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CLINOPYROXENE AMPHIBOLITE BOUDINS FROM THREE VALLEY GAP, BRITISH COLUMBIA

EDWARD D. GHENT[1], J. NICHOLLS[1], MAVIS Z. STOUT[1]
& BRIAN ROTTENFUSSER[2]

ABSTRACT

Clinopyroxene amphibolite (±garnet) boudins, up to 13 m in maximum dimension, occur within metasedimentary gneisses of the Shuswap Complex near Three Valley Gap, British Columbia. Contacts between amphibolite and gneiss are sharp and the foliation in the gneiss is conformable to the contacts. The boudins contain hornblende-plagioclase-clinopyroxene–quartz±garnet±ilmenite±biotite± chalcopyrite±pyrite. Textural relationships, general chemical homogeneity within mineral grains, and the regular distribution of elements among coexisting minerals are consistent with equilibrium crystallization. Quartz–sillimanite–K-feldspar–biotite–garnet and trondhjemite migmatite occur within the metasedimentary rocks.

From comparisons with experimental and computed phase equilibria, the boudins and enclosing gneisses are inferred to have recrystallized between 620° and 685°C and load pressures of 6-7 kbars. The enclosing gneisses recrystallized under conditions of $P_{H_2O} < P_s$ and order-of-magnitude calculations suggest the possibility of gradients in f_{H_2O} between the cores of the boudins and the enclosing gneiss.

SOMMAIRE

Des boudins d'amphibolite clinopyroxène (±grenat), d'une grandeur maximale allant jusqu'à 13 m, se trouvent dans des gneiss métasédimentaires du complexe Shuswap près de Three Valley Gap, en Colombie-Britannique. Les contacts entre l'amphibolite et le gneiss sont nets et la foliation du gneiss est parallèle aux contacts. Les boudins contiennent de la hornblende-plagioclase-clinopyroxène-quartz± grenat±ilménite±biotite±chalcopyrite±pyrite. La texture, l'homogénéité chimique générale des grains minéraux et la distribution régulière des éléments dans les minéraux présents sont en accord avec la cristallisation en équilibre. On retrouve du quartz–sillimanite–feldspath-K–biotite–grenat et de la migmatite trondhjémite parmi les roches métasédimentaires.

Par comparaison entre l'équilibre de phases expérimental et calculé, les boudins et le gneiss qui les contient semblent s'être cristallisés entre 620° et 685°C et à des pressions de 6 à 7 kbars. Les gneiss ont recristallisé dans des conditions de $P_{H_2O} < P_s$ et des calculs approximatifs suggèrent un gradient de f_{H_2O} entre le centre des boudins et le gneiss qui les contient.

(Traduit par la Rédaction)

INTRODUCTION

Clinopyroxene amphibolite boudins occur within upper amphibolite facies paragneisses of the Shuswap Complex near Three Valley Gap, British Columbia (Fig. 1). A detailed chemical and petrological study of these boudins has been made. The following problems have been investigated: (1) what was the protolith of the amphibolite? (2) How does the mineralogy of these amphibolites compare with that of metamor-

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[1] Department of Geology, University of Calgary, Calgary, Alberta, Canada T2N 1N4

[2] Research Council of Alberta, Edmonton, Alberta, Canada

phosed mafic rocks of the amphibolite-granulite facies transition in other areas, e.g., Broken Hill, Australia? (3) Under what *P-T* conditions did the amphibolites equilibrate? (4) Under what $f(H_2O)$ conditions did the amphibolites equilibrate? (5) Were there gradients in $f(H_2O)$, or other components, between the boudins and the enclosing paragneisses during metamorphism?

REGIONAL METAMORPHIC SETTING

Metamorphosed pelitic rocks between Revelstoke and Three Valley Gap, British Columbia, contain muscovite-quartz-kyanite±sillimanite at lower grades of metamorphism. These assemblages give way to muscovite-quartz-K-feldspar-sillimanite which persists over a lateral distance of nearly 11 km. However, rocks near Victor Lake, about 5 km east of Three Valley Gap, contain quartz – alkali feldspar – sillimanite with aggregates of sillimanite as pseudomorphs of kyanite prisms (Hill 1975; Ghent – unpublished). Metasedimentary rocks at Three Valley Gap contain rare sillimanite which is coarse grained and coexists with alkali feldspar. No primary muscovite occurs at the Three Valley Gap outcrop. The pelitic assemblages at Three Valley Gap are thus indicative of at least upper amphibolite facies metamorphic conditions (Turner 1968).

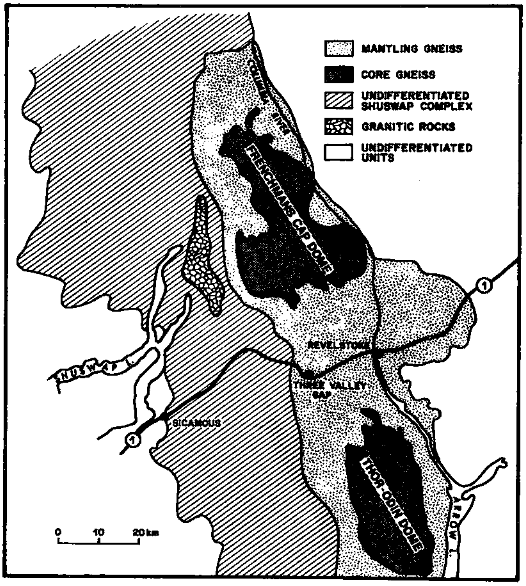


FIG. 1. Simplified geologic map of part of the eastern Canadian Cordillera showing location of Three Valley Gap outcrop. Modified from Reesor & Moore (1971).

FIELD RELATIONSHIPS

The Shuswap Complex is characterized by the occurrences of major gneiss domal complexes spaced at about 65 to 80 km intervals along the eastern part of the Shuswap outcrop (Reesor & Moore 1971). The Thor-Odin domal complex has been divided into four lithologically distinct zones: (1) the Core Zone comprising migmatitic and granitic rocks in the central part of the complex; (2) the Mantling Zone, largely composed of metasedimentary rocks; (3) the Fringe Zone which partly overlaps and partly surrounds the Mantling Zone and is characterized by large amounts of granitic and pegmatitic rocks, and (4) the Supracrustal Zone that lies outside of the gneiss complex and forms a cover to the gneiss (Reesor & Moore 1971).

The amphibolite boudins described in this paper occur in the Mantling Gneisses of the structural depression between the Thor-Odin gneiss dome and the Frenchman's Gap gneiss dome (Fyles 1970, Fig. 1). The boudins occur within metasedimentary gneisses on one continuous road-cut on the south side of the Trans-Canada highway approximately 20 km west of Revelstoke (Figs 2, 3). The amphibolite boudins occur as trains of elongate streamlined bodies which range from less than 30 cm to greater than 13 m in maximum dimension. The trains of boudins outline broad folds.

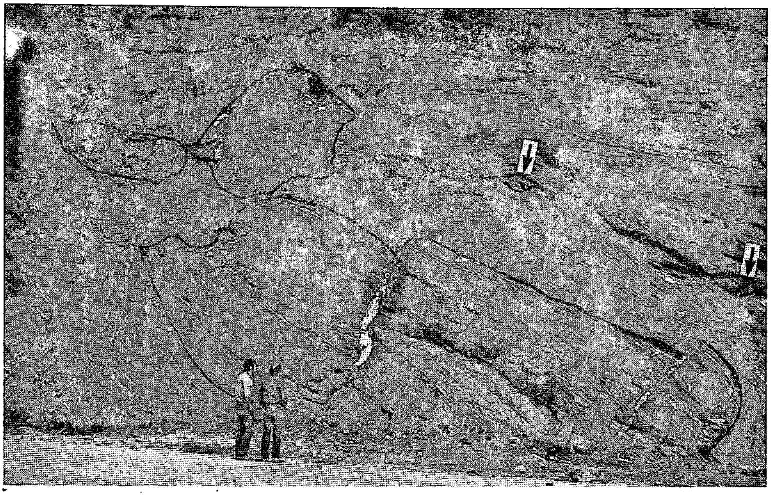
The dominant rock type at the outcrop is quartz-plagioclase-biotite paragneiss which forms the host for the amphibolite boudins. Foliation in the paragneisses is wrapped around the boudins. Feldspar-rich compositional layering within the boudins is more or less parallel to the long direction of the boudins and is bent at the margins of the boudins. Both the enclosing paragneisses and the amphibolite boudins are cut by pegmatite veins (Figs. 2, 3).

