearing, and that the alignment of groundmass actinolite and mica indicates synkinematic crystallization. Thus, as many plutonic contacts cut across shear or schistosity planes, metamorphism to greenschist facies must have occurred before intrusion of the bulk of the plutonic rocks in zone 2. Exposed plutonic–volcanic interfaces (*e.g.*, in the west of 2B) show that amphibolite-grade rocks extend only about 50 m from the plutonic contacts.

In the zone-2 area, most of the plutonic rocks belong to the Nelson suite, intruded from about 170 *Ma* (Petö 1974); therefore, metamorphism, folding and shearing of the early Jurassic formations (190–175 *Ma*) must have occurred soon after their deposition. It is thus unlikely that simple burial caused metamorphism of the Rossland volcanic assemblage, especially in zone 2, where it has been demonstrated that load pressures were low. Rather, metamorphism seems to have been related to a general thermal uprising associated with pluton production at depth, possibly culminating in the development of the Shuswap gneiss domes to the north of the Nelson–Rossland area.

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REFERENCES

BEDDOE-STEPHENS, B. (1977): *The Petrology of the Rossland Volcanic Rocks, Southern British Columbia.* Ph.D. thesis, Univ. Durham, Durham, England.

——— (1982): The petrology of the Rossland volcanic rocks, southern British Columbia. *Geol. Soc. Amer. Bull.* (in press).

——— & LAMBERT R. ST. J. (1981): Geochemical, mineralogical and isotopic data relating to the origin and tectonic setting of the Rossland volcanic rocks, southern British Columbia. *Can. J. Earth Sci.* **18**, 858-868.

BROWN, E.H. (1977): The crossite content of Ca-amphibole as a guide to pressure of metamorphism. *J. Petrology* **18**, 53-72.

CHOUDHURI, A. (1974): Distribution of Fe and Mg in actinolite, hornblende and biotite in some precambrian metagraywackes from Guyana, South America. *Contr. Mineral. Petrology* **44**, 45-55.

COOPER, A.F. (1972): Progressive metamorphism of metabasic rocks from the Haast Schist Group of southern New Zealand. *J. Petrology* **13**, 457-492.

——— & LOVERING, J.F. (1970): Greenschist amphiboles from Haast River, New Zealand. *Contr. Mineral. Petrology* **27**, 11-24.

DEER, W.A., HOWIE, R.A. & ZUSSMAN, J. (1962): *Rock-Forming Minerals. 3. Sheet Silicates.* Longmans, London.

DOUGLAS, R.J.W., GABRIELSE, H., WHEELER, J.O., STOTT, D.F. & BELYEA, H.R. (1970): Geology of western Canada. *In* Geology and Economic Minerals of Canada (R.J.W. Douglas, ed.). *Geol. Surv. Can. Econ. Geol. Rep.* **1**.

FREBOLD, H. (1959): Marine Jurassic rocks in Nelson and Salmo areas, southern British Columbia. *Geol. Surv. Can. Bull.* **49**.

——— & LITTLE, H.W. (1962): Palaeontology, stratigraphy and structure of the Jurassic rocks in Salmo map-area, British Columbia. *Geol. Surv. Can. Bull.* **81**.

FYLES, J.T. (1970): Preliminary map of the Rossland area. *B. C. Dep. Mines Petroleum Resour. Prelim. Map* **4**.

GLASSLEY, W. (1974): A model for phase equilibria in the prehnite–pumpellyite facies. *Contr. Mineral. Petrology* **43**, 317-332.

GRAPES, R.H. & GRAHAM, C.M. (1978): The actinolite–hornblende series in metabasites and the so-called miscibility gap: a review. *Lithos* **11**, 85-97.

HASHIMOTO, M. (1972): Reactions producing actinolite in basic metamorphic rocks. *Lithos* **5**, 19-31.

HELZ, R.T. (1973): Phase relations of basalts in their melting range at P_{H_2O} = 5kb as a function of oxygen fugacity. I. Mafic phases. *J. Petrology* **14**, 249-302.

KUNIYOSHI, S. & LIOU, J.G. (1976): Contact metamorphism of the Karmutsen volcanics, Vancouver Island, British Columbia. *J. Petrology* **17**, 73-99.

