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Petrology of orthoamphibole-cordierite gneisses from the Orijärvi area, southwest Finland

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ABSTRACT

In this paper we report comprehensive data on mineral assemblages and mineral chemistry for 34 orthoamphibolite gneisses from Orijärvi, Träskböle, and Perniö in southwestern Finland, classic areas first reported on by Eskola 75 years ago. In addition we present an analysis of phase relationships in these samples. Most of the protoliths for our samples are apparent altered mafic volcanics of Archean age. By far the most common assemblage is quartz + plagioclase + cordierite + anthophyllite + biotite + ilmenite, although we observed five samples containing coexisting anthophyllite and gedrite and several containing almandine-rich garnet. Temperatures estimated from garnet-biotite are 550–600 °C for the samples, and pressure estimated by other authors is about 3 kbar. The metamorphism of these rocks was therefore different from two other well-studied orthoamphibolite localities: about 50 °C higher T and similar P to the Post Pond Volcanics of Vermont, and 50 °C lower T and several kbar lower P than the Ammonoosuc Volcanics in southwestern New Hampshire.

Analyses of coexisting cordierite and orthoamphiboles indicate that the same assemblage occurs for a wide range in composition of these minerals, particularly Mg/(Mg + Fe). Although we cannot rule out systematic variations in such variables as f_{O_2} and μH_2O, we believe that the assemblages are of high variance and therefore the mineral compositions are controlled by bulk composition. The few samples we found that had cummingtonite coexisting with cordierite and anthophyllite or gedrite provided clues to the behavior of this mineral. Cummingtonite and cordierite have reacted in several samples to form thin rims of gedrite in a texturally late, and probably prograde, reaction whose progress must be dependent upon $\mu NaAlO_2$.

An unusual texture found in several samples was the development of armored aluminous enclaves in which the highly aluminous minerals corundum, spinel, and högbomite (along with magnetite) are separated from host gedrite by a moat of cordierite. These evenly spaced enclaves may represent compositional heterogeneities inherited from the protolith, which have evolved texturally during metamorphism. What is particularly interesting about these enclaves is an abrupt compositional change in adjacent gedrite in which Al content rises dramatically at enclave margins, whereas Mg and Si contents drop concurrently. The compositional change reflects coupled lattice diffusion of Mg and Si toward the enclave (to grow cordierite rims) and Al out of the enclave on a scale of up to 200 μm. Fe does not appear to have participated in this mass transfer.

INTRODUCTION

Cordierite-anthophyllite and cordierite-gedrite rocks are chemically unusual rock types characterized by enrichment in Mg, Al, and Ti and by moderate to extreme depletion in alkalis and Ca. Unlike many other metamorphic rocks, they cannot be linked simply to one kind of protolith, for example as pelitic schists to shales and amphibolites to mafic volcanics. The origin of protoliths for cordierite-orthoamphibole rocks is a problem that has long been recognized by metamorphic petrologists and is the basis for numerous papers (e.g., Eskola, 1914, 1915, 1950; Tilley, 1937; Floyd, 1965; Vallance, 1967; Grant, 1968; Froese, 1969; de Rosen-Spence, 1969; Chinner and Fox, 1974; James et al., 1978; Schermerhorn, 1978; Kamineni, 1979; Franklin et al., 1981; Robinson et al., 1982; Hudson and Harte, 1985; Reinhardt, 1987; Schumacher, 1988). Hypotheses for the origin of cordierite-orthoamphibole rocks include (1) contemporaneous metamorphism and metasomatism (Eskola, 1914; Tilley, 1937; Floyd, 1965); (2) a residuum from partial melting (Grant, 1968; Hoffer and Grant, 1980); and (3) chemical alteration of the protolith, followed by metamorphism (Tilley and Flett, 1929; Tuominen and Mikkola, 1950; Vallance,

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1967; Froese, 1969; Chinner and Fox, 1974; Schermerhorn, 1978; Schumacher, 1988).

Studies of cordierite-orthoamphibole rocks have been inspired, at least in part, by their common association with massive Fe-Cu-Zn-Pb sulfide deposits, as well as by the enigma of production of their protoliths. Occurrences of cordierite-orthoamphibole have a wide geographic distribution, for example, in Canada (de Rosen-Spence, 1969; Froese, 1969; Lal and Moorhouse, 1969; Kamineni, 1975, 1979; James et al., 1978), in New England (Robinson and Jaffe, 1969a; Robinson et al., 1971; Schumacher, 1983; Spear, 1980), Cornwall (Tilley and Flett, 1929; Tilley, 1937; Chinner and Fox, 1974), Australia (Vallance, 1967), Norway (Stout, 1972), and India (Sharma and McRae, 1981). The classic locality for the study of cordierite-orthoamphibole rocks, however, is in southwestern Finland in the vicinity of Orijärvi.

The rocks of Orijärvi were made famous in the early 1900s by Eskola's studies of them in the formulation of the metamorphic facies concept and the study of metasomatism (Eskola, 1914, 1915, 1950). Tuominen (1951) criticized the idea that metasomatic processes could have produced the unusual rock compositions observed at Orijärvi, and Schermerhorn (1978) reexamined the role of metasomatism in the origin of these rocks. Other research in the Orijärvi region has concentrated on the regional structure (Tuominen, 1957; Bleeker and Westra, 1987), the synorogenic intrusive granites including those in whose contact aureole the cordierite-orthoamphibole gneisses are developed (Mikkola, 1955; Tuominen, 1961, 1966a, 1966b), and the massive sulfide ore deposits (Varma, 1954; Latvalahti, 1979). This paper presents the first modern systematic petrologic investigation of the cordierite-orthoamphibole rocks, in particular a microprobe study of mineral compositions to test the topological hypotheses made by Eskola regarding the stability of various amphibole-bearing assemblages.

In this report, we present data on the petrography and mineral chemistry of orthoamphibole and clinoamphibole, as well as other minerals, from a large sampling of orthoamphibolites from Orijärvi, Perniö, and Träskböle. The study was initially undertaken to test the hypothesis of Froese (1969) that there might be systematic reduction in Fe/(Fe + Mg) of ferromagnesian minerals, including amphibole, in the vicinity of metamorphosed massive sulfide deposits caused by sulfidation reactions (see also Nesbitt and Essene, 1983). We did not find such systematic variations, but concluded that a reexamination of Eskola's classic locality using modern techniques was worth reporting.

We will therefore (1) describe the bulk compositions that can produce the assemblage cordierite + orthoamphibole + biotite so common in southwestern Finland; (2) discuss the substitution mechanisms that have operated in the orthoamphibole; (3) report the element partitioning between coexisting cordierite, orthoamphibole, biotite, and garnet; and (4) review Eskola's observations and predictions of the chemography of the assemblages in these rocks and show how our data confirm or refute them. In addition, we will discuss in detail the formation of aluminous enclaves containing corundum, spinel, and högbomite in a gedrite gneiss from the Perniö area. These enclaves formed in a diffusion process that produced significant chemical zoning in gedrite and that may have important implications for the diffusional behavior of Al in metamorphic rocks.

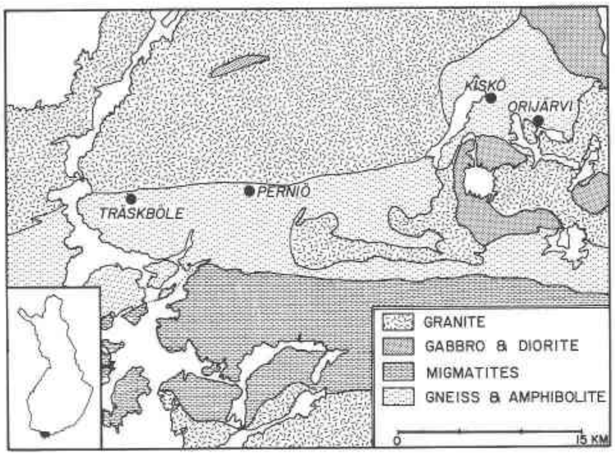

Fig. 1. Generalized geologic and location map of the Träskböle-Orijärvi area, southwestern Finland, from Eskola (1914), showing the relationship of intrusive granite to the gneiss and the amphibolite belt from which the orthoamphibolite samples were collected.