PETROGRAPHY OF AMPHIBOLITES

Amphibolite boudins generally show weak foliation. Most amphibolites contain numerous veins and layers of granoblastic plagioclase-quartz, up to 4 mm thick, which are generally parallel to the boudin elongation and terminate

TABLE 1. MODAL ANALYSES OF AMPHIBOLITES FROM THREE VALLEY GAP, B.C.

Sample No.	amph.	plag.	qtz.	cpx	opaques	apatite	biotite	epidote	garnet	plag./amph+cpx
BR 1	59.8	36.5	1.0	1.8	0.4	0.1	0.4	-	-	0.59
BR 2	63.6	32.3	2.1	1.7	0.1	0.1	0.1	-	-	0.50
BR 3	53.8	36.8	2.0	7.0	0.2	<0.1	<0.1	0.2	-	0.60
BR 4	57.5	38.4	2.9	0.8	0.1	0.1	0.1	0.1	-	0.66
BR 5	61.7	35.4	1.3	1.4	<0.1	0.1	-	<0.1	-	0.56
BR 6	46.9	47.8	<0.1	3.9	0.2	<0.1	-	0.5	-	0.94
BAR 1Y	40.4	36.6	0.5	7.2	1.5	-	-	0.2	13.6	0.77
BAR 2Y	48.1	39.0	0.5	5.8	1.2	-	-	-	5.4	0.72



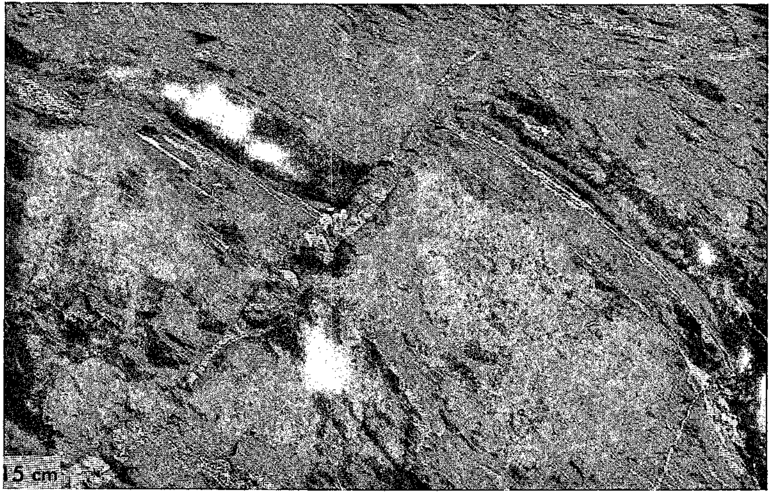


FIG. 2. (top). Photograph of part of Three Valley Gap outcrop showing largest amphibolite boudin sampled (bottom of photograph, outlined in black ink); smaller boudins near the top of the photograph are also outlined.

FIG. 3. (bottom). Detail of part of the largest amphibolite boudin. Note offset of boudin–paragneiss contact cut by pegmatite vein. Biotite-rich selvages are concentrated along contact.

at the boudin edges. No pronounced lineations were observed.

The principal minerals of the amphibolite are hornblende and plagioclase with lesser amounts of quartz, clinopyroxene, biotite, and opaque minerals (Table 1). Garnet is a less common, but important member of some amphibolite assemblages.

Hornblende and plagioclase form even-grained, generally granoblastic aggregates which average about 0.5 mm in diameter. Both minerals contain inclusions of opaque minerals and quartz. Garnet is also poikilitic, containing inclusions of quartz, feldspar, opaque minerals, and less common hornblende.

Grain boundaries of quartz and plagioclase commonly meet at angles near 120°, suggesting a close approach to textural equilibrium (compare Binns 1964). The general lack of optical zoning in minerals is also consistent with equilibrium crystallization and this general chemical homogeneity within grains was confirmed by electron probe microanalysis (Tables 4 *et seq.)* Clinopyroxene-hornblende grain boundaries are generally smooth and regular and do not suggest disequilibrium.

Hornblende is rarely rimmed by light green actinolite (BR-6)* and garnet and biotite are partly retrograded to chlorite. Epidote veins cut across the granoblastic fabric and suggest late crystallization.

PETROGRAPHY AND MINERALOGY OF HOST ROCKS

The predominant rock types at Three Valley Gap are metasedimentary gneisses showing compositional banding. The metasedimentary lithologies are dominantly semi-pelites and feldspathic psammites with minor pelite. The most common mineral assemblage is quartz-biotite-plagioclase. Some samples contain, in addition to plagioclase (An_{35-40}), untwinned alkali feldspar ($2V\alpha$ moderate) and myrmekite. Diopside and garnet are less common members of mineral assemblages in the gneisses, and no cordierite was detected.

Sillimanite-bearing gneisses are rare, but significant, at Three Valley Gap. Coarse sillimanite occurs 9 m from the largest boudin sampled (Fig. 2). Sillimanite prisms are prominent on foliation surfaces and feldspar-quartz segregations occur within the sillimanite gneisses.

The sillimanite-bearing gneisses contain the assemblage quartz-plagioclase-alkali feldspar-biotite-garnet-sillimanite-myrmekite-ilmenite. Muscovite occurs as a sericitic alteration product of sillimanite prisms and rarely in fine lepidoblastic intergrowth with altered biotite. In neither occurrence is the muscovite considered to have been stable at the maximum grade of metamorphism.

Garnets vary in texture from subidioblastic to granoblastic with very irregular margins. Quartz is the most common inclusion, but ilmenite, biotite, and fibrolitic to coarse sillimanite are also included in both cores and margins of garnet grains. Electron microprobe analyses of garnets (Table 12) indicate that they are chemically zoned with Fe and Mn increasing from core to rim and Mg decreasing from core to rim. This type of Mn zoning has also been observed in garnets from other high-grade terrains (e.g. Grant & Weiblen 1971). Garnet from pelitic rocks at Three Valley Gap generally has a far lower CaO content than garnet- and staurolite-zone garnets from pelites of the Esplanade Range (Ghent 1975).

Biotite is deep red-brown, lepidoblastic, and often associated with sillimanite. Electron microprobe analyses indicate that the biotite is chemically homogeneous and has more TiO_2 than biotites from lower grade rocks in the Esplanade Range (cf. Table 12 with Ghent 1975).

Plagioclase shows glide twinning and strain shadows. Electron microprobe analyses indicate a limited amount of chemical zoning (An_{18-27}, Or $_{0.5-2.3}$). Alkali feldspar is untwinned with a moderate negative $2V$ and locally contains regular albite lamellae $\leq$.003 mm in width. Myrmekite occurs at some contacts between alkali feldspar and plagioclase.

Sillimanite which is not included in garnet is coarse-grained, up to 0.4 mm in sections cut normal to the *c* axis, and occurs in segregations. Fibrolitic sillimante occurs within garnet, suggesting that initial aluminum silicate growth occurred as fibrolite which was preserved from conversion to coarse sillimanite by inclusion within growing garnet.

Feldspar-quartz segregations within the sillimanite gneisses contain plagioclase (An_{27}) and no detectable alkali feldspar, suggesting that their composition is well-removed from minimum-melting compositions in the "Granite"-H_2O system (e.g. Winkler 1976).

Trondhjemite pegmatite veins cut the metasedimentary gneisses and boudins (Fig. 3), and are considered to post-date the main period of metamorphism. Plagioclase in the pegmatite is sodic (about An_{25}), chemically zoned, and typically shows glide twinning. Sericitization of feldspar is widespread. Other minerals include quartz, coarse muscovite and biotite (typically chloritized), tourmaline and garnet.