LEAKE, B.E. (1965): The relationship between tetrahedral aluminium and the maximum possible octahedral aluminium in natural calciferous and subcalciferous amphiboles. *Amer. Mineral.* **50**, 843-851.

LIOU, J.G. (1971): Analcime equilibria. *Lithos* **4**, 389-402.

——— (1973): Synthesis and stability relations of epidote, $Ca_2Al_2FeSi_3O_{12}(OH)$. *J. Petrology* **14**, 381-413.

———, KUNIYOSHI, S. & ITO, K. (1974): Experimental studies of the phase relations between greenschist and amphibolite in a basaltic system. *Amer. J. Sci.* **274**, 613-632.

LITTLE, H.W. (1960): Nelson area, west-half, British Columbia. *Geol. Surv. Can. Mem.* **308**.

——— (1962): Trail map-area, British Columbia. *Geol. Surv. Can. Pap.* **62-5**.

——— (1963): Rossland map-area, British Columbia. *Geol. Surv. Can. Pap.* **63-13**.

——— (1964): Geology of Salmo map-area, British Columbia. *Geol. Surv. Can. Map* **1154A**.

MIYASHIRO, A. & SEKI, Y. (1958): Enlargement of the compositional field of epidote and piemontite with rising temperature. *Amer. J. Sci.* **256**, 423-430.

NITSCH, K.H. (1968): Die Stabilität von Lawsonit. *Naturwiss.* **55**, 388.

——— (1971): Stabilitätsbeziehungen von Prehnit und Pumpellyithaltigen Paragenesis. *Contr. Mineral. Petrology* **30**, 240-260.

PETÖ, P. (1974): Plutonic evolution of the Canadian Cordillera. *Geol. Soc. Amer. Bull.* **85**, 1269-1276.

SWEATMAN, T.R. & LONG, J.V.P. (1969): Quantitative electron probe microanalysis of rock-forming minerals. *J. Petrology* **10**, 332-379.

TAGIRI, M. (1977): Fe–Mg partition and miscibility gap between coexisting calcic amphiboles from the southern Abukuma plateau, Japan. *Contr. Mineral. Petrology* **62**, 271-282.

TURNER, F.J. (1968): *Metamorphic Petrology.* McGraw Hill, New York.

WINKLER, H.G.F. (1974): *Petrogenesis of Metamorphic Rocks.* Springer-Verlag, New York.

APPENDIX

Mineral analysis and recalculation

All analytical data on minerals plotted in Figures 3 to 8 and tabulated in Table 2 were obtained using a Cambridge Instruments Geoscan II electron microprobe (wavelength-dispersion technique). Standards comprised metals, oxides and simple silicates, and data correction followed the procedures described by Sweatman & Long (1969). Relative errors for the major elements are less than ± 3%, and detection limits lie in the range 0.02–0.05 wt. %.

The calculation of atomic proportions in the unit formulae assumed the stoichiometric number of oxygens to be present, excluding those attributable to H_2O. The distribution of Fe^{3+} and Fe^{2+} in magnetite was calculated assuming exactly 24 cations *per* 32 oxygens.

Assuming that Fe^{2+} in calcic amphibole is partitioned between the M_{1-3} and M_4 sites, and Na likewise between the A and M_4 sites, the maximum Fe_2O_3 can be calculated by progressively oxidizing FeO until one of the following conditions is met: (1) Si+Al (total) = 8.000 (cations *per* 23 oxygens); (2) $Ti+Al^{vi}+Cr+Mn+Mg+Fe^{2+}+Fe^{3+} = 5.000$ (zero FeM_4); (3) $Na_A = 0.000$. Condition 2 usually forms the limiting case, and the maximum value for $Na(M_4)$ is then equal to 2.000–Ca.

A solution for the minimum Fe_2O_3 consistent with stoichiometry is governed by the following conditions: (1) $Ca+Fe(M_4) = 2.000$ (*i.e.*, zero NaM_4); (2) $Fe^{3+} = 0$. In the Rossland amphiboles, condition 1 normally forms the limiting case.

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