GEOLOGIC SETTING

The Orijärvi area (Fig. 1) is located in the Svecofennian supracrustal belt, which is approximately 1800 m.y. in age (Simonen, 1980). Trending roughly east-west across southern Finland, the belt consists of varying proportions of metamorphosed sedimentary and volcanic rocks. In the Orijärvi vicinity, the lower Svecofennian group reaches a maximum thickness of 3000 m and is composed mostly of felsic volcanics, primarily pyroclastics and lavas, with some agglomerates and tuffs. Limestones, iron formations, and arenaceous sediments occur as thin interbeds. The middle Svecofennian group is 500–1000 m thick and consists of intermediate and mafic pyroclastics and lavas with minor carbonate layers. The upper Svecofennian group, less than 3000 m thickness, is composed of arenaceous and argillaceous sediments that are now phyllites, mica schists, and gneisses. A detailed description of the stratigraphy can be found in Mikkola (1955).

Supracrustal rocks of the Orijärvi region were folded, regionally metamorphosed, and intruded by granodiorite during the Svecokarelian orogeny (1800–1900 Ma; Simonen, 1980). The first phase of folding, F_1, produced isoclinal folds with axes plunging gently to the east and a prominent foliation in all rock types. The second generation of folds, F_2, is also isoclinal but with subvertical axes plunging steeply to the southwest (Tuominen, 1957).

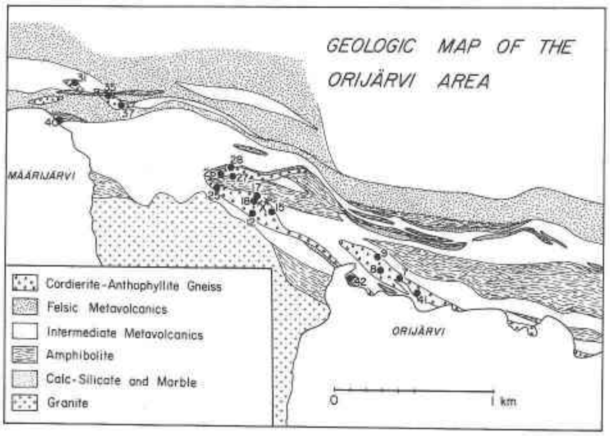

Fig. 2. Detailed lithologic map of the area between Lakes Orijärvi and Määrijärvi in the vicinity of the Orijärvi massive sulfide mine, showing the locations of the OR-prefix samples (Table 1) which come from the mine area (shown by crossed picks symbol). Base map courtesy of Heiki Puustajärvi (personal communication).

The rocks were regionally metamorphosed to the amphibolite facies at P-T conditions estimated to be 3 kbar and 650 °C (Latvalahti, 1979). Synorogenic intrusion of granodiorite caused contact metamorphism at the same or slightly lower P-T conditions (Eskola, 1915). The cordierite-orthoamphibole rocks formed in the lower portion of the lower Svecofennian group in the contact aureole of the large synorogenic intrusion.

The Orijärvi area lies in southwestern Finland near 60°13′N and 23°32′E. Orijärvi and Perniö samples were collected from the Orijärvi mining region in Finland during the summer of 1980 by J.S.S. She collected samples from an area approximately 3 km by 2 km; locations are shown in the large-scale geologic map of Figure 2. In addition, Träskböle samples were collected by P. M. Orville in 1967 and were obtained from his collections at Yale University.

PETROGRAPHY AND MINERAL CHEMISTRY

Mineral assemblages

The dominant metamorphic rocks of the supracrustal belt are fine-grained gneisses (leptites) and amphibolites. The gneisses are composed of quartz and feldspars with subordinate amounts of muscovite, biotite, cordierite, hornblende, and Fe-rich garnet. The amphibolites consist mostly of hornblende, cummingtonite, and plagioclase (about An_{50}), with lesser biotite and ilmenite. Of greatest interest in this study are the orthoamphibolite gneisses that occur with skarns and sulfide ores in the contact aureole of the granodiorite.

Recognition of the cordierite-orthoamphibole rocks in the field is facilitated by their characteristic appearance. Elongated anhedral porphyroblasts of blue-gray cordierite up to 5 by 8 cm are unevenly distributed on the rock surface and protrude prominently to form a knotty texture. Quartz, orthoamphibole, and biotite are intergrown in the porphyroblasts. Orthoamphibole, most commonly anthophyllite and more rarely gedrite, occurs intergrown with cummingtonite and is observed on the weathered surface as long prismatic blades or as fanlike bunches. At Perniö, the texture of these rocks is developed spectacularly into arrays of amphibole florettes up to 9 cm in diameter embedded in dark purple cordierite.

Mineral assemblages observed in the orthoamphibole gneisses are given in Table 1. The most common assemblage is quartz + plagioclase + anthophyllite + cordierite + biotite + ilmenite. About one-quarter of the samples have gedrite in addition to, or in place of, anthophyllite and 10% have garnet in addition to cordierite. Cummingtonite occurs as an accessory mineral in some samples. Six samples contained coexisting orthoamphiboles (OR-26A, OR-27D, OR-40B, OR-40C, PN-3C, and 218-B), and four samples contained coexisting cummingtonite and anthophyllite (OR-26A, OR-26B, OR-40C, and 215). In only two samples did gedrite coexist with cummingtonite (OR-40C and OR-26A). Magnetite, rutile, and pyrrhotite are relatively common minor constituents, whereas corundum, spinel, and högbomite have a very restricted occurrence in aluminous enclaves in gedrite gneisses from Perniö and Träskböle.

In thin section, orthoamphiboles most commonly have a highly elongated, bladed appearance, and may occur in radiating sprays or even in florettes as described above (Fig. 3). Anthophyllite shows a great variation in color, with the more Fe-rich grains being a considerably darker gray-brown than the Mg-rich ones, which are essentially colorless. Most gedrite also has pronounced color and is pleochroic from gray-blue to gray-brown. It may be distinguished from coexisting anthophyllite by its darker color. Coexisting anthophyllite + gedrite shows extensive but uneven distribution of fine microscopic exsolution lamellae, as has been reported for other occurrences (Spear, 1980). Schumacher and Czank (1987) have reported lamellae several thousand angstroms wide of chesterite and jimthompsonite in anthophyllites from Orijärvi, based on HRTEM studies. Cummingtonite may be very difficult to distinguish from anthophyllite if the orientation of a grain is not appropriate to show the nonparallel extinction. Small blades of cummingtonite are commonly intergrown with sprays of anthophyllite in two-amphibole rocks or may even occur as thin rims on anthophyllite. Where cummingtonite is present, it cannot be demonstrated to be in contact with cordierite. In fact, in one sample (OR-26A), amphibole crystals within large poikiloblastic cordierite have cummingtonite cores and gedrite rims, and only the gedrite is in contact with cordierite (Fig. 4). This clear reaction texture suggests that the lack of coexistence of cummingtonite + cordierite may be a late metamorphic or even retrograde effect, and that coexistence of cummingtonite + cordierite may be possible under some metamorphic conditions. This contrasts with Eskola's (1914) assertion that these minerals never coexist and constitutes important evidence regarding phase relations, to be discussed below.

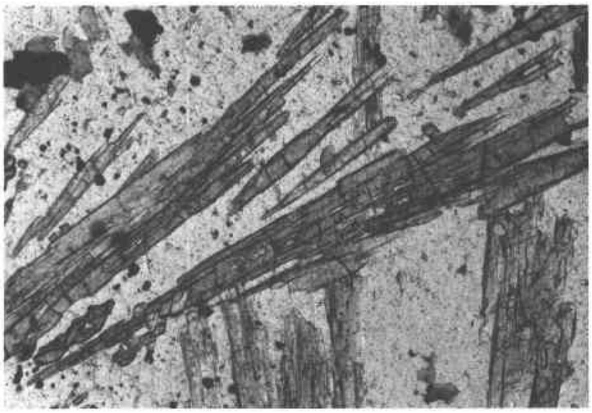

Fig. 3. Photomicrograph showing spray of coarse anthophyllite blades in fine-grained matrix of biotite, quartz, and plagioclase. Horizontal field of view is 2.4 mm.

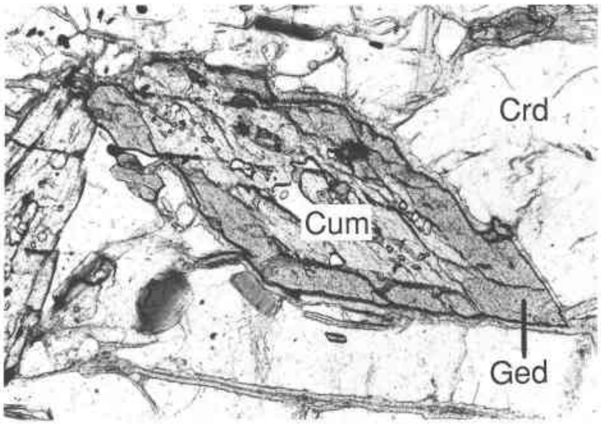

Fig. 4. Photomicrograph of sample OR-26A showing reaction of cummingtonite against enclosing cordierite to form reaction rim of gedrite. Note the very sharp boundary between cummingtonite and gedrite. Horizontal field of view is 1.2 mm.