CHEMISTRY AND ORIGIN OF THE AMPHIBOLITE BOUDINS

Chemical analyses of the major, minor, and selected trace elements have been made on four samples of Three Valley Gap boudins (Tables 2, 3). These analyses, when recalculated on an H_2O-free basis, are similar to the chilled margins of dolerite sills (McDougall 1962; Gunn 1962, 1966; cf. Analyses 5, 6, 7 and 8, Table 2). CIPW norms for Three Valley Gap boudins are compared to chilled dolerites and other ortho-amphibolites in Figure 4. The Three Valley Gap boudins, when described on a water-free igneous basis, range from oversaturated hypersthene-normative to slightly undersaturated, olivine-normative tholeiites. The boudins are generally higher in Na_2O than chilled dolerites. Soda varies within the boudins, but the variation is not systematic.

Titanium in Three Valley Gap amphibolites is significantly lower than in analyses of orthoamphibolites presented by Wilson & Leake (1972), Van de Kamp (1970), Engel & Engel (1962),

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*Numbers refer to samples held at the Department of Geology, University of Calgary

Evans & Leake (1960) and Poldervaart (1955).

The trace-element contents of Three Valley Gap amphibolites, with the exception of Cr, are uniform from sample to sample. Except for Cr, the standard error on the mean ($\sigma x/\sqrt{N}$) of the four analyses is less than the standard deviation for each element. This comparison suggests that the variation is due to analytical uncertainty rather than natural variation. Certainly the two cannot be separated given the present data.

Ni, Cr, Co and Sr are present in concentrations similar to those in dolerite sills (Table 3). Rb, however, is much more abundant in the boudins than in dolerite sills and this abundance is reflected in the K/Rb ratios (Table 3). If the boudins were dolerites with original K/Rb ratios similar to those in dolerite sills in Tasmania and Antarctica, then there has been significant redistribution of one or both of these elements during metamorphism. The problem of K/Rb ratios in metabasites has recently been considered by Elliot (1973), Field & Elliot (1974) and Field & Clough (1976). Elliot (1973) and Field & Elliot (1974) suggested that amphibolitization of gabbro can involve increases in both K and Rb. In an amphibolite-granulite transition zone in Norway, Field & Elliot (1976) reported that both K and Rb are more abundant and K/Rb ratios are lower in rocks from the amphibolite

TABLE 2. CHEMICAL ANALYSES OF CLINOPYROXENE-BEARING AMPHIBOLITE BOUDINS

	wt%	1	2	3	4	5	6	7	8
	SiO_2	53.60	52.80	55.14	51.36	54.15	53.74	52.76	51.07
	TiO_2	0.61	0.63	0.68	0.67	0.66	0.66	0.51	0.45
	Al_2O_3	14.06	14.47	14.49	14.57	14.65	15.53	13.37	15.73
	Fe_2O_3	1.04	1.22	1.30	1.29	1.23	0.77	1.81	1.00
	FeO	7.33	7.75	7.71	8.35	7.92	8.42	7.37	7.93
	MnO	0.17	0.12	0.12	0.18	0.15	0.15	0.15	0.17
	MgO	7.92	7.33	5.98	8.16	7.47	6.78	10.02	10.74
	CaO	10.83	10.65	8.93	10.42	10.39	11.16	12.42	11.02
	Na_2O	1.83	2.57	2.84	2.34	2.44	1.67	1.17	1.44
	K_2O	0.60	0.65	1.03	0.97	0.83	1.04	0.40	0.37
	P_2O_5	0.16	0.08	0.10	0.10	0.11	0.08	0.02	0.08
	H_2O+	1.11	0.94	1.09	1.13				
	H_2O-	0.15	0.19	0.19	0.19				
	Total	99.41	99.40	99.60	99.73				
					CIPW Norms				
	Q	5.92	1.87	5.66		3.14	4.84	4.49	
	or	3.55	3.84	6.09	5.73	4.90	6.15	2.36	2.19
	ab	15.48	21.75	24.03	19.80	20.65	14.13	9.90	12.18
	an	28.38	26.03	23.75	26.39	26.57	31.81	30.05	35.36
di	wo	10.15	10.98	8.31	10.29	10.13	9.62	13.13	7.84
	en	6.01	6.25	4.43	5.91	5.76	5.09	8.40	4.92
	fs	3.63	4.25	3.62	3.92	3.94	4.23	3.86	2.45
hy	en	13.72	12.00	10.47	12.21	12.85	11.79	16.55	21.53
	fs	8.28	8.16	8.56	8.11	8.78	9.79	7.61	10.71
	fo				1.55				0.21
	fa				1.13				0.11
	mt	1.51	1.77	1.88	1.87	1.78	1.12	2.62	1.45
	il	1.16	1.20	1.29	1.27	1.25	1.25	0.97	0.85
	ap	0.38	0.19	0.24	0.24	0.26	0.19	0.05	0.19

1: BR 2; 2: BR 3; 3: BR 4; 4: BR 5; 5: Av. of 1-4 on H_2O-free basis;

6: Av. of 13 chilled margins, Tasmanian dolerite sills (McDougall 1962). Recalculated H_2O-free.

7: Chilled margin, hypersthene dolerite sill, Antarctica (Gunn 1962). Recalculated H_2O-free.

8: Chilled margin, olivine tholeite sill, Antarctica (Gunn 1966). Recalculated H_2O-free.

TABLE 3. TRACE-ELEMENT ANALYSES (PPM) OF CLINOPYROXENE-BEARING AMPHIBOLITE BOUDINS

	1	2	3	4	5	7	8
Ni	104	150	127	127	127(9.4)*	85	249
Cr	500	100	125	375	275(97.4)	142	352
Co	75	88	88	75	82(3.8)	60	62
Cu	50	70	40	50	53(6.3)		
Zn	80	85	90	120	94(9.0)		
Sr	100	100	100	100	100(0.0)	126	100
Rb	125	144	157	157	146(7.6)	30	12
K/Rb	40	40	55	51	47	111	256

Samples numbers are the same as those in Table 2 with the exception of 6 for which no trace-element data are available. Analyses by R.R. Barefoot of the Geological Survey of Canada, Calgary using AAS. Standard deviations are 10 ppm for all elements except Cu (5 ppm), Zn (5 ppm) and Sr (25 ppm).
*Numbers in parentheses refer to one standard error on the mean.

TABLE 4. ELECTRON MICROPROBE ANALYSES OF HORNBLENDES FROM THREE VALLEY GAP, B.C.

wt%	BR-1	BR-2	BR-3	BR-4	BR-5	BR-6	BAR-1Y	BAR-2Y
SiO_2	44.2	45.1	44.7	43.1	44.6	45.4	42.6	42.5
TiO_2	1.2	1.0	1.1	1.2	1.0	1.0	2.2	2.5
Al_2O_3	11.7	11.9	12.4	12.6	12.0	10.7	13.0	12.6
FeO*	17.0	13.3	14.7	16.2	13.9	14.5	16.5	17.1
MnO	0.3	0.2	0.2	0.3	0.2	0.2	0.1	0.1
MgO	11.0	12.7	11.7	10.4	11.9	11.8	10.0	9.8
CaO	11.3	11.6	11.4	11.2	11.6	11.8	12.0	11.8
Na_2O	1.5	1.3	1.4	1.4	1.2	1.6	1.4	1.5
K_2O	1.2	1.0	1.1	1.2	1.3	0.9	1.5	1.6
Sum	99.4	98.1	98.7	97.6	97.7	97.9	99.3	99.5
			Numbers of ions on basis of 23 oxygens					
Si	6.51	6.59	6.54	6.45	6.58	6.70	6.30	6.30
Al	1.49	1.41	1.46	1.55	1.42	1.30	1.70	1.70
Sum	8.00	8.00	8.00	8.00	8.00	8.00	8.00	8.00
Al	0.46	0.57	0.68	0.67	0.67	0.56	0.57	0.50
Ti	0.13	0.11	0.12	0.14	0.11	0.11	0.25	0.28
Fe^{2+}	2.10	1.63	1.80	2.03	1.72	1.79	2.04	2.12
Mn	0.04	0.02	0.02	0.04	0.02	0.02	0.01	0.01
Mg	2.42	2.77	2.55	2.32	2.62	2.59	2.20	2.17
Sum Fm	13.15	13.10	13.17	13.20	13.14	13.07	13.07	13.08
Ca	1.78	1.82	1.79	1.80	1.83	1.87	1.90	1.87
Na	0.43	0.37	0.40	0.41	0.34	0.46	0.40	0.42
K	0.23	0.19	0.21	0.23	0.24	0.17	0.28	0.30
Sum Na	15.59	15.48	15.57	15.64	15.55	15.57	15.65	15.67
			Numbers of ions on basis of 13 cations, excluding Ca, Na, K					
Si	6.40	6.51	6.45	6.36	6.51	6.66	6.27	6.26
Al	1.60	1.49	1.55	1.64	1.49	1.34	1.73	1.74
Al	0.40	0.53	0.56	0.55	0.58	0.51	0.52	0.45
Ti	0.13	0.11	0.12	0.13	0.11	0.11	0.24	0.28
Fe^{3+}	0.79	0.61	0.62	0.67	0.48	0.28	0.26	0.28
Fe^{2+}	1.27	0.99	1.15	1.33	1.22	1.50	1.77	1.83
Mn	0.04	0.02	0.02	0.04	0.02	0.02	0.01	0.01
Mg	2.37	2.73	2.52	2.29	2.59	2.58	2.19	2.15
Ca	1.75	1.79	1.76	1.77	1.82	1.85	1.89	1.86
Na(M4)	0.25	0.21	0.24	0.23	0.18	0.15	0.11	0.14
Na(A)	0.17	0.15	0.15	0.17	0.16	0.30	0.29	0.29
K(A)	0.22	0.18	0.20	0.23	0.24	0.17	0.28	0.30

Ca+Na+K in excess of two assigned to A site. The resulting Fe^{3+} is the maximum value consistent with stoichiometry.

*Total Fe as FeO. Sum Fm = Si+Al+Fe+Mn+Mg; Sum Na = sum·Fm +Ca+Na+K

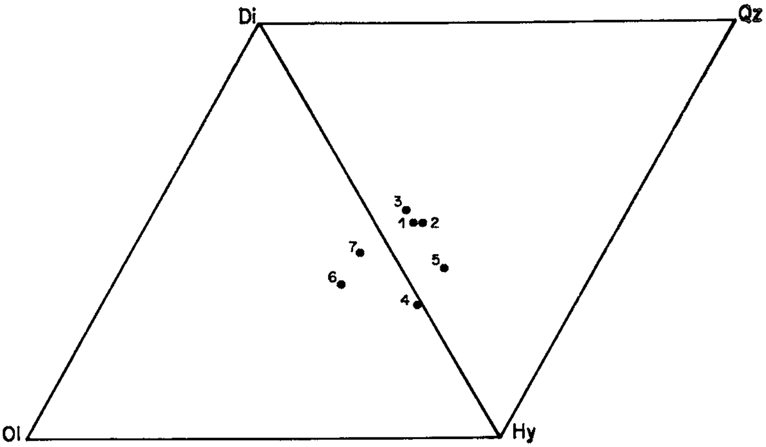

FIG. 4. Triangular diagrams showing normative proportions of hypersthene (Hy), quartz (Qz), diopside (Di) and olivine (Ol) for (1) average of 4 amphibolites from Three Valley Gap; (2) average of 13 chilled margins, Tasmanian dolerite sills (McDougall 1962); (3) chilled margin, hypersthene dolerite sill, Antarctica (Gunn 1962); (4) chilled margin, olivine tholeiite sill, Antarctica (Gunn 1966); (5) average of 32 Scottish epidiorites (van de Kamp 1970); (6) average Connemara striped amphibolite (Evans & Leake 1960); (7) average of 200 amphibolites (Poldervaart 1955).

facies. In addition to the analytical evidence, the occurrence of biotite selvages at the contacts of the Three Valley Gap boudins and the enclosing quartzo-feldspathic rocks suggests mobility of the alkalis.

The clinopyroxene amphibolite boudins are inferred to be ortho-amphibolites, that is, the protolith was basalt. Field relationships and chemistry suggest that the boudins were probably basaltic flows or intrusions which were metamorphosed and yielded by rupture whereas the enclosing metasedimentary gneisses yielded by flow.

TABLE 5. ELECTRON MICROPROBE ANALYSES OF HORNBLENDES RECALCULATED ON THE BASIS OF 15 CATIONS EXCLUDING Na+K

	BR-1	BR-2	BR-3	BR-4	BR-5	BR-6	BAR-1Y	BAR-2Y
Si	6.51	6.60	6.56	6.45	6.59	6.72	6.31	6.32
Al^{IV}	1.49	1.40	1.44	1.55	1.41	1.28	1.69	1.68
Al^{VI}	0.54	0.65	0.70	0.67	0.68	0.59	0.58	0.53
Ti	0.13	0.11	0.12	0.14	0.11	0.11	0.24	0.28
Fe^{+3}	0.03	-0.02	-0.10	-0.04	-0.09	-0.17	-0.07	-0.14
Fe^{+2}	2.06	1.65	1.91	2.07	1.81	1.96	2.12	2.27
Mn	0.04	0.02	0.02	0.04	0.02	0.03	0.01	0.01
Mg	2.41	2.77	2.56	2.32	2.62	2.60	2.21	2.17
Ca	1.78	1.82	1.79	1.80	1.84	1.87	1.91	1.88
Fm(4)	0.22	0.18	0.21	0.20	0.16	0.13	0.09	0.12
Na(A)	0.43	0.37	0.40	0.41	0.34	0.46	0.40	0.43
K(A)	0.23	0.19	0.21	0.23	0.25	0.17	0.28	0.30

The resulting Fe^{3+} is the minimum value consistent with stoichiometry. The cummingtonite component as measured by Fe, Mg and Mn (= Fm in M_4 site is a maximum value).

MINERALOGY OF THE AMPHIBOLITE BOUDINS

Hornblende. The calcic amphibole analyses have been recaluculated both on the basis of 23 oxygen atoms and on fixed numbers of cations. The first method assumes that all the iron is ferrous (Table 4). For a review of the methods of recalculations using fixed numbers of cations see Stout (1972). The contents of the actual formula

TABLE 6. ELECTRON MICROPROBE ANALYSES OF CLINOPYROXENES FROM THREE VALLEY GAP, B.C.

wt%	BR-2	BR-3	BR-4	BR-6	BAR-1Y	BAR-2Y
SiO_2	53.6	53.4	53.1	53.5	52.4	53.0
TiO_2	0.1	0.2	0.1	0.1	0.2	0.2
Al_2O_3	2.2	2.3	2.6	1.3	2.0	1.9
FeO	8.1	10.4	10.7	9.4	10.8	11.2
MnO	0.4	0.4	0.4	0.3	0.2	0.2
MgO	13.1	12.6	12.1	12.9	12.2	12.0
CaO	23.4	21.7	22.0	22.8	22.7	22.5
Na_2O	0.4	0.6	0.4	0.4	0.4	0.4
Sum	101.3	101.6	101.5	100.7	100.9	101.4
	Numbers of ions on basis of 6 oxygens					
Si	1.97	1.97	1.96	1.99	1.96	1.97
Al	0.03	0.03	0.04	0.01	0.04	0.03
Sum	2.00	2.00	2.00	2.00	2.00	2.00
Al	0.06	0.07	0.08	0.05	0.05	0.05
Ti	0.00	0.01	0.00	0.00	0.01	0.01
Fe	0.25	0.32	0.33	0.29	0.34	0.35
Mn	0.01	0.01	0.01	0.01	0.00	0.00
Mg	0.71	0.69	0.67	0.72	0.68	0.66
Ca	0.92	0.86	0.87	0.91	0.91	0.90
Na	0.03	0.04	0.03	0.03	0.03	0.03
Sum of all cations	3.98	4.00	3.99	4.01	4.02	4.00

unit are bracketed between the calculations providing *maximum* possible Fe^{3+} consistent with stoichiometry (Table 4) and *minimum* possible Fe^{3+} consistent with stoichiometry (Table 5).