Cordierite is readily identified in thin section by its typical spongy, inclusion-filled appearance and by the common pleochroic haloes around tiny included monazites. Polysynthetic twinning at 60° angles occurs but is not common. Cordierite is ubiquitous in orthoamphibolites, but generally does not show any particular textural relationship to orthoamphibole blades. In several samples, however (e.g., 218, 336), cordierite rinds of uniform thickness armor aluminous enclaves containing corundum, spinel, and högbomite and separate these highly aluminous phases from surrounding orthoamphibole. These enclaves form a texture of special interest in the orthoamphibolites and will be described in detail below.

Table 1. Mineral assemblages and selected compositional data

	ATH	GED	CUM	CRD*	BT*	GRT*	PL**	QTZ	ILM	RT	MAG	PO	SPL	CRN
OR-7B	X			0.278	0.406		30	X	X					
OR-8A	X			0.265	0.375		31	X	X					
OR-9A	X			0.188	0.243			X	X	X				
OR-9E	X			0.190	0.278		20	X	X	X				
OR-12A	X			0.173	0.220			X	X	X				
OR-12B	X			0.368	0.492	0.838		X	X			X		
OR-15	X			0.279	0.365		85	X	X					
OR-18B	X			0.200	0.254		45	X	X	X				
OR-25A		X		0.348	0.468			X			X			
OR-26A	X	X	X	0.340	0.518		21	X	X					
OR-26B	X		X		0.365		28	X	X					
OR-27D	X	X		0.306	0.461		15		X					
OR-28B	X			0.318	0.457		X	X						
OR-31C	X			0.327	0.430			X	X					
OR-35B	X			0.237	0.320		90	X				X		
OR-37	X			0.210	0.275			X	X	X				
OR-40B	X	X		0.365	0.518		50	X	X					
OR-40C	X	X	X	0.370	0.515		48	X	X					
OR-41	X			0.248	0.377		X	X	X					
OR-42C	X			0.269	0.403			X	X					
PN-1A	X			0.228	0.295			X	X			X		
PN-2B	X			0.333		0.850		X	X					
PN-3A	X			0.307	0.420	0.807		X	X			X		
PN-3B	X			0.300	0.392	0.795	40	X	X			X		
PN-3C	X	X		0.240	0.325				X		X		X	X
213	X			0.210	0.282			X	X	X				
215	X		X	0.225	0.341		X	X	X					
216	X			0.240	0.328			X	X		X			
216-B	X			0.256	0.336		36	X	X	X				
218-A	X			0.180	0.212				X	X	X		X	X
218-B	X	X		0.186	0.209		3		X	X	X		X	X
336		X		0.145							X		X	X
343		X					90	X						
343-A		X		0.266		0.777		X	X		X			

* Fe/(Fe + Mg).
** Mol% An.

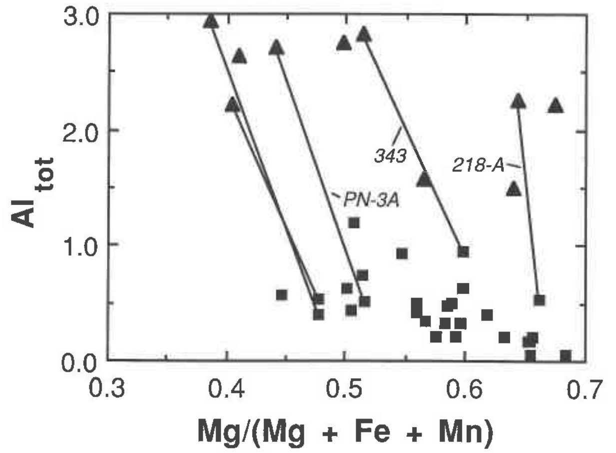

Fig. 5. Plot of Al_{tot} content vs. Mg/(Mg + Fe + Mn) for anthophyllite (squares) and gedrite (triangles). Coexisting orthoamphibole pairs are indicated by tie lines. Note the trend toward decreased Al_{tot} with increased Mg/(Mg + Fe + Mn). Three amphibole samples (two gedrite, one anthophyllite) that fall within a broadly defined orthoamphibole miscibility gap (see text) are indicated.

Microprobe analyses

Polished thin sections of all samples listed in Table 1 were analyzed using the electron microprobe. Analyses were made on a Cameca MS-64 equipped with Tracor Northern TN-2000 EDS system at the Department of Geology and Geophysics, Yale University. Operating conditions included 15 kV accelerating potential, 5 nA beam current, and 1–2 μm spot size. Simple oxides and silicates were used as standards, and data were reduced using standard matrix corrections. Selected samples were chosen at random for WDS analysis on an ARL SEMQ microprobe at Virginia Tech to confirm the earlier analyses, and excellent agreement was found. The compositions reported in the tables are not averages, but rather are single analyses taken from groups of data for each sample. Each reported composition is representative of that mineral in that sample. Structural formulas were calculated on an anhydrous basis assuming 23 O atoms for amphibole, 11 O atoms for biotite, and 18 O atoms for cordierite.

Representative analyses of orthoamphiboles and cummingtonite are presented in Table 2. The names anthophyllite and gedrite have been used to describe varieties of orthoamphiboles with A-site plus $^{[4]}Al$ of less than or greater than 1.0, respectively, following the suggested nomenclature of Leake (1978). Ideal end-member magnesioanthophyllite is taken to be $Mg_7Si_8O_{22}(OH)_2$, and ideal gedrite to be $Na_{0.5}(Mg,Fe)_{3.5}Al_{1.5}Si_6Al_2O_{22}(OH)_2$ (Robinson et al., 1971).

In assemblages of anthophyllite + cordierite from Orijärvi and Träskböle, the anthophyllite contains 0–4 wt% Al_2O_3 and its ratio Mg/(Mg + Fe) varies from 0.45 to 0.70. Anthophyllite from the Perniö locality contains 2.5–7 wt% Al_2O_3 and has Mg/(Mg + Fe) varying from 0.52 to 0.62. There is an apparent subtle inverse relationship between the Al_2O_3 content and Mg/(Mg + Fe) for both orthoamphiboles which can be seen in Figure 5. In particular, anthophyllite shows a tendency toward increased

Table 2. Representative microprobe analyses of amphibole

	OR-8A A*	OR-12A A	OR-12B A	OR-26A A	OR-26A G*	OR-26A C*	OR-26B A	OR-26B C	OR-27D A	OR-27D G	OR-40B A
SiO_2	52.10	55.54	49.79	52.74	42.94	52.31	53.24	54.61	51.76	42.61	51.06
TiO_2	0.16	0	0.12	0	0.46	0	0	0	0	0.47	0
Al_2O_3	2.83	0.31	3.24	0.90	14.64	0.71	1.88	0.67	3.00	15.50	2.28
FeO	24.13	18.54	29.66	28.94	28.82	29.31	22.86	22.40	26.54	25.87	29.25
MnO	0.50	0.35	0.43	0.26	0.41	0.16	0.19	0.67	0.19	0.54	0.49
MgO	17.52	22.85	13.59	15.43	10.54	15.64	19.01	19.34	15.99	11.64	15.24
CaO	0.16	0.19	0	0.13	0.20	0	0.22	0.30	0.24	0.14	0.28
Na_2O	0.44	0.43	0.71	0.10	1.26	0	0.57	0.32	0.53	1.71	0.40
K_2O	0	0	0	0	0	0	0	0	0	0	0.12
Total	97.85	98.21	97.53	98.50	99.27	98.13	97.97	98.31	98.25	98.48	99.11
23 O atom formulas											
Si	7.643	7.880	7.555	7.844	6.424	7.821	7.740	7.892	7.642	6.340	7.601
Al	0.357	0.051	0.445	0.156	1.576	0.125	0.260	0.108	0.358	1.660	0.399
Total	8.000	7.931	8.000	7.950	8.000	7.946	8.000	8.000	8.000	8.000	8.000
Al	0.129	0	0.134	0.003	1.006	0	0.063	0.006	0.164	1.058	0.001
Ti	0.018	0	0.14	0	0	0	0	0	0	0.052	0
Fe	2.960	2.200	3.762	3.599	3.606	3.664	2.779	2.707	3.276	3.219	3.641
Mn	0.062	0.042	0.056	0.032	0.054	0.020	0.023	0.082	0.024	0.069	0.062
Mg	3.835	4.835	3.073	3.421	2.351	3.485	4.120	4.165	3.521	2.583	3.382
Ca	0.024	0.029	0	0.020	0.033	0	0.034	0.047	0.037	0.022	0.044
Total	7.028	7.106	7.039	7.075	7.050	7.169	7.019	7.007	7.022	7.003	7.130
Na	0.126	0.115	0.208	0.028	0.367	0	0.159	0.088	0.150	0.493	0.116
K	0	0	0	0	0	0	0	0	0	0	0.024
Total	0.126	0.115	0.208	0.028	0.367	0	0.159	0.088	0.150	0.493	0.140
Fe/(Fe + Mg)	0.436	0.313	0.550	0.513	0.605	0.512	0.403	0.394	0.482	0.555	0.518

* A = anthophyllite; G = gedrite; C = cummingtonite.