Many workers have attempted to correlate hornblende composition with metamorphic grade (see Raase 1974). According to Raase (p. 234), there is some overlap but nevertheless there is a clear overall trend of increasing Ti content with metamorphic grade. Two of the Three Valley Gap hornblendes which coexist with ilmenite have Ti contents (0.25 and 0.28, Table 4) near the upper limit for hornblendes from hornblende granulites (Raase 1974). Other Three Valley Gap hornblendes, however, have no more Ti (0.11-0.14) than hornblendes from lower grade rocks. The Three Valley Gap hornblendes, however, generally contain more Ti than lower grade hornblendes from the Esplanade Range (Ghent & DeVries 1972).

Raase (1974) has presented a graph of Al^{VI} atoms per formula unit of hornblende plotted against Si atoms per formula unit. He claims that the Al^{VI}-Si content of hornblendes is largely controlled by the pressure attending metamorphism and he has drawn a line which generally separates hornblendes crystallized under higher pressure conditions from those crystallized under lower pressure conditions (Fig. 5). Hornblendes from Three Valley Gap (Tables 4, 5), using recalculated analyses with *minimum* Fe^{3+} consistent with stoichiometry, plot on the low-pressure side of Raase's curve whereas hornblendes from the garnet and staurolite-kyanite zones of the Esplanade Range (Ghent & DeVries 1972) generally plot on the high-pressure side (Fig. 5). Hornblendes from Three Valley Gap are also clearly separable from those of the Esplanade Range when compared on a plot of total Na+K atoms per formula unit against Al tetrahedral atoms per formula unit (Fig. 6). These differences, based on the chemistry of a *single* mineral, should be interpreted with caution.

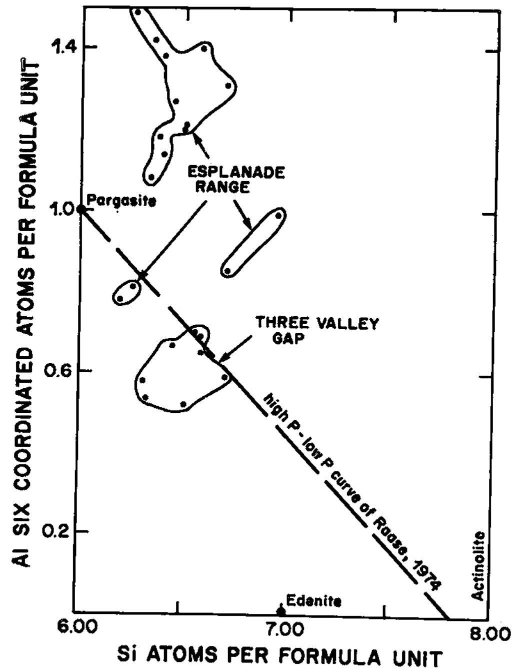

Fig. 5. Plot of six-fold coordinated Al atoms per formula unit against Si atoms per formula unit for Three Valley Gap hornblendes and Esplanade Range hornblendes (Ghent & DeVries 1972). Raase (1974) claims that the line shown separates hornblendes recrystallized at relatively higher pressures (points above line) from those recrystallized at relatively lower pressures (points below line).

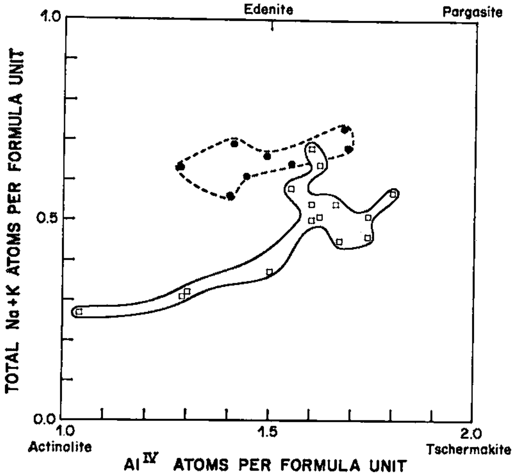

Fig. 6. Plot of Na+K atoms per formula unit against tetrahedral Al atoms per formula unit for Three Valley Gap hornblendes (circles) and Esplanade Range hornblendes (squares, Ghent & DeVries 1972).

Clinopyroxenes. Clinopyroxenes are present in all amphibolite boudins from Three Valley Gap. Electron microprobe analyses of clinopyroxene indicate the largest compositional variation among samples is in the Mg/Fe ratio (Table 6). Other elements show relatively little between-sample variation. Individual clinopyroxene grains are compositionally homogeneous and between-grain compositional variation within a given sample is small.

The Na and Al contents of Three Valley Gap clinopyroxenes are comparable to those of clinopyroxenes from the Adirondacks (Engel *et al.* 1964) and other areas of upper amphibolite to granulite facies metamorphism. Assuming all Fe is assigned as ferrous, the mol fraction of Ca-Tschermak's pyroxene molecule (taken as the number of Al cations in tetrahedral coordination) ranges from 0.01 to 0.04 and the mol fraction jadeite pyroxene molecule (taken as the number of Na cations per formula unit) ranges from 0.03 to 0.04 (Table 6).

Fe-Mg distribution between coexisting clinopyroxene and hornblende. Regular distribution of Fe and Mg can be used as an indication of approach to equilibrium. In favorable circumstances, Fe-Mg distribution between coexisting minerals can be used to estimate *P* and *T* of crystallization (e.g. Råheim & Green 1974). The distribution of Fe and Mg between coexisting clinopyroxene and hornblende can be presented as a distribution coefficient, K_D. which is equal to (FeO/MgO cpx/FeO/MgO hbl). Six pairs of coexisting clinopyroxenes and hornblendes from Three Valley Gap (Tables 4, 6) yield K_D's which range from 0.54 to 0.66. Five of the values of K_D, however, cluster between 0.54 and 0.59. These values of K_D are comparable to those from upper amphibolite to hornblende granulite facies rocks reported by Engel *et al.* (1964) and by Binns (1965a, b).

TABLE 7. COMPOSITIONS (MOLECULAR %) OF PLAGIOCLASE FROM THREE VALLEY GAP, B.C.

	An	Or	Range in An	Range in Or
BR-1	32	2.7	30-36	2.3-3.2
BR-2	62	0.8	61-66	0.5-0.9
BR-3	49	1.3	47-49	0.9-1.9
BR-4	46	0.6	43-46	0.3-1.0
BR-5	47	1.4	45-47	1.0-2.2
BR-6	32	1.6	31-33	0.8-2.3
BAR-1Y	42	2.3	39-44	1.9-2.8
BAR-2Y	42	1.7	41-45	0.7-2.2

Compositions calculated from electron microprobe analyses

TABLE 8. ELECTRON MICROPROBE ANALYSES OF GARNETS FROM AMPHIBOLITES, THREE VALLEY GAP, B.C.

wt. %	BAR-1Y	BAR-2Y
SiO_2	38.4	38.3
TiO_2	0.05	0.1
Al_2O_3	21.0	21.0
FeO*	27.4	28.1
MnO	1.1	1.1
CaO	7.9	8.0
MgO	4.8	4.1
	100.6	100.7

Numbers of ions on basis of 12 oxygens	BAR-1Y	BAR-2Y
Si	3.01	3.01
Ti	.003	.007
Al	1.94	1.94
Fe	1.79	1.84
Mn	0.06	0.06
Ca	0.66	0.67
Mg	0.56	0.48
Σ all cations	8.02	8.01
End-member molecular proportions		
almandine	58	60
spess.	2	2
grossular	21	22
pyrope	18	16

*Total Fe as FeO

TABLE 9. ELECTRON MICROPROBE ANALYSES OF ILMENITES FROM AMPHIBOLITES

wt. %	BAR-1Y	BAR-2Y
TiO_2	52.3	52.6
Al_2O_3	<0.1	<0.1
FeO*	46.4	46.1
MnO	1.4	1.4
MgO	0.1	0.2
Sum	100.2	100.3

Numbers of ions on basis of 3 oxygens	BAR-1Y	BAR-2Y
Fe	0.98	0.97
Mn	0.03	0.03
Mg	0.00	0.01
ΣFe+Mn+Mg	1.01	1.01
Ti	0.99	1.00

*Total Fe as FeO

Plagioclase. Plagioclase from Three Valley Gap amphibolites ranges from An_{30} to An_{66} (Table 7). Individual samples contain plagioclase of more restricted composition and individual grains show slight An enrichment at grain margins. The entire range in plagioclase composition can be observed in two samples which occur within 5 m of one another. This relationship suggests that one should exercise extreme caution in using anorthite content of plagioclase coexisting with hornblende in high-variance assemblages as an indicator of metamorphic grade (see also Ghent & DeVries 1972).

Plagioclase within veins and layers contained in the boudins has a composition similar to that within the mafic parts of the boudin, e.g., An_{55} in veins within BR-2 (Table 7). The parameter $\Gamma=[2\theta(131)+2\theta(220)-4\theta(1\bar{3}1)]$ has been measured on four plagioclase separates. A plot of Γ against composition shows that most of the Three Valley Gap plagioclase lies near the curve for plutonic plagioclase and is comparable in structural state to plagioclase from other high-grade terrains (compare Binns 1965b).

Biotite, garnet, epidote, ilmenite and other opaque minerals. Small amounts of red-brown biotite are present in most samples of amphibolite (Table 1). Some of the biotite is partly altered to chlorite. Biotite from metabasites (Table 10) is less aluminous and richer in TiO_2 than biotite from metapelites (Table 12).

Electron microprobe analyses of garnet rims adjacent to clinopyroxene and hornblende are presented in Table 8. The only chemical variation observed is in Mg/Fe ratio which amounts to a 2% difference in the pyrope molecule.

Opaque minerals are present in all samples of amphibolites, but in most the opaque minerals are altered to a mixture of Fe-Ti oxides. Unaltered ilmenite is present in two samples and the two ilmenites are identical in composition within experimental error (Table 9). Except for MnO, the ilmenites contain little else in solid solution and recalculation of the analyses suggests little of the iron is ferric. These ilmenites are comparable in composition to those from lower grade amphibolites of the Esplanade Range (Ghent & DeVries 1972).

Sulfide phases are dominantly pyrite with rare chalcopyrite. Epidote occurs both in the groundmass and in veins which cross-cut the foliation (BR-6). The epidote is inferred to be related to a late-stage retrograde metamorphism. Green actinolite is also present in samples which contain abundant epidote. The epidote is optically negative and contains a moderate amount of Fe^{3+} and very little Mn (Table 11).

Comparison of mineralogy with other metamorphic terrains. Kanisawa (1969) described garnet-amphibolites in the low-pressure Abukama metamorphic belt in Japan and argued that the bulk compositions of garnet amphibolites are different from clinopyroxene amphibolites. Hornblendes associated with garnet are rich in Al_2O_3 and poor in CaO, whereas those associated with clinopyroxene are rich in CaO and poor in Al_2O_3 (see Table 4). At this grade of metamorphism, metabasites with relatively high CaO/Al_2O_3 can contain clinopyroxene whereas rocks with relatively low CaO/Al_2O_3 can contain garnet. Binns (1964) described garnet and clinopyroxene amphibolites associated with orthoclase-sillimanite-bearing pelitic rocks (his Zone B mineral assemblages) at Broken Hill, Australia. He inferred that calcium-rich rocks contain clinopyroxene and more iron-rich rocks contain garnets. Some samples contain both garnet and clinopyroxene. In the Three Valley Gap rocks the hornblendes and clinopyroxene in garnet-bearing metabasites are relatively Fe-rich compared with those from garnet-free assemblages.

Variation within boudins. Amphibolite samples from the centers of boudins have a higher clinopyroxene:hornblende ratio (BR3, 5 m from contact, Table 1) than do amphibolite samples from the margins of the boudins (BR2, 4, Table 1). Bulk-chemical analyses (Table 2) reveal variations in several oxides, e.g., CaO and Na_2O, but these are not systematic.

The average anorthite content of plagioclase ranges from An_{46} to An_{62} within a single boudin but again the variation is not uniform (Table 7). $K_D{}^{\text{Fe-Mg}}{}^{\text{ cpx-hbl}}$ ranges from 0.66 in the center of the boudin to 0.56 and 0.59, respectively, at its edges.

Evidence for approach to chemical equilibrium. Before we attempt to infer pressure, temperature, and fugacities of volatile species attending metamorphism of the boudins, it is worth considering the evidence that the rocks recrystallized under conditions approaching chemical equilibrium. Textural evidence, including approach to grain-boundary equilibrium and general lack of replacement textures, has been described previously.

Electron microprobe analyses indicate that most of the major phases are chemically homogeneous within grains and within hand samples. Element partitioning between coexisting minerals is regular and individual distribution coefficients, e.g. FeMg for hornblende-clinopyroxene, show little variation.

ESTIMATES OF PHYSICAL CONDITIONS OF METAMORPHISM

Load pressure and temperature. Pelitic rocks at Three Valley Gap contain coarse sillimanite whereas rocks to the east contain kyanite and

TABLE 10. ELECTRON MICROPROBE ANALYSIS OF BIOTITE FROM THREE VALLEY GAP, BRITISH COLUMBIA

BR-1		Number of ions on anhydrous basis of 220	
SiO_2	37.6	Si	5.63
TiO_2	2.7	Al	2.37
			8.00
Al_2O_3	14.9	Al	0.25
		Ti	0.30
FeO*	18.5	Fe	2.32
MnO	0.1	Mn	0.01
MgO	13.2	Mg	2.95
			5.83
Na_2O	0.06	Na	0.02
K_2O	9.5	K	1.81
			1.83
Sum	96.6		

* Total Fe as FeO

TABLE 11. ELECTRON MICROPROBE ANALYSIS OF EPIDOTE FROM THREE VALLEY GAP, BRITISH COLUMBIA

wt%	BR-6	Number of ions on anhydrous basis of -25 anionic charge		
SiO_2	38.1	Si	2.985	
TiO_2	0.2	Al	0.015	
Al_2O_3	26.2	Al	2.38	Pistacite content is 21 molecular percent
Fe_2O_3*	10.7	Ti	0.02	
MnO	0.2	Fe^3	0.63	
MgO	0.04	Mn	0.02	
CaO	23.3	Mg	0.00	
Sum	98.7	Ca	1.95	

*Total Fe calculated as Fe_2O_3

TABLE 12. ELECTRON MICROPROBE ANALYSES OF GARNET AND BIOTITE FROM PELITIC SAMPLES (3VG-3)

	Garnet			Biotite
wt%	core	interior	rim	
SiO_2	38.7	38.7	38.6	36.7
TiO_2	-	-	-	2.2
Al_2O_3	21.6	21.5	21.5	19.2
FeO*	30.9	31.4	32.8	17.2
MnO	0.7	0.9	1.4	-
MgO	.8.1	7.2	6.1	12.1
CaO	1.0	1.1	1.0	-
Na_2O	-	-	-	0.3
K_2O	-	-	-	9.9
Sum	101.0	100.8	101.4	97.6
Numbers of ions on basis of -24 anionic charge for garnet and -44 charge for biotite				
Si	2.99	3.01	3.01	Si 5.40
Al	0.01	--	--	Al 2.60
Sum	3.00	3.01	3.01	Sum 8.00
Al	1.96	1.97	1.98	Al 0.72
				Ti 0.24
Fe	2.00	2.04	2.14	Fe 2.12
Mn	0.04	0.06	0.09	Mg 2.64
Mg	0.86	0.83	0.71	Sum 5.72
Ca	0.08	0.09	0.08	Na 0.08
Sum	2.98	3.02	3.02	K 1.86
				Sum 1.94

*Total Fe as FeO

kyanite pseudomorphed by sillimanite. These data suggest that metamorphism at Three Valley Gap took place in the sillimanite stability field and that the *P-T* path of progressive metamorphism was above the Al_2SiO_5 triple point (Fig. 7).