Al_{tot} with decreasing Mg/(Mg + Fe), although a similar, though less clearly defined, tendency also occurs in the gedrite. In the assemblages of gedrite + cordierite from all three sample areas, gedrite samples vary from 9 to 17 wt% Al_2O_3, with the bulk of the gedrite samples between 13 and 16 wt% and their ratios of Mg/(Mg + Fe) range from 0.38 to 0.70. Stout (1972, p. 110) noted a similar pattern in anthophyllite from Telemark, Norway, in which anthophyllite with less than 2.0 Fe atoms per formula unit had no $^{[6]}Al$, whereas those with greater Fe showed a strong positive correlation between Fe and $^{[6]}Al$.

Other minerals analyzed as part of the study include biotite, cordierite, garnet, and plagioclase. Representative biotite analyses are given in Table 3, and summary chemical data for all four ferromagnesian minerals and plagioclase are given in Table 1. Data for minerals in the aluminous enclaves are in a separate section below.

Element distributions

Figures 5 and 6 summarize important compositional features of the orthoamphiboles using plots suggested by previous studies (Robinson et al., 1971; Spear, 1982; Robinson et al., 1982). Figure 5 illustrates the characteristic enrichment of Fe in gedrite compared to coexisting anthophyllite. The Fe-Mg distribution is quite similar to that found by Spear (1980, 1982). Note also, as pointed out above, the trends of increasing Al_{tot} with decreasing Mg/(Mg + Fe) in both anthophyllite and gedrite. Spear (1982) did not observe this effect for orthoamphiboles with a wide range of composition from Vermont. The chemical trends are likely caused by the progressive destabilization of cordierite in the bulk compositions with lower Mg/(Mg + Fe). Lower modal cordierite would result in more Al being available for incorporation into the orthoamphiboles.

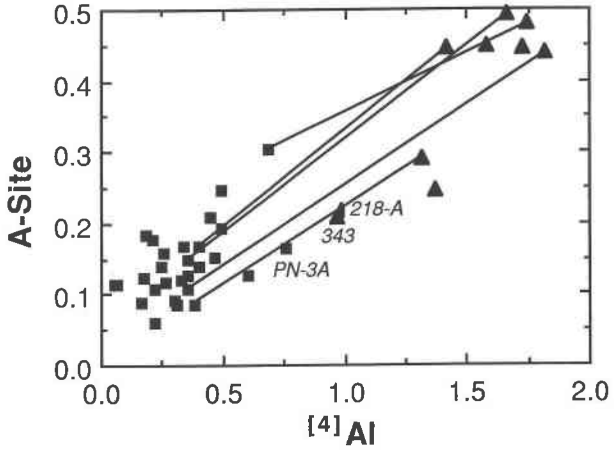

Fig. 6. Plot illustrating the relation of A-site occupancy and $^{[4]}Al$ for anthophyllite (squares) and gedrite (triangles). Anthophyllite-gedrite pairs are shown by tie lines, and three amphibole samples that fall within the miscibility gap are indicated. Note that the anthophyllite samples scatter around a line of slope 0.5, suggesting a relatively regular ratio of edenite to tschermakite substitutions among the group.

The data in Figure 6 for orthoamphibole pairs also nicely illustrate the gedrite-anthophyllite miscibility gap (Spear, 1980; Robinson et al., 1982). Despite the limited

Table 2—*Continued*

OR-40B G	OR-40C A	OR-40C G	OR-40C C	PN-2B A	PN-3C A	PN-3C G	215 A	215 C	218-B A	218-B G	336 G	343-A G
40.92	50.99	44.36	51.97	50.89	50.51	42.58	52.31	51.55	53.57	46.10	46.99	42.40
0.24	0.52	0	0	0	0	0.41	0	0	0	0.28	0	0
16.55	3.06	12.54	1.42	4.26	5.59	16.33	3.70	2.79	3.21	13.41	13.39	15.80
27.74	27.86	28.32	29.15	26.19	21.96	22.72	22.22	22.42	19.71	18.30	17.03	24.12
0.68	0.43	0.26	0.41	0.32	0.40	0.48	0.78	0.50	0	0	0.23	0.33
10.04	14.54	10.93	15.01	15.66	18.65	13.75	19.21	19.41	21.59	18.49	19.99	13.62
0.48	0.024	0.50	0.35	0.32	0.41	0.44	0.18	0.35	0.14	0.21	0.19	0.30
1.50	0.031	1.00	0	0.87	1.01	1.70	0.55	0	0.61	1.61	0.90	1.56
0	0	0	0	0	0.12	0	0	0	0	0	0	0
98.15	97.95	97.91	98.31	98.51	98.65	98.41	98.96	97.02	98.88	98.40	98.71	98.13
23 O atom formulas												
6.186	7.612	6.687	7.764	7.503	7.311	6.252	7.531	7.576	7.594	6.584	6.632	6.277
1.814	0.288	1.313	0.236	0.497	0.689	1.748	0.469	0.424	0.406	1.416	1.368	1.723
8.000	8.000	8.000	8.000	8.000	8.000	8.000	8.000	8.000	8.000	8.000	8.000	8.000
1.135	0.151	0.915	0.013	0.244	0.265	1.077	0.159	0.059	0.129	0.843	0.859	1.033
0.026	0.059	0	0	0	0	0.045	0	0	0	0.029	0	0
3.506	3.478	3.570	3.642	3.228	2.658	2.788	2.675	2.755	2.336	2.185	2.010	2.986
0.086	0.054	0.033	0.051	0.039	0.049	0.060	0.095	0.062	0	0	0.027	0.041
2.263	3.238	2.457	3.343	3.441	4.025	3.010	4.122	4.252	4.564	3.938	4.206	3.008
0.078	0.038	0.080	0.055	0.050	0.063	0.069	0.28	0.056	0.022	0.033	0.029	0.047
7.094	7.018	7.055	7.104	7.002	7.060	7.049	7.079	7.184	7.051	7.028	7.131	7.115
0.439	0.087	0.291	0	0.248	0.282	0.482	0.153	0	0.169	0.446	0.247	0.447
0	0	0	0	0	0.022	0	0	0	0	0	0	0
0.439	0.087	0.291	0	0.248	0.304	0.482	0.153	0	0.169	0.446	0.247	0.447
0.608	0.518	0.592	0.521	0.484	0.398	0.481	0.402	0.393	0.339	0.357	0.323	0.498

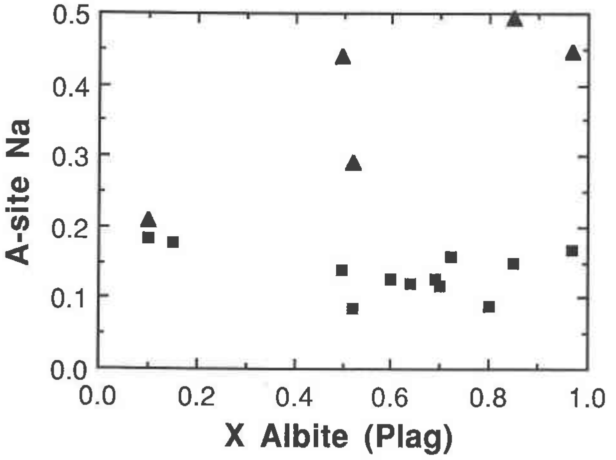

Fig. 7. Plot showing Na in the A-site vs. albite content of plagioclase. Symbols are the same as in Figures 5 and 6. Note that the Na content of A-sites in gedrite seems to correlate more strongly with plagioclase composition than that of A-site occupancy in anthophyllite, which seems to be independent of the Na content of coexisting plagioclase.

number of pairs, some inconsistency in gap width can be seen and probably reflects the range in temperature over which these samples equilibrated. In fact, three samples from the higher-*T* western end of the field area in Träskböle and Perniö, 343, 218-A, and PN-3A, all contain one amphibole which falls well within the gap. We presume that these samples must have equilibrated at temperatures above the crest of the gedrite-anthophyllite solvus which Spear (1980) suggests is at about 600 °C (±25 °C). We have used data on coexisting garnet and biotite from three samples, OR-12B, PN-3A, and PN-3B, to calculate metamorphic temperatures for the Orijärvi-Perniö area.

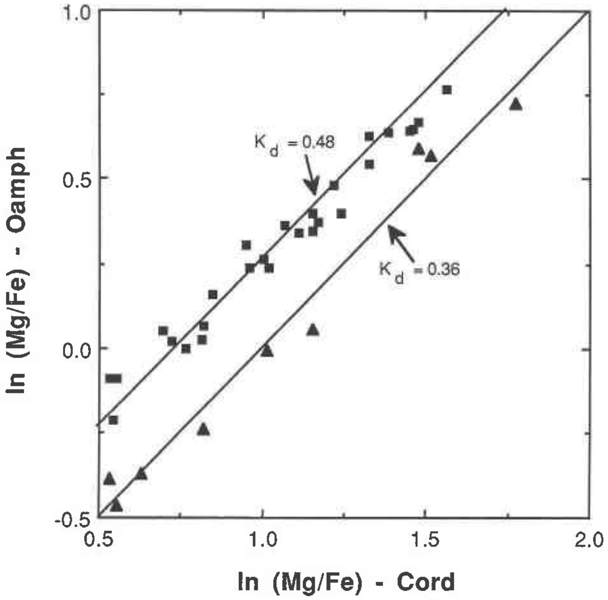

Fig. 8. Plot showing the distribution of Fe and Mg between orthoamphiboles and cordierite. Symbols are the same as in the previous figures. The numbers on the diagram indicate the slopes of the least-squares best-fit lines through each set of data, and therefore the mean K_d (Mg-Fe) (see text) for anthophyllite-cordierite (0.48) and gedrite-cordierite (0.36).

The garnets are sufficiently close to almandine-pyrope solid solutions to allow use of the garnet-biotite thermometer of Ferry and Spear (1978), with almandine and pyrope activities calculated using the model of Hodges and Crowley (1985). Calculated temperatures are 575 °C for PN-3A, 580 °C for PN-3B, and 600 °C for OR-12B. These temperatures are reasonably consistent with data

TABLE 3. Representative microprobe analyses of biotite

	OR-8A	OR-12B	OR-27D	OR-35B	OR-40B	218-B
SiO_2	38.25	36.10	35.64	38.98	35.70	40.19
TiO_2	1.54	1.34	1.68	1.05	1.91	0.72
Al_2O_3	18.54	18.06	18.28	16.40	17.43	15.35
FeO	15.46	19.83	19.27	14.18	21.48	10.02
MnO	0	0	0.25	0	0.26	0
MgO	14.38	11.49	12.77	16.89	11.09	20.66
Na_2O	0.65	0.54	0.72	0.80	0.50	0.95
K_2O	8.02	8.23	7.99	7.77	7.94	7.82
Total	96.84	95.59	96.60	96.25	96.31	95.71
			11 O atom formulas			
Si	2.773	2.725	2.662	2.831	2.702	2.874
Al	1.227	1.275	1.338	1.169	1.298	1.126
Total	4.000	4.000	4.000	4.000	4.000	4.000
Al	0.357	0.332	0.271	0.235	0.429	0.168
Ti	0.084	0.076	0.095	0.057	0.109	0.038
Fe	0.937	1.252	1.203	0.861	1.359	0.600
Mn	0	0	0.015	0	0.016	0
Mg	1.554	1.294	1.442	1.828	1.251	2.202
Total	2.932	2.954	3.006	2.981	3.164	3.008
Na	0.091	0.080	0.105	0.112	0.074	0.132
K	0.742	0.792	0.761	0.720	0.766	0.713
Total	0.833	0.872	0.866	0.832	0.840	0.845
Fe/(Fe + Mg)	0.376	0.492	0.458	0.320	0.521	0.214

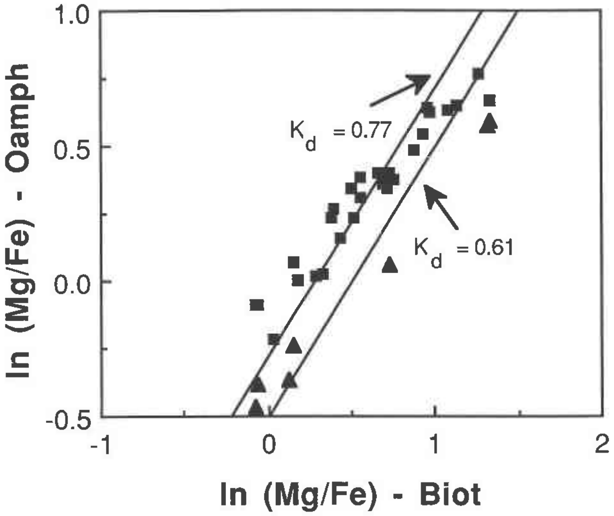

Fig. 9. Plot showing the distribution of Fe and Mg between orthoamphibole and biotite. Symbols are the same as in the previous diagrams. Numbers on the diagram show the mean K_d (Mg-Fe) for anthophyllite-biotite (0.77) and gedrite-biotite (0.61). Note that the scatter is slightly greater in this diagram than in Figure 8, possibly because of greater degree of postequilibration readjustment in biotite compositions.

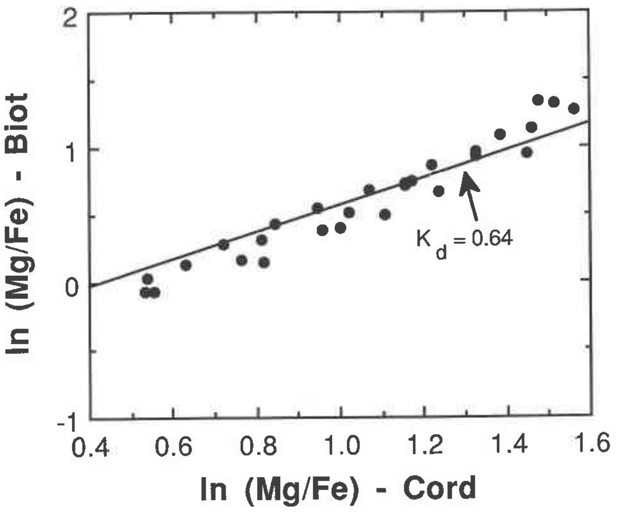

Fig. 10. Plot showing distribution of Fe and Mg between cordierite and biotite. Mean K_d (Mg-Fe) is 0.64. The relatively low scatter is an indication of the small temperature range of equilibration for the samples.

reported by Schreurs (1985) and with the observed orthoamphibole compositions and are about 15–65 °C higher than the Post Pond orthoamphibolites (Spear, 1980) and about 50–75 °C lower than Amphibole Hill (Robinson et al., 1971).

The relation of A-site occupancy to $^{[4]}$Al is shown in Figure 6. For most samples there is a clear correlation of A-site and $^{[4]}$Al which reflects the operation of the edenite substitution superimposed on Tschermak's substitution. The three higher-*T* samples noted above not only fall within the solvus limits, but also seem to be anomalously low in A-site occupancy for the $^{[4]}$Al content. This indicates a predominance of the Tschermak over the edenite substitution in these samples, which may be either caused by higher temperature or by low Na concentrations in the bulk rock. The general scatter of the data in Figure 6 is very likely caused by random differences in Na content from rock to rock. Na in the A-site reflects the extent of the edenite substitution, which should be controlled by the activity of $NaAlO_2$ in the rock and therefore by the activity of albite in the plagioclase in a quartz-bearing rock. Figure 7 is a plot of Na in the A-site of anthophyllite and gedrite vs. the mole fraction of albite in plagioclase. Despite the paucity of data, there appears to be a positive correlation for gedrite, but virtually no correlation, or perhaps a slight negative one, for anthophyllite. There is a similarly poor correlation for orthoamphibole-plagioclase pairs reported by Spear (1980), but the range in plagioclase composition he observed (approximately An_{10}–An_{40}) is considerably less than that of the Finnish samples (An_{10}–An_{90}).