Analyses of garnet rims in contact with clinopyroxene (Tables 6, 8) yield distribution coefficients for Fe-Mg which can be used to estimate P_s (load pressure) and T (Råheim & Green 1974). The distribution coefficient [K_D=(FeO/MgO) garnet/(FeO/MgO) clinopyroxene] for the two samples is 7.1±0.4. Råheim & Green (1974) experimentally studied the variation of K_D as a function of P_s, T, and composition. They derived the following equation from the experimental results

$$T°K = \frac{3686 + 28.35\,P(\text{kbar})}{\ln K_D + 2.33}$$

Application of this equation to data from Three Valley Gap clinopyroxene-garnet assemblages yields the linear equation, T=859.2+6.6082P.

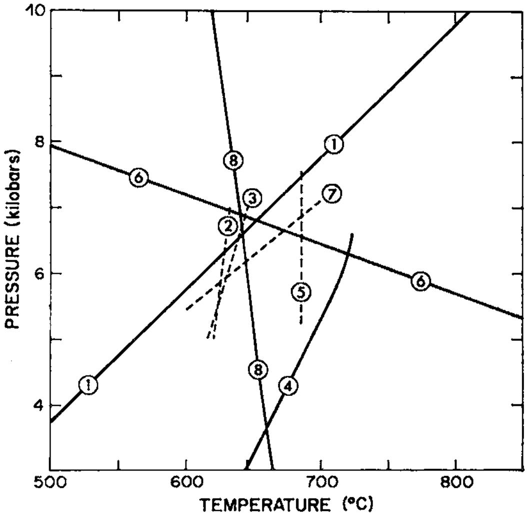

FIG. 7. Pressure-temperature diagram showing experimental and computed phase equilibria relevant to Three Valley Gap rocks. Curves shown in the diagram are: (1) kyanite-sillimanite (Holdaway 1971); (2) garnet-clinopyroxene (Råheim & Green 1974); (3) alkali feldspar-plagioclase (Stormer 1975); (4) muscovite+quartz=sanidine +sillimanite+H_2O (P_s=P(H_2O) — Chatterjee & Johannes 1974); (5) garnet-biotite (Thompson 1976); (6) minimum stability of garnet $Fe_{72}Mg_{28}$ composition; curve is metastable in kyanite stability field (Thompson 1976); (7) garnet-plagioclase-sillimanite-quartz (Ghent 1976); (8) H_2O-saturated solidus for granite (Piwinskii 1968; Boettcher & Wyllie 1968).

The uncertainty in the estimate of T due to analytical uncertainty is about ±15°C.

Metasedimentary rocks at the same outcrop contain coexisting alkali feldspar and plagioclase. Stormer (1975) reviewed the two-feldspar geothermometer originally proposed by Barth. Alkali feldspar is compositionally zoned and it is difficult to relate this zoning to the equilibrium composition of the coexisting plagioclase. The *maximum* albite component in alkali feldspar measured in two samples is Ab_{25} which coexists with plagioclase of Ab_{82} composition. Substitution of these compositions into Stormer's equation (18) (1975, p. 670) yields 617°C at 5 kbar, and 640°C at 7 kbar (Fig. 7).* It should be emphasized however, that selection of other alkali feldspar compositions leads to *lower* estimates of temperature at the same pressure.

Thompson (1976) has proposed an empirical geothermometer based on the exchange of Fe and Mg between coexisting garnet and biotite in pelitic rocks. The geothermometer was calibrated from temperature estimates based on other phase equilibria. Application of this geothermometer to garnet-biotite from Three Valley Gap yields a garnet rim – biotite temperature of 685°C (Fig. 7), but garnet core – biotite and garnet interior – biotite temperatures are 777°C and 757°C, respectively. Thompson (1976) has discussed possible errors in the calibration of this geothermometer and points out that the uncertainty may be on the order of 50°C.

According to Tracy *et al.* (1976), using the calculated *P-X* loops of Thompson (1976), the assemblage garnet-sillimanite-quartz (+biotite) *without* cordierite must indicate higher pressure than garnet of the same composition *with* cordierite. Garnet from 3VG-3 (Table 12), which coexists with sillimanite-biotite-quartz but not cordierite, should yield an estimate of *minimum* pressure at a given temperature. Using the data and equations of Thompson (1976), a *P-T* curve for garnet of composition $Fe_{72}Mg_{28}$ was calculated (Fig. 7). Intersection of this curve with *P-T* curves based on garnet-clinopyroxene and two-feldspar equilibria yield P (minimum) and T

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*Stormer & Whitney (1976, pers. comm.) have modified equation (18) of Stormer (1975) to fit experimental data for the microcline – low albite solvus. Using this modified equation (18) we obtain 704°C at 5 kbar and 728°C at 7 kbar. The equilibration temperature of these samples is likely to be bracketed by estimates based on sanidine-albite data (Stormer 1975) and microcline – low albite data (Stormer & Whitney 1976, pers. comm.), but the effect of an intermediate structural state cannot be precisely evaluated.

within the *kyanite* stability field (Fig. 7). Using the estimate of temperature based on garnet rim – biotite equilibria yields a *minimum* pressure of about 6500 bars.

Ghent (1975, 1976), Schmid & Wood (1976) and Tracy *et al.* (1976), have suggested that quantitative estimates of pressure of metamorphism, at a given temperature, can be made from the equilibrium

$$3CaAl_2Si_2O_8 = Ca_3Al_2Si_3O_{12} + 2Al_2SiO_5 + SiO_2 \quad (1)$$

provided that some estimates of mixing properties of $CaAl_2Si_2O_8$ in plagioclase and $Ca_3Al_2Si_3O_{12}$ in garnet can be made (for an earlier view, see Kretz 1959). Using an ideal solution model with $a^{plagioclase}_{CaAl_2Si_2O_8} = X^{plagioclase}_{CaAl_2Si_2O_8}$ and $a^{garnet}_{Ca_3Al_2Si_3O_{12}} = (X^{garnet}_{Ca_3Al_2Si_3O_{12}})^3$ and the mineral compositions for garnet rim (Table 1) and plagioclase (An_{20}), a P-T equilibrium curve can be calculated (Fig. 7, Curve 7). This curve intersects the garnet-clinopyroxene and the two-feldspar curves near 5900 bars and 630°C and garnet rim – biotite equilibria near 6900 bars and 685°C. Ghent (1976) has pointed out that assigning all CaO to grossular component will yield maximum estimates of pressure at a given temperature for this equilibrium. If the effect of non-ideality is taken into account, the position of curve 7 (Fig. 7) will be changed. Using Orville's (1972) value of $\gamma_{CaAl_2Si_2O_8} = 1.276$ for An_{20} at 700°C and estimates of Margules parameters from Schmid & Wood (1976) with a modified equation 2.1 of Ganguly & Kennedy (1974), a pressure of about 7700 bars at 620°C is obtained. This estimate of pressure is well within the kyanite stability field.

Schmid & Wood (1976) also noted that pressures estimated by this equilibrium for rocks of the Ivrea-Verbano zone, Italy, fall within the kyanite stability field for rocks which contain sillimanite. They argued that, in view of the uncertainties in the kyanite-sillimanite boundary (Holdaway 1971) these pressures are not inconsistent with the Al_2SiO_5 phase diagram. It is possible, however, that the estimate of the ratio $\gamma^{garnet}_{CaAl_2Si_3O_{12}} / \gamma^{plagioclase}_{CaAl_2Si_2O_8}$ may be too high.