Fe-Mg distribution between ferromagnesian phases in the orthoamphibolites is displayed in Figures 8, 9, and 10, which are similar to plots used by Spear (1982). The straight lines have slopes of 1.0 and are drawn by eye through each set of data. The vertical position of each line gives the mean K_d (Mg-Fe) for that mineral pair. The distribution of data in Figure 8 (orthoamphibole vs. cordierite) is considerably more regular than that in Figure 9 (orthoamphibole vs. biotite). This effect is undoubtedly caused by a relative insensitivity of orthoamphibole-cordierite K_d (Mg-Fe) to changes in *T* compared to orthoamphibole-biotite K_d (Mg-Fe). The mean K_d (Mg-Fe) values for the Orijärvi samples are 0.36 (range = 0.34–0.39) for gedrite-cordierite, 0.48 (0.43–0.54) for anthophyllite-cordierite, 0.61 (0.48–0.72) for gedrite-biotite, and 0.77 (0.61–0.98) for anthophyllite-biotite. Mean K_d (Mg-Fe) for biotite-cordierite is 0.64 (see Fig. 10). These values are about 15–25% higher than similar ratios from the Post Pond volcanics, Vermont (Spear, 1982) and undoubtedly reflect higher metamorphic temperatures in Finland (about 550–600 °C) than in Vermont (535 °C).

PHASE RELATIONS

The assemblages reported in this study are of considerable interest because of the wide range of bulk compositions represented by the orthoamphibole-bearing rocks. Figure 11 illustrates the chemographic relationships of mineral compositions in Al-Fe-Mg subspace of KNFMASH for the ferromagnesian phases anthophyllite, gedrite, cummingtonite, cordierite, and garnet, but exclusive of biotite. It is clear that this diagram does not function well as a phase diagram because of significant amounts of unrepresented components in several of the phases, notably Ca and Mn in garnet, and Na in gedrite.

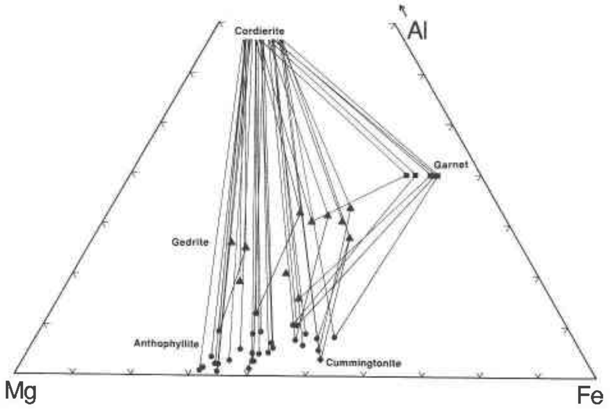

Fig. 11. Ternary Fe-Mg-Al diagram illustrating the chemography of ferromagnesian phases and assemblages (exclusive of biotite) in the Orijärvi orthoamphibolites, based on microprobe analyses. Anthophyllite is indicated by filled circles, gedrite by triangles, cummingtonite by diamonds, and garnet by squares.

In addition, there may well be a range in temperature as large as 50 °C within the group of samples plotted, but it is nonetheless interesting to note the rather wide spread of mineral compositions within the assemblages cordierite + gedrite + anthophyllite and cordierite + anthophyllite + garnet (± gedrite). The similarly large variation within cordierite + anthophyllite assemblages is to be expected for a two-phase assemblage even without a variation in intensive parameters. The spread in three-phase triangles may be great enough, however, to be taken as evidence for local variation in bulk composition (most assemblages are not particularly low variance) or in μH_2O from rock to rock. If the assemblages portrayed in Figure 11 are related by reaction, the cordierite-gedrite-anthophyllite triangles would be predicted to shift toward the Mg side of Figure 11 with progress of a multivariant reaction such as anthophyllite + cordierite + ab component of plag = gedrite. The involvement of albite component is required by the substantial Na content of the gedrite.

Schematic phase relations in the generalized composition space FeO-MgO-Al_2O_3 have been shown by Robinson and Jaffe (1969a) and by Robinson et al. (1982) for a wide variety of metamorphic grades. Robinson and Jaffe (1969a) suggested that the observations of Eskola (1914) required a chemography such as that shown in Figure 12a. Of particular interest to them was the issue of the relationship of anthophyllite, cordierite, and cummingtonite. They suggested that because cummingtonite was slightly more Mg rich than anthophyllite, cummingtonite + cordierite assemblages would be limited to Mg-rich compositions and would be reacted away by progressive leftward movement, with increasing grade, of the three-phase triangle defined by cummingtonite + cordierite + anthophyllite in Figure 12a.

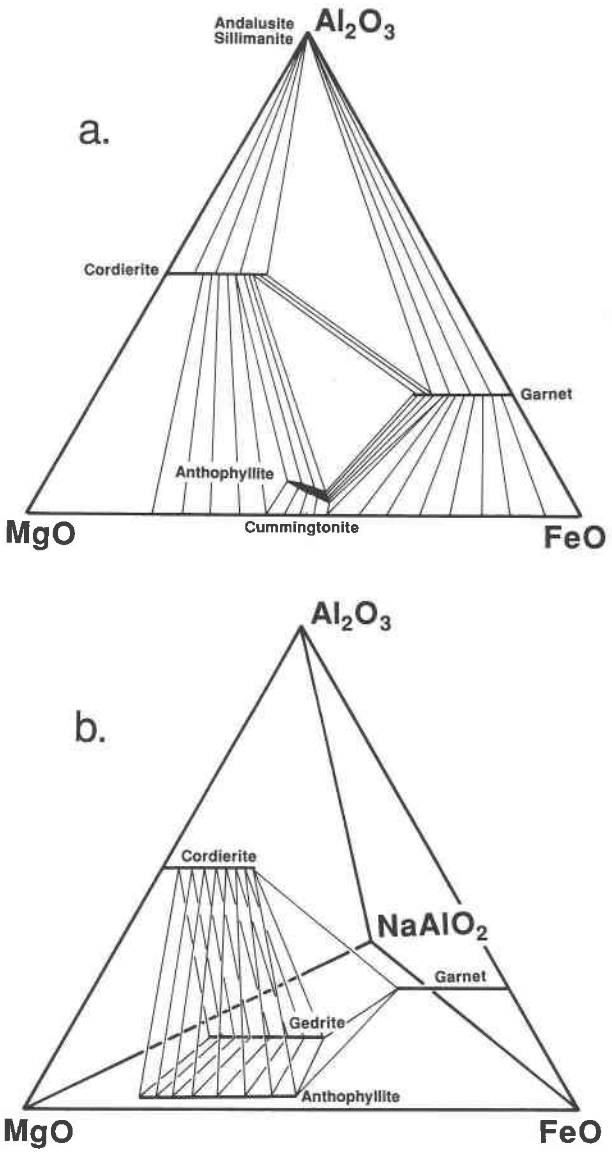

Fig. 12. (**a**) Chemographic relationships (projected from SiO_2 and H_2O) in orthoamphibolites from Orijärvi (Träskböle) based on observations of Eskola (1914) as interpreted by Robinson and Jaffe (1969a). (**b**) Generalized chemographic relationships from the observations of this study, shown in the Al_2O_3-MgO-FeO-$NaAlO_2$ tetrahedron projected from SiO_2 and H_2O. Note especially the composition subspace just behind the front face of the tetrahedron in which multivariant three-phase assemblages, cordierite + anthophyllite + gedrite define planes.

Our observations suggest a slightly more complicated chemography than that of Robinson and Jaffe (1969a), although the paucity of cummingtonite-anthophyllite pairs in our data set precludes a decisive statement regarding cummingtonite relations. Our best choice of a composition space for illustrating the phase relations is the tetrahedron Al_2O_3-FeO-MgO-$NaAlO_2$, shown in Figure 12b. The relative abundance of anthophyllite-gedrite pairs requires that both phases be shown explicitly. Most orthoamphibolite bulk compositions fall within the space outlined by the planes defined by cordierite + anthophyllite + gedrite, although the few garnet-bearing samples fall within the four-phase volume at the Fe-rich end of this three-phase space.

One observation of this study, which was noted above and which bears on the role of cummingtonite in the phase relations, is illustrated in Figure 4. In several samples, cummingtonite grains within large, spongy cordierite grains have reacted with cordierite to form rims of orthoamphibole, but in this case it is gedrite, not anthophyllite as cited for this general reaction texture by Robinson et al. (1982). The thin gedrite reaction rim shown in Figure 5 has a very sharp boundary against both cummingtonite and cordierite. Cummingtonite in this texture typically has less than 1 wt% Al_2O_3, whereas gedrite has between 15 and 17 wt%. Although the rimming textures suggest a simple reaction between host and inclusions and the Al can be accounted for in reaction between cordierite and cummingtonite, the gedrite also contains substantial Na (>1.5 wt%), which is not available in the local environment. The source of Na is presumably plagioclase, the only major Na reservoir in the rock. Therefore the reaction of cummingtonite plus cordierite to gedrite, which is obviously a multivariant net-transfer reaction in the simple FMASH composition space, must actually be described in NFMASH. Although our samples do not allow us to demonstrate the effect, we can predict that the presence or absence of gedrite reaction rims probably depends upon the plagioclase composition in the rock, i.e., on $\mu NaAlO_2$. Therefore, gedrite would be found in rocks with sodic plagioclase, whereas, in the presence of calcic plagioclase, cummingtonite plus cordierite would remain stable. The limiting plagioclase composition presumably shifts toward higher anorthite content with increasing metamorphic grade.

ALUMINOUS ENCLAVES

Petrography and mineral chemistry

Armored enclaves containing moderately to very aluminous minerals have been reported from relatively few gedrite-cordierite gneisses, including Träskböle (Eskola, 1914, p. 179–181), Ontario (James et al., 1978), India (Lal et al., 1984), and the Italian Alps (Droop and Bucher-Nurminen, 1984), although the most detailed report is from southern New Hampshire (Robinson and Jaffe, 1969b; Schumacher and Robinson, 1987). The report by Eskola is of single crystals or polycrystalline masses of sillimanite separated from the enclosing anthophyllite (or gedrite) gneiss by thin rims of cordierite. Robinson and Jaffe (1969b, p. 410–418) observed this texture in the New Hampshire rocks, although with corundum as well as aluminum silicate, and described it as a step in a series of decompression reactions whereby sillimanite (or kyanite), gedrite, and quartz first reacted to form cordierite, then sillimanite (or kyanite) + gedrite was replaced by cordierite + corundum (Robinson and Jaffe, 1969b, Fig. 7, p. 413). Corundum is not a primary, but a secondary phase, in their explanation. They also observed a rich variety of aluminous assemblages containing the above minerals as well as spinel, staurolite, calcic plagioclase, and rutile. Schumacher and Robinson (1987) reported sapphirine, in addition, and performed a detailed petrologic analysis of the enclave-forming process.

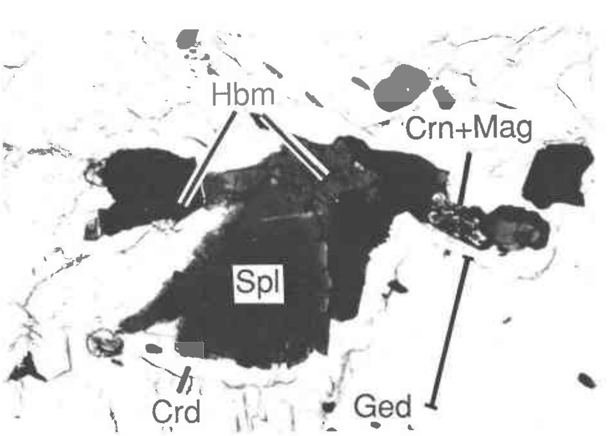

Fig. 13. Photomicrograph of a typical aluminous enclave from sample 336. Horizontal field of view is 2.2 mm. Gedrite (Ged) host encloses oxide aggregate consisting of magnetite (opaque), aluminous spinel (Spl), högbomite (Hbm), and magnetite-corundum symplectite, all separated from gedrite by a rim of cordierite (Crd). The bar in the lower right corner of the photograph indicates the position of the microprobe traverse in gedrite shown in Figure 14.

Eskola did not report observing corundum in the enclaves, but in our samples it is an essential constituent. In fact, we observed no sillimanite or quartz in enclaves, only various mixtures of corundum, spinel, magnetite, chlorite, and högbomite. This latter aluminate mineral is commonly ascribed to being secondary after spinel, but gives every appearance of being primary in our samples. A photomicrograph of a typical enclave is shown in Figure 13. In this particular sample (PMO 336), point counting reveals that the total rock comprises 72% by volume of gedrite-rich host rock and 28% enclaves, of which 15.8% are oxide cores and 12.2% are chlorite-cordierite rims. The host rock is 98.2% gedrite, 1.5% cordierite, and 0.3% magnetite. The oxide cores to the enclaves are 34.6% magnetite-corundum symplectite, 25.6% discrete magnetite, 37.7% aluminum spinel, and 2.1% högbomite. Enclave rims are 75.5% cordierite and 24.5% chlorite.

Electron microprobe analyses indicate that the magnetite and corundum are essentially stoichiometric, except that the magnetite has detectable but minor V_2O_5 (<0.5 wt%). Compositions of the other phases in the enclave are as follows: cordierite—$Mg_{1.71}Fe_{0.28}Al_{3.99}Si_{5.01}O_{18}$; spinel—$Mg_{3.86}Fe^{2+}_{4.16}Ti_{0.03}Fe^{3+}_{0.59}Al_{15.35}O_{32}$; högbomite—$Mg_{2.30}Fe^{2+}_{3.51}Zn_{0.02}Mn_{0.01}Al_{15.55}Fe^{3+}_{0.77}\square_{0.84}Ti_{0.84}O_{32}$; chlorite—$(Mg_{3.97}Fe_{0.66}Al_{1.33})Si_{2.70}Al_{1.30}O_{10}(OH)_8$. Host gedrite shows substantial variation in Al_2O_3 content, from about 17 wt% at the enclave margin to less than 5 wt% away from enclaves. A microprobe traverse in gedrite adjacent to an

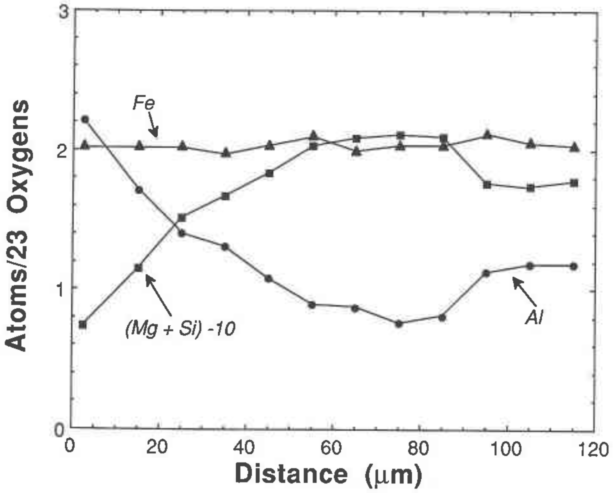

Fig. 14. Gedrite zoning profile for Al, (Mg + Si) and Fe adjacent to the aluminous enclave from sample 336 shown in Figure 13. Note that (Mg + Si) has been scaled so as to be consistent in magnitude with Fe and Al.

enclave margin, shown in Figure 14, demonstrates that the shift in Al is balanced by Mg and Si, in an almost perfect Mg-Tschermak's substitution, with virtually no change in Fe content along the traverse.

Genesis of Orijärvi enclaves

The scenario we envision for formation of the enclaves starts with a coarse gedrite-rich gneiss containing roughly evenly spaced intergrowths of magnetite and corundum, perhaps similar to the bits of symplectite left in the enclave shown in Figure 13. In some gedrite gneiss samples, we have seen such magnetite-corundum intergrowths, but without any enclave development. We have no definitive explanation for the origin of these intergrowths, but believe they may represent original heterogeneities in the altered volcanic protolith. Accepting the arguments of Robinson and Jaffe (1969b) that the enclave-forming reactions occurred during decompression, we argue that under conditions at, or just following, the peak of metamorphism, the coarse gedrite began to react with the oxide intergrowths. The assemblage can be shown on a diagram such as Figure 15, assuming that magnetite was passive and did not participate in the reaction. An approximate bulk composition for the rock is shown in the figure, as is a representative gedrite composition (the gedrite point farther from the Al corner). The initial net transfer reaction would have been gedrite + corundum = cordierite + spinel + H_2O. Note that the composition subspace in which reaction occurs is corundum saturated rather than quartz saturated, but that after the reaction the new tie line from spinel to cordierite isolates the bulk composition from corundum. Figure 15 also shows the chemography following reaction, including the variable range of post reaction gedrite, shown as the bar, limited by the most Al-rich gedrite adjacent to the enclaves (see Fig. 14).