About 5 km east of Three Valley Gap, stable muscovite+quartz disappears in the sillimanite stability field. At Three Valley Gap, the production of alkali feldspar – sillimanite assemblages is considered to be subsolidus (see discussion below). When compared to breakdown curves for muscovite + quartz and beginning-of-melting curves for "granite" with $P(H_2O) < P_s$ (Kerrick 1972, p. 954, his Fig. 5), a *maximum* pressure of *about* 7 kbar is suggested. A more precise estimate could be made from consideration of solid-solution effects and the effect of sodic plagioclase (Thompson & Algor, pers. comm. 1976). This *approximate* estimate of *maximum* pressure is reasonably consistent with those discussed above.

Fluid compositions. Estimates of fluid compositions in high-grade metamorphic rocks can be made from experimental and computed phase equilibria (Ghent 1975) or from studies of fluid inclusions (Touret 1971; Hollister & Burruss 1976). In the present study we focus our attention on experimental and computed phase equilibria involving mixed volatiles. We infer that the boudins and the enclosing matrix crystallized at the same P_s and T and examine the fluid compositions that could have equilibrated with the contrasting boudin and matrix mineral assemblages.

The presence of alkali feldspar+sillimanite+quartz and the lack of stable muscovite sets a limit on the *maximum* $f(H_2O)$ at a given P_s and T for the enclosing pelitic rocks. For the equilibrium muscovite+quartz=sanidine+sillimanite+H_2O (2), Chatterjee & Johannes (1974; also Fig. 7 curve 4) give

$$\log f_{H_2O} = 8.9197 - 5285/T + + 0.0248\,(P - 1/T \qquad (2a)$$

Using the estimates of P_s and T from the previous section and correcting for solid solution in alkali feldspar, we can apply this equation to the pelitic samples at Three Valley Gap. The activity of $KAlSi_3O_8$ in alkali feldspar can be estimated from formulations of Margules parameters for $NaAlSi_3O_8$ solid solutions by Thompson & Waldbaum (1969) and from equation 80a of Thompson (1967, p. 353). Results are $f(H_2O) = 2136$ bars at 630°C and 5.9 kbar, and $f(H_2O) = 4857$ bars at 685°C and 6.9 kbar. These values of $f(H_2O)$ are significantly less than pure H_2O at the same P and T (Table 13).

Schmid & Wood (1976) have derived an equilibrium constant for the equilibrium phlogopite+sillimanite+quartz=pyrope+K-feldspar+ H_2O (3).

TABLE 13. ESTIMATES OF $f(H_2O)$ IN EQUILIBRIUM WITH MINERAL ASSEMBLAGES IN PELITIC ROCKS

Reaction	T	P_s	$f(H_2O)$	$f^*(H_2O)$	Source of experimental data
2) muscovite+quartz= sanidine+sillimanite+ H_2O	630 685	5900 6900	<2136 <4857	4219 6321	Chatterjee & Johannes (1974)
3) phlogopite+sillimanite+ quartz=K-feldspar+ pyrope+H_2O	630 685	5900 6900	212 757	4219 6321	Schmid & Wood (1976)

$f^*(H_2O)$ is the value of the fugacity of pure H_2O at the P_s and T specified.

The equation is :

$$\ln f(H_2O) + \ln a^{\text{alkali-feldspar}}_{KAlSi_3O_8} + \ln a^{\text{garnet}}_{Mg_3Al_2Si_3O_{12}} - \ln a^{\text{biotite}}_{KMg_3AlSi_3O_{10}(OH)_2} = - \frac{16975}{T} + 20.53 \quad \frac{(P-1)\,0.2748}{T} \qquad (3a)$$

This equilibrium can be applied to the assemblage biotite-sillimanite-quartz-alkali feldspar-garnet in the enclosing pelitic rocks. According to Wones (1972), phlogopite-annite deviates only slightly from ideal solution behavior. We take $a^{\text{biotite}}_{KMg_3AlSi_3O_{10}(OH)_2} = X^3$ Mg in the octahedral site. The garnet is dominantly almandine-pyrope (Table 12) and according to Schmid & Wood (1976), $W_{\text{FeMg garnet}} \sim 0$. The same expression used for $a_{KAlSi_3O_8}$ in equation (2a) is used in this equation. Using the temperatures and pressures quoted previously, the estimated fugacities of H_2O calculated are significantly less than the maximum values calculated from equation (2a) (Table 13).

According to Chatterjee & Froese (1975) the assemblage K-feldspar-sillimanite-quartz can form under subsolidus conditions only when $P(H_2O)$ is less than P_{total} (using the aluminum silicate P-T diagram of Richardson *et al.* 1969). Kerrick (1972) has computed beginning-of-melting curves for "granite" for conditions of $P(H_2O) < P_{\text{total}}$. At total pressures of 6-7 kbar and T near 690°C, $P(H_2O)$ must be at least 0.5 P_{total} for beginning of melting (see also Thompson 1974). Thus, calculations of $f(H_2O)$ for Three Valley Gap samples are consistent with subsolidus formation of K-feldspar-sillimanite-quartz and suggest that partial melting did not occur in the metasedimentary rocks.

Froese (1973) studied the assemblage quartz-K-feldspar-biotite-garnet-sillimanite from both the core zone and mantling zone of the Thor-Odin gneiss dome. He inferred a temperature range of 200°C for this assemblage and water pressure appreciably less than total pressure. His calculations, however, were based upon a total pressure of 3 kbar.

It is more difficult to make estimates of $f(H_2O)$ from the boudin mineral assemblages because of the lack of experimental data on stability of hornblendes and lack of data on mixing properties of hornblende solid solutions. For example, the reaction tremolite=diopside+enstatite+quartz+H_2O (4) studied by Boyd (1959) does not provide a good model for stability of more complex natural hornblendes. The maximum stability of natural hornblendes has been studied by several workers, but the breakdown products have not been well-characterized and reversal brackets at several sets of $P_s = P(H_2O)$ and T are not available. We have made an *order of magnitude* estimate of the *minimum* $f(H_2O)$ at which hornblende within the boudins would be stable. Hornblende from mafic hornblende granulites at Broken Hill, Australia, has a maximum stability near 800°C at $P(H_2O) = P_s = 1000$ bars (Binns 1964). If the $P(H_2O)$–T slope of this breakdown curve for this hornblende is drawn through 800°C parallel to that of the tremolite breakdown [reaction (4)] and the ΔV_{solids} is assumed to be the same as that for reaction (4), we can derive the following equilibrium-constant equation:

$$\log f_{H_2O} = - \frac{6037}{T} + 8.44 + \frac{0.125\,(P-1)}{T} \qquad (5)$$

Using this expression, we calculate $f(H_2O)$ near 370 bars at 530°C/5900 bars and $f(H_2O)$ near 1090 bars at 685°C/6900 bars. These *minimum values* are slightly above those estimated for the pelitic assemblages (Table 13). If the maximum stability temperature of hornblende is below 800°C at 1 kbar, these minimum $f(H_2O)$ limits will be raised, whereas if the maximum stability temperature is greater than 800°C, the minimum estimates of $f(H_2O)$ will be lowered. If the *order of magnitude* estimates from equation (5) are approximately correct, it is possible that there is a very small gradient in $f(H_2O)$ from boudins to matrix. Obviously, more accurate experimental data on both reaction (3) and the stability of hornblende would be desirable. Although the modal proportions of hornblende-clinopyroxene vary from margins to cores of boudins, the lack of change in the mineral assemblage and the distribution coefficient K_D FeMg for hornblende-clinopyroxene suggest that if there are gradients in the intensive variables of metamorphism from margins to cores of boudins, they must be very small.

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Appendix

Electron probe microanalysis techniques. Analytical data on minerals were collected on an ARL-EMX electron probe microanalyzer. Data were reduced according to the methods outlined by Bence & Albee (1968) and Albee & Ray (1970). Analyzed minerals including hornblende, clinopyroxene and garnet were run as unknowns to check on the accuracy of the analytical techniques.

Whole-rock analysis techniques. Major and minor oxide determinations by J. Nicholls, M. Z. Stout and D. W. Fiesinger using methods described by Carmichael *et al.* (1968).

Replicate determinations agree to within 0.03% except for H_2O, CaO, MgO and SiO_2. The agreement for CaO, MgO and SiO_2 was within 0.05%, whereas H_2O was only within 0.1%.