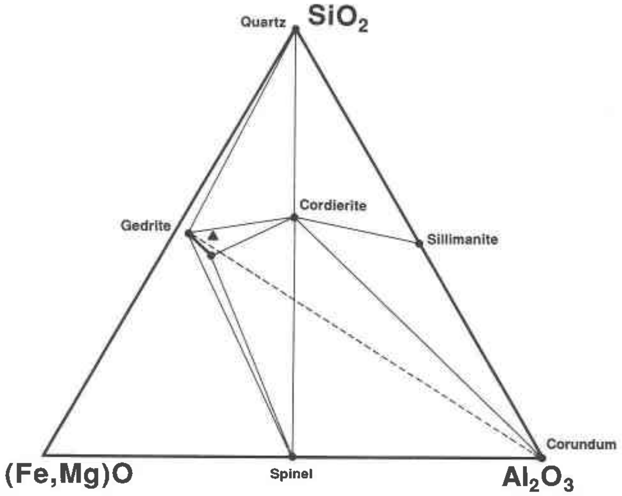

Fig. 15. Ternary (Fe,Mg)O-Al_2O_3-SiO_2 plot projected from H_2O showing the phase relations in aluminous orthoamphibolites before and after the development of armored aluminous enclaves. The filled triangle indicates the approximate bulk composition of silica-undersaturated gneisses containing gedrite + cordierite, such as sample 336, that contain corundum before enclave formation. The reaction Ged + Crn = Crd + Spl + H_2O caused the formation of the enclaves (see text) and caused the breaking of the tie line (dashed) from gedrite to corundum in favor of the new tie lines (solid), especially those from high-Al gedrite to cordierite, and from cordierite to spinel, the latter of which isolates gedrite from corundum. The line connecting the two gedrite compositions reflects the zoning shown in Figure 14.

However, the above reaction does not fully explain the peculiar texture of the enclaves in which cordierite forms a complete rim and none of the oxides are in contact with gedrite. The postreaction chemography of Figure 15 only precludes the coexistence of gedrite and corundum.

In order to explain both the gedrite zoning (Fig. 14) and the nucleation and growth of the cordierite rims, a second process is required. This second process is diffusion, and, to model it, we defined an exchange component $MgSiAl_{-2}$ that describes imperfectly but adequately the shift in gedrite composition adjacent to enclaves (there is also a minor edenite exchange vector, $NaAl\square_{-1}Si_{-1}$ that we will ignore in this treatment). There is some crystal chemical justification for definition of a $MgSiAl_{-2}$ component in orthoamphiboles (see Stout, 1972).

The initial net transfer reaction given above, in which the volume of gedrite decreases (that is, in which the edges of the gedrite grains were partially resorbed), must have enriched the remaining proximal gedrite in edenite component because there was no local sink for Na. Edenite may therefore be considered to have increased in the resorbed gedrite rim as an inert marker, or Kirkendall, effect. Enrichment of tschermakite component in rim gedrite may also have been amplified in this manner by preferential consumption of Mg and Si and, to a much lesser extent, Fe, in production of cordierite. The key to this process is the inhibition of further nucleation or growth of spinel with continued resorption of gedrite in reaction with corundum. Production of only cordierite at the enclave margins would have resulted in a significant increase of tschermakite component in the resorbed gedrite rims. The resorption reaction therefore may have established a strong concentration gradient, and therefore a negative chemical potential gradient, for the component $MgSiAl_{-2}$ in the gedrite, resulting in net outward diffusional transfer of Al.

Localization of spinel in the interiors of enclaves away from gedrite rims indicates that the spinel-producing net transfer reaction ceased before the cordierite-producing reaction. The relatively Fe-rich spinel produced by initial gedrite reaction with corundum must have nucleated on the preexisting aluminous minerals in the enclave, whereas the cordierite rim first nucleated on the aluminous minerals but then grew and thickened outward toward the gedrite, the source of Mg and Si. It is likely, though impossible to prove, that spinel nucleation difficulties, coupled with physical isolation of preexisting spinel grains from the gedrite rims, kinetically retarded further spinel production. Schumacher and Robinson (1987) proposed a similar mechanism to explain the separation of high-Al minerals from gedrite by cordierite rims in the enclaves from southwest New Hampshire. It is also likely that this coupled diffusion process operated virtually contemporaneously with the net transfer reaction, rather than as a separate, later event. If the zoning in gedrite (Fig. 14) developed during peak metamorphism as a result of volume diffusion in a chemical potential gradient, then virtually no Fe was transferred as compared to Mg, Si, and Al. There are two possible reasons for this behavior: low diffusional transfer velocity for Fe caused by inefficient volume diffusion of this ion, and much lower driving force, i.e., chemical potential gradient, for Fe than for the other components. There is no a priori reason to expect diffusion of Fe to be so much slower than for the other species, and therefore the latter explanation seems more likely. A reduced gradient in μFe relative to μMg could be due to the fact that the principal product mineral in the rim-forming process was an unzoned Mg-rich cordierite.

The proposed diffusion scenario is analogous to that proposed by Thompson (1959) for the development of monomineralic zones in a binary chemical system. It is, however, complicated by the extra component and the fact that one of the sources of a diffusing component is a phase that has the diffusing component as one of its solid solution exchange vectors. Also in contrast to the Thompson model, the diffusion process we describe is strongly self-limiting in that there is a finite, and rather small, amount of corundum at the Al-rich end of the diffusion pair. This may well be the limiting factor that restricts the scale of zoning in gedrite to about 100 μm, although volume diffusion rates, particularly for Al, may also be limiting. In either case, it is an important point that volume diffusion of Al on the scale of at least 100 μm is possible under metamorphic conditions. We refer the reader to Schumacher and Robinson (1987) for a very detailed general treatment of the process of enclave formation.

Finally, the substantial volume of chlorite found with cordierite in the rim is almost certainly a secondary hydration of the cordierite, perhaps nearly contemporaneous with the formation of the cordierite itself. Note that the Fe/(Fe + Mg) of the chlorite and cordierite, as listed above, are virtually identical.

SUMMARY

We have examined the petrology of a number of cordierite-bearing orthoamphibolites from Eskola's (1914) classic locality of the Orijärvi mine and adjacent areas in southwestern Finland. These rocks are similar to orthoamphibolites described from other localities, notably the well-described localities from New England. A number of samples contain relatively complex assemblages consisting of multiple amphiboles, cordierite, biotite, and garnet; we found several three-amphibole assemblages (anthophyllite, gedrite, and cummingtonite), as well as a substantial number of anthophyllite + gedrite assemblages. We have documented metamorphic conditions of about 550–600 °C for the Orijärvi area that are in accord with earlier studies and indicate that conditions are approximately those of the crest of the orthoamphibole two-phase region (Robinson et al., 1982). Several of our samples from the higher temperature part of the area contain single orthoamphiboles with compositions straddling the gaps found in the lower temperature two-amphibole rocks.

Phase relations in the cordierite-orthoamphibole gneisses, as shown in various projected subspaces within the NFMASH composition space, are fairly regular and indicate that most assemblages are high variance to the extent that bulk compositions typically control mineral chemistry. The most interesting question concerning phase relations of the Orijärvi gneisses is the involvement of cummingtonite, dealt with by Eskola (1914) and Robinson and Jaffe (1969a). Our observations and data suggest that cummingtonite + cordierite was a stable association up to peak metamorphic conditions, but that either at or near peak conditions these two minerals reacted to form gedrite in common bulk compositions. The gedrite-forming reaction must have involved some sodic phase, presumably plagioclase, and may have been retarded in rocks with more calcic plagioclase, and therefore lower albite activity.

The most petrographically unusual feature of the higher-grade samples is the occurrence of armored aluminous enclaves containing corundum, magnetite, spinel, högbomite, and cordierite, in which the cordierite separates all other phases from contact with gedrite. Eskola (1914) reported much simpler enclaves of sillimanite and cordierite from his samples. There are relatively few reports of similar texturally and mineralogically complex enclaves, suggesting that the phenomenon of enclave formation is not common. The production of the minerals and textures of the enclaves is a result of two processes.

The first is a late-stage reaction, possibly caused by decompression, in which coarse host gedrite and small aluminous intergrowths reacted to form cordierite and other aluminous products. In Orijärvi, at least some of the aluminous intergrowths were corundum rich, whereas in New Hampshire they all appear to have contained kyanite or sillimanite. The second, which accompanied and amplified the development of the unusual armored texture of cordierite rims, was caused by enrichment of resorbed gedrite margins in tschermakite component. Strong gedrite zoning was produced by diffusion of Mg and Si through the gedrite toward the enclaves (to grow additional cordierite) and the consequent counterdiffusion of Al away from the enclaves. The process can therefore be viewed in sum as a complex volume interdiffusion of Mg, Si, and Al, with very little involvement of Fe. The growth of cordierite rims is therefore analogous to the development of monomineralic zones through diffusion first discussed by Thompson (1959). Although this process occurs only on a 100 μm scale, it does clearly indicate mobility of Al in volume diffusion at metamorphic conditions.